SNS ECONOMIC POLICY COUNCIL REPORT

Swedish Policy for Global Climate

2020

John Hassler (chair)
Björn Carlén
Jonas Eliasson
Filip Johnsson
Per Krusell
Therese Lindahl
Jonas Nycander
Åsa Romson
Thomas Sterner

SNS

SNS Economic Policy Council Report 2020

SNS Economic Policy Council Report 2020

Swedish Policy for Global Climate

John Hassler (chair)
Björn Carlén
Jonas Eliasson
Filip Johnsson
Per Krusell
Therese Lindahl
Jonas Nycander
Åsa Romson
Thomas Sterner

TRANSLATION: Clare Barnes

SNS

SNS
Box 5629
SE-114 86 Stockholm, Sweden
Phone: +46 8 507 025 00
www.sns.se

SNS, Center for Business and Policy Studies, is an independent, non-profit organization that brings together the worlds of academia, business and government for knowledge-sharing and dialogue on key societal issues. SNS is a membership-based organization with 260 corporate and institutional members.

SNS *Economic Policy Council Report 2020:*
Swedish Policy for Global Climate
John Hassler (chair), Björn Carlén, Jonas Eliasson, Filip Johnsson, Per Krusell, Therese Lindahl, Jonas Nycander, Åsa Romson, Thomas Sterner

Translation: Clare Barnes
Graphic design: Patrik Sundström

ISSN 1652-8050
ISBN 978-91-88637-59-8

Contents

PUBLISHER'S FOREWORD

CLIMATE POLICY is a complex area that requires many different perspectives. Insights from many scientific fields, including the natural sciences and the social sciences, are necessary to find ways of reducing carbon dioxide emissions. This was SNS's point of departure when appointing the SNS Economic Policy Council 2020, and also the reason for which the number of council members was increased. As usual, the council is dominated by economists, but for this year's report, it also includes climate researchers who are experts in law, natural science, and technology. The participating economists have different specializations in their climate research, including macroeconomics, behavioral economics, analysis of different policy instruments, and sustainability. The members of the council are presented at the end of the report on pp. 353–355.

The SNS Economic Policy Council 2020 examines the natural science basis for understanding climate change and analyzes Swedish climate policy, while also highlighting a number of central questions that need answers. One is whether local climate targets can contribute to effective climate policy, and another, whether Sweden should keep its nuclear power for climate reasons.

SNS's hope is that this report will lead to increased knowledge about climate change and the measures that can improve the effects of climate policy. Our aim is that the researchers' analysis and proposals will contribute to a broad and constructive discussion, in Sweden as well as internationally, about how policy should be framed so as to achieve the desired reductions in carbon dioxide emissions.

The report's authors are responsible for its analysis, conclusions, and proposals. As an organization, SNS does not have an opinion on these; SNS's task is to initiate and present research-based analyses of important societal issues.

Markku Rummukainen, professor of climatology at Lund University, climate adviser for the IPCC's national hub at SMHI, and member of the Swedish Climate Policy Council, has reviewed a draft of this report at a seminar, as has *Svante Axelsson*, national coordinator for the Fossil Free Sweden initiative. SNS thanks them both for their valuable comments.

SNS also wishes to thank the Jan Wallander and Tom Hedelius Foundation for its financial support.

Stockholm, November 2020
MIA HORN AF RANTZIEN
CEO, SNS

Summary

In this report, our aim is to address the question of *how* policy can achieve the desired reductions in carbon dioxide emissions. The report takes for granted that action on the climate issue is necessary, so the focus is not on how much less carbon dioxide we should emit, whether this be globally, nationally, locally, or individually.

The question of *how* cannot be answered by natural science alone, but it does require an understanding of how the global climate system works and how it is affected by the concentration of greenhouse gases in the atmosphere. An understanding of how carbon circulates between different reservoirs, such as the atmosphere, biosphere, and the oceans, is needed. Social science is also required in order to understand how the global economy works and how different types of climate policy impact the use of fossil fuels and other fuels. Finally, it is important to know how international agreements can emerge and be maintained. Part 1 of this report therefore begins with a description of these complicated, interlinked systems.

In Part 2, we describe Swedish climate policy and analyze it using

the systems description from Part 1, while also presenting suggestions for changes to Swedish climate policy. Part 3 concludes the report by providing our answers to some salient questions about current climate policy.

We, the authors of this report, have all conducted research on climate issues. Our backgrounds are quite mixed; we represent different disciplines in the social sciences, law, and natural sciences. We agree on the descriptions of the climate system and the global economy, as well as on the description of the mechanisms through which climate policy has an impact and why climate policy is necessary. Conclusions about the most effective policy depend on, among other things, assessments of the relative strength of various mechanisms. In most cases, our assessments are similar and we agree on our recommendations, but occasionally our assessments differ. In those cases, this is clearly stated.

Economists analyze how policy can be used to influence the decisions of individuals and businesses in a market, such as on the use of fossil fuels. This, along with the fact that many—but not all—of us on the Economic Policy Council 2020 are economists, has meant that our answers to *how* generally use economic methods, although we do not reject other approaches. We have tried to consider perspectives from other sciences whenever possible, but the composition of the group has meant that these are largely outside the scope of our analyses in this report.

1.1 Part I

1.1.1 What causes climate change?

For the Earth's climate to be in equilibrium, the incoming flow of energy from the sun must be balanced by an equal outward flow from Earth to space. More greenhouse gases in the atmosphere lead to an imbalance between the inflow and outflow of energy, resulting in an increase in the average temperature of the Earth until balance is regained. How much the temperature needs to rise before this balance is achieved is not known with certainty, because it is very difficult to assess the strength of some feedback mechanisms, particularly cloud formation.

The most commonly used interlinked global climate and carbon system models show that the global average temperature increases by an approximately constant number of degrees for every additional emitted unit of carbon dioxide. However, there is great uncertainty about the quantitative relationship, because different models give different results. The IPCC provides an interval of 0.8–2.5 degrees Celsius per 1 trillion tons of carbon. So far, globally, we have released almost 600 billion tons. If sensitivity is as low as 0.8 degrees, we can release three times as much again, which would take a couple of hundred years at current emission rates, and still not exceed 2 degrees of warming. If the sensitivity is 2.5 degrees, we can only release another 200 billion tons (which would take 20 years at current rates) and emissions must cease immediately and entirely to keep the world below 1.5 degrees of warming.

Using simulation modelling, research has tried to identify the risk of "tipping points." These are self-reinforcing mechanisms that may cause irreversible change in some parts of the climate system once a critical level of climate change has been reached. Assessing the risks of such mechanisms occurring is genuinely difficult, not least because they typically cannot be calibrated against historical observations.

There is very limited scientific support for the perception that soon it will be “too late” to act, that we are approaching a situation in which climate change will accelerate out of control. Equally, there is very limited scientific support for the idea that the warming now being observed is not linked to manmade emissions. Based on scientific evidence, we cannot rule out climate sensitivity being so small that there is no urgency to reduce emissions, but nor can we rule out climate sensitivity being so great that we have already exceeded the emissions level that would keep us below 1.5 degrees Celsius of warming.

1.1.2 What impact will climate change have?

The extent of the predicted climate change, and its effects, will depend on the scale of future emissions. The commitments now decided under the Paris Agreement are estimated to lead to global warming of around 3 degrees Celsius, with a substantial uncertainty interval. A more pessimistic scenario, with emissions continuing to increase throughout this century, has a predicted warming of 4.3 degrees, with an uncertainty interval of 3.2–5.4 degrees.

There are many aspects to climate change. Sea levels are estimated to rise by half a meter to a meter over this century and, even if the number of tropical storms does not increase, it is likely that the very strongest ones will be more frequent. There is uncertainty about its effects on agriculture, because carbon dioxide in itself boosts plant growth, but climate change could have negative consequences. Densely populated areas, including parts of Asia, may experience heat waves during which it is physiologically impossible to work outdoors.

Depending on the region and the ability to adapt, climate change's impact on economies and people's well-being will vary greatly. One summary of studies that review the global consequences shows damage at about 5 percent of GDP at 2 degrees Celsius of warming, with 10 percent at 3 degrees, although there is wide variation in the studies' results. Climate change does not threaten the survival of humanity, but it may have catastrophic consequences for some countries.

Our assessment is that the direct effects in Sweden will be small compared to our GDP. Indirect effects caused by the impact of climate change on the world around us, such as trade, migration, international conflicts, and an increased need for international aid could be significant, but are very difficult to assess.

1.1.3 The global energy system

Global energy supply is dominated by fossil fuels, which have stood at around 80 percent for many decades. Fossil-based energy sources also dominate the supply of energy in the EU, but not in Sweden. In 2017, renewable sources of energy represented 39 percent of Sweden's energy supply, with nuclear fuel at 31 percent and fossil fuels at 26 percent.

One important difference between energy sources is whether they are plannable. For example, the supply of energy from wind cannot be planned, it just depends on how much wind there is. A larger share of non-plannable power will increase variation in electricity prices, boosting the profitability of plannable forms of power that have enough flexibility. This includes the combustion of gas or biofuels, as well as storage and measures that increase variations in demand. Differences in plannability mean that forms of power with different average costs per supplied unit of energy can be profitable at the same time.

Conventional oil is traded on a global market and is cheap to extract and transport in relation to its price. Reduced use in Sweden tends to increase use somewhere else; a drop in domestic oil use leads to *leakage*. The situation is different for coal, where a fall in demand in one part of the world is not likely to lead to substantial increases in use somewhere else. Consequently, Swedish exports of fossil-free electricity to countries with a large share of coal power can have a major effect on overall emissions.

The price of renewable energy has fallen over the last few years and the global use of these energy forms has risen, but without any decline in the use of fossil fuels. Simply lowering the price of green energy is not enough to achieve the necessary reduction in carbon dioxide emissions. Instead, we need global policies that result in a sufficiently high price for carbon emissions. These policies are not yet in place.

1.1.4 Climate policy—theoretical starting points and practical considerations

Successful climate policy requires global coordination. Lower emissions entail costs for the emitter, while the benefits—as reduced climate change—are distributed around the world. This creates what is called a free-rider problem, which means that international agreements on policy are necessary.

Immediately banning all emissions is prohibitively costly, so other political solutions must be used. Centrally deciding plans for individual emitters would, in practice, lead to an extremely expensive transformation, one so expensive that it risks being politically impossible. Instead, the most cost-effective climate policy is to set a price on emissions, via taxes or an emissions trading system. In some situations, control via targets, regulations, and subsidies for technology may be beneficial, but this cannot replace a price on emissions. Even a moderate global price on emissions would have a large effect.

Climate policy affects the distribution of income and wealth. Even though such effects would probably not be large in countries like Sweden, they must be considered to gain broad policy acceptance. A policy that puts a price on emissions generates significant government revenues, thus generating a revenue base from which to compensate people who are particularly affected. However, this compensation should not entail reducing the price of emissions.

As stated above, there is a great deal of uncertainty about the scale of climate change and how much damage it will cause. Calculations show that an intelligent climate policy, based on the global pricing of greenhouse gas emissions, is a cheap form of insurance against the worst-case scenarios. In reality, there seems to be little reason to worry that a global carbon dioxide price will be too high.

1.1.5 Transforming the energy system

One important issue is the speed at which different fossil fuels should be phased out. Research results consistently show that the value of using conventional oil and gas is much greater than using coal. Conventional oil and gas can probably be used until they run out, without this posing a threat to the climate, whereas the opposite is true for coal and non-conventional reserves of gas and oil. Most of these reserves should stay in the ground.

Swedish ambitions for climate policy require the exchange of fuel and technology, as well as the introduction of techniques for capturing and storing carbon dioxide (CCS). Sweden has good natural conditions for wind power. Solar power currently accounts for only a very modest share of energy supply; even if it is making advances, it will probably be limited to niche production in decentralized systems for the foreseeable future.

Bioenergy is an important element of Sweden's energy supply, accounting for around 25 percent. However, the combustion of biofuel produces carbon dioxide emissions that have the same climate effects as carbon dioxide from fossil sources. The difference between biofuel and fossil fuel is that growing forests to produce biofuel absorbs carbon dioxide from the atmosphere, giving Swedish silviculture the chance to increase the amount of carbon stored in forests and in soil. This also potentially allows increased biomass extraction over time. However, there is substantial uncertainty about the climate benefit of imported biofuel, although work is being conducted on biofuel certification.

In Sweden, nuclear power contributes about 40 percent of the total electric power generation. A decision has been made to decommission the Ringhals 1 and 2 reactors, based on a commercial evaluation by the owners. Whether or not this is compatible with socioeconomic and climate policy considerations is quite unclear.

Capturing and storing carbon dioxide will be a vital part of achieving ambitious global climate targets. The conditions for carbon sequestration in forests and soils are good in Sweden. Sweden also has great potential for the use of CCS technology to capture and store carbon dioxide from major sources of emissions, such as co-generation plants for heat and electricity, cement, and steel manufacturing. The cost per captured ton of carbon dioxide, using current technology, is of the same order as the Swedish carbon dioxide tax. However, the current price of emission allowances is too low to make this technology commercially viable.

1.1.6 International measures to combat climate change

The Kyoto Protocol was negotiated in 1997; the idea was to use a top-down process to make international agreements about the extent to which participating countries would reduce their carbon dioxide emissions. Instead, under the Paris Agreement, each party unilaterally decides and submits its own emission reduction plan. The countries cannot then renege on this and are expected to gradually increase their commitments. Agreement on a global price for emissions has not been an important part of international negotiations.

EU member states have coordinated their commitments under the Paris Agreement; this shared EU commitment entails a 40 percent reduction in emissions by 2030 for the EU as a whole. The EU's reduction in emissions will be achieved partly through its emissions trading system (EU ETS), which covers just over 40 percent of emissions, and partly through the effort sharing regulation (ESR) that covers the remainder. The EU's long-term target is to reduce the emission of greenhouse gases to 80-95 percent of 1990's levels by 2050. In December 2019, the leaders of all EU member states, excluding Poland, agreed on the more ambitious target of making the EU climate-neutral by 2050.

The EU ETS was reformed in 2018, when the decision was made to reduce the number of emission allowances issued every year at a faster rate. A system is also being introduced to automatically cancel emission allowances if too many of them are saved. After these reforms, measures to reduce emissions will lead to more emission allowances being cancelled, but ones that increase demand for emission allowances will reduce cancellations and increase emissions.

As part of the EU's regulations for burden sharing, member states have agreed on the allocation of responsibility for reducing emissions outside the ETS. Richer countries, such as Sweden, are obligated to do more. To prevent significant differences in marginal abatement costs within the EU, member states can trade emission allocations with each other, allowing reductions in emissions to be distributed across the union in a cost-effective manner.

Climate clubs offer a way to deal with climate policy's free-rider problem. Within a climate club, a common emission price is implemented and imports from countries outside the club are subject to a tariff. This tariff can either be charged in relation to how much carbon dioxide is emitted in the production of an imported good, or as a general tariff. There are legal and practical problems that must be solved before climate clubs can become reality, but solutions to these problems should be sought.

1.2 Part II

1.2.1 Sweden's carbon dioxide emissions

Fossil fuel use increased globally, including in Sweden, until the oil crises of the 1970s. This trend broke in Sweden in around 1970, but not in the world as a whole. The use of fossil fuels within Sweden's borders almost halved between 1970 and 1990 due to the rapid expansion of nuclear power and combined power and heating. This decline has continued, but at a considerably slower rate and, if emissions related to Swedish consumption are included, there has actually been no downward trend in emissions. Sweden's territorial contribution to increased levels of atmospheric carbon dioxide, i.e. net total emissions minus the net capture in forests and soils, has fallen significantly between 1990 and 2017.

1.2.2 Sweden's climate policy targets

The Swedish Climate Policy Framework includes a long-term emissions target, two milestone targets, and one target specifically for the transport sector.

The long-term target states that Sweden's net emissions of greenhouse gases will be zero by 2045, then be negative. This should be achieved through Swedish territorial emissions being at least 85 percent lower than in 1990. The remaining emissions should be compensated for by using supplementary measures, including the separation of carbon dioxide from biogenic emissions, paying for reduced emissions in other countries, and increasing carbon sequestration in forests and soils.

Unlike the long-term target, the milestone targets are for emissions in the ESR sector, i.e. the parts of the economy that are not covered by EU emissions trading. These targets state that by 2030 greenhouse gases will be 63 percent lower than they were in 1990, and by 2040 they will be 75 percent lower. In 2030, 8 percent of the reduction may come from supplementary measures, with 2 percent in 2040.

The target for the Swedish transport sector is a 70 percent decrease in emissions by 2030. However, the comparator year is 2010 and no part of this target may be achieved using supplementary measures.

The transport sector target has a much greater stipulated reduction in emissions than the rest of the ESR sector. Compared to 2015, emissions from the transport sector must decrease by 66 percent, while for other parts of the ESR sector this figure is 8 percent.

Swedish targets for reducing emissions are more ambitious and more focused on emissions within Sweden's borders than is necessary under the targets agreed within the EU. These state that in Sweden in 2030, emissions must not exceed 26 million tons within the ESR, compared to the Swedish target of 21 million tons. EU regulations place no restrictions on how much of the reduction in emissions may be achieved using supplementary measures.

1.2.3 Swedish climate policy instruments

The most important instruments in Swedish climate policy are of a fiscal nature, but many others are also used, such as product requirements, emission reduction obligations, and infrastructure planning.

The carbon dioxide tax is levied on fossil fuels in relation to their carbon content. It was introduced in 1991 and has been gradually increased to the current level of SEK 1,180 per ton of carbon dioxide. For gasoline, this corresponds to a tax of SEK 2.62 per liter. In 2018, the Swedish government's total income from the carbon dioxide tax was SEK 23 billion; the majority of fossil fuel use in Sweden that is outside the emissions trading system is now subject to the full carbon dioxide tax.

The electricity certificate system provides extra income for some suppliers of renewable energy, particularly wind power. The cost is borne by the electricity user, but there are exceptions for energy-intensive industries. In 2018, electricity certificates were an extra cost to consumers of SEK 0.036 per kWh, resulting in income of SEK 2.7 billion for the electricity producers in the system.

An emissions reduction obligation was introduced for transport fuel in Sweden in 2018, so a proportion of biofuel must be blended into all gasoline and diesel sold in Sweden. The requirement for 2020 is that 4.2 percent must be blended into gasoline and 21 percent into diesel. The idea is that these proportions will increase over time, but exactly how fast this should occur has not yet been decided. Biodiesel costs around SEK 8-10 per liter to manufacture, while the price of diesel, excluding taxes, is around SEK 3.

A "bonus-malus system" was also introduced in Sweden in 2018. This stipulates that a buyer of a car that does not emit any carbon dioxide, such as an electric car, receives a bonus of SEK 60,000. This bonus is reduced in relation to the car's stated carbon dioxide emissions per kilometer, and there is no bonus for cars that emit more than 60 grams of carbon dioxide per kilometer. Instead, cars that emit more than 95 grams per kilometer are subject to an extra tax, malus, which increases with the car's carbon dioxide emissions.

The Klimatklivet (climate stride) scheme was established in 2015, and is a funding system for investments to reduce emissions within the ESR sector. Examples of investments supported by Klimatklivet include charging stations for electric vehicles, biogas facilities, biofuel stations, and investments in energy efficiency. Funding was granted to 3,200 projects between 2015 and 2018, at a cost of SEK 4.8 billion. In addition to the abovementioned fiscal instruments, there are smaller funding schemes, such as Industriklivet (industry stride) which provides funding for Swedish industry and financial support for households that install solar panels.

1.2.4 Analysis and discussion

The more ambitious milestone target for 2030 than the one agreed within the EU brings increased costs for Sweden, but may provide benefits—for example, through greater opportunities to influence climate policy in other countries. The assessment of the Economic Policy Council is that costs do not need to be unreasonably high in relation to income if they are based upon the use of carbon dioxide tax and supplementary measures, such as paying other EU member states to reduce their emissions or supporting CCS technology for biogenic sources of emissions.

Several arguments have been presented for a target specifically for the transport sector. The sector is responsible for around half of Sweden's emissions in the ESR sector. Emissions here have fallen less than in other sectors, despite the existence of technology that can reduce emissions. However, the target for the transport sector has been set so tightly that there is a risk that the transformation pressure is much greater than in other ESR sectors. Given the other targets, emissions in the transport sector must fall considerably faster than in the rest of the economy. Calculations by the National Institute of Economic Research (Konjunkturinstitutet) show that if this target is to be achieved, the tax on carbon dioxide may need to be six times higher in the transport sector than in other ESR sectors. Rapid transformation of the transport sector also risks leading to increased emissions in other countries, both through their use of conventional oil and if vehicle electrification leads to reduced electricity exports—and thus more use of coal power in Germany and Poland. The risk of the latter is greater the sooner this transformation takes place in Sweden.

The reasoning behind the long-term emissions target for 2045 is that Sweden has a moral responsibility to lead the way and encourage other countries to be more ambitious. This is a legitimate argument. Another stated reason is that Sweden's long-term competitiveness can benefit from being at the leading edge of this transformation. However, a focus on increasing Sweden's competitiveness may undermine the idea that other countries should be able to copy climate-friendly technologies quickly and easily. Another argument supporting Sweden's climate target is that we can show how this transformation will not result in the huge disadvantages that some people fear. However, for this argument to be valid, policy must focus on measures that provide significant reductions in emissions in relation to the cost to citizens.

One problem with the long-term target for 2045 is that it includes emissions that occur in Sweden, but which are covered by the EU's emissions trading system. A basic tenet of this system is that it is irrelevant in which EU member state the reduction in emissions occurs. According to current regulations, the allocation of emission allowances will continue until 2057, but unless these regulations change the Swedish targets will conflict with the EU ETS. The risk is that Sweden will need to try to steer emissions within the EU ETS away from Sweden to other parts of the EU, contravening the founding principle of the trading system—this should not happen. However, this conflict disappears if the allocation of emission allowances within the EU ETS is reduced more quickly to correspond to the Swedish targets for reducing emissions.

A general result from economics is that the costs for reducing emissions are minimized if different emitters have to pay the same price for their emissions. The mechanism behind this is that with a common price, different parts of the economy have the same costs for marginal reductions in emissions. Swedish carbon dioxide taxes have become more homogenous, but other instruments have led to large and increasing cost differences between various marginal emissions reductions. The National Institute of Economic Research and the Swedish National Audit Office have shown that some measures that are used have costs as high as SEK 6,000–8,000 per ton of carbon dioxide; this leads to unnecessarily high costs because it would have been possible to achieve the same reduction in emissions at a much lower cost. Alternatively, greater reductions in emissions could have been achieved for the same cost as at present.

Another problem with Swedish climate policy is that the incentives to increase the sequestration of carbon in forests and soils are too weak or entirely absent. Such measures should be subsidized at the same level as the price of carbon dioxide emissions.

The same lack of adequate incentives applies to separating carbon dioxide from flue gases, with around 23 million tons of carbon dioxide being released from 27 of the biggest industrial facilities as emissions from biogenic and fossil sources. The incentive to use existing technology to capture these flue gases is weak (for fossil sources it is the price of emission allowances in the EU ETS) or non-existent (for the biogenic sources). For an estimated cost of around SEK 23 billion per year, i.e. SEK 2,300 per Swede annually, these emissions, equivalent to half of Sweden's emissions of carbon dioxide, could disappear.

1.3 Policy proposals

1.3.1 Clarify that the goal of climate policy is to reduce global emissions

The link between Swedish climate policy and global emissions must be clearer. The Swedish climate policy should therefore clarify that the Swedish climate targets are intermediate and aim to contribute to the world becoming climate neutral. Where a conflict between the targets for Swedish emissions and global climate benefit can be identified, the latter must be prioritized. On the council, we are not in complete agreement about how significant these conflicts currently are, but we do agree that they may arise and that the responsible authorities should be given the task of quantifying them.

1.3.2 Only provide funding for technology that contributes to global climate benefit

In some cases, Swedish climate policy risks being disguised as industrial support policy. As part of climate policy, support for climate-friendly technology should only be provided if it is likely to bring global climate benefit through rapid dissemination to other parts of the world.

1.3.3 More homogenous costs for emissions reduction

Calculations show that the multitude of Swedish climate instruments has resulted in major differences in the cost of emissions reduction in different sectors of society. This must be taken seriously. These differences are only motivated to quite a limited extent by arguments based on global climate benefits, leading to unnecessary costs that hamper Sweden's potential to demonstrate that transformation does not need to be insurmountably expensive.

1.3.4 Reformulate the long-term target for Swedish climate neutrality in 2045

The council is in agreement that there should be no delays to Sweden's long-term target of being carbon neutral by 2045. However, with the exception of Åsa Romson, we believe that the target should not include self-imposed restrictions on the number of supplementary measures, which should be able to exceed 15 percent. Measures in other EU member states where it can be guaranteed that emissions reductions are occurring in a safe and credible manner, and the implementation of CCS technologies, are vital elements of an effective global climate policy and should not be restricted. The Swedish aim of leading the way forward should include such measures. Increasing the level of ambition, so that Sweden becomes carbon neutral considerably earlier than 2045, should be possible if these restrictions are lifted and match the regulations agreed within the EU. However, Åsa Romson's opinion is that the target's current wording should not be changed. One of her main arguments is that countries such as Sweden can be a good example through specific reductions in territorial emissions.

No control of Swedish emissions within the EU ETS

Regarding problems that may arise due to the inclusion of emissions within the EU ETS in the long-term target, the council is in agreement that these should be managed without Sweden introducing new instruments that result in emitting entities moving to other EU member states.

1.3.5 Consider abolishing or reformulating the target for the transport sector

The Swedish target for the transport sector entails both costs and benefits, although it is questionable whether any climate benefit will result from achieving it. On the world oil market, any reduction in oil use in Sweden leads to increased use in other countries. Also, the Swedish market is too small to promote technological development in the transport sector. If the target is achieved through electrification in Sweden before the production of electric power in countries like Germany and Poland has become considerably less fossil-intensive, there is a risk it will lead to increased emissions in these countries through reduced exports of Swedish fossil-free electricity. In addition, the climate benefit is unclear if it is achieved using biofuel, particularly if Sweden continues to import large amounts of it.

Sweden should contribute to the European transport system becoming fossil-free at the rate permitted by the expansion of fossil-free electric power in the EU. We should actively support this development, but in step with the rest of the EU. It is difficult to see that the Swedish transport sector target is an effective means for this. Therefore, with the exception of Jonas Eliasson and Åsa Romson, the Economic Policy Council is of the view that Sweden should consider abolishing or reformulating the target for the transport sector.

Jonas Eliasson chooses not to express an opinion on whether the transport sector target should be reformulated.

Åsa Romson believes that abolishing the target for the transport sector is undesirable. Her position is that the transport target plays a particularly important role in climate policy, and thus for Sweden's contribution to global climate policy, as it emphasizes tangible transformation in the near future. In addition, lower emissions in the transport sector will probably not only reduce climate gases, but also provide important societal benefits, such as new industrial development, reduced health impacts from poor air and noise pollution, as well as the economic use of land and lower construction costs. Removing or diluting the transport target will obscure the potential for climate benefits or other transport benefits in Sweden. According to Åsa Romson, revising the target may also be interpreted as lowering the level of ambition.

1.3.6 Finance the capture and storage of biogenic carbon dioxide

We all take the position that Sweden should introduce a system for financing the capture and storage of biogenically produced carbon dioxide. There should be legal guarantees that the price for this follows the Swedish carbon dioxide tax. It is likely that this would create enough of an incentive to capture biogenically generated carbon dioxide equivalent to all emissions from Swedish road traffic.

1.3.7 Continued reform of the EU ETS

Sweden should push for continued reforms of the EU ETS. One such reform would be the introduction of a transparent price floor in the system. This price floor does not need to be high for it to be effective, and should be automatically increased at the same rate as the EU's nominal increase in GDP.

1.3.8 Push for an international agreement on a minimum price for emissions

Sweden should work forcefully towards an international agreement for a minimum price on emissions. As yet, there have been no serious global negotiations about emissions prices. Within the EU, Sweden should push for the inclusion of a minimum emissions price in negotiations for free trade agreements, which could clear the way for broad climate clubs with homogenous emissions prices and adequate incentives to remove the free-rider mechanism.

Outside the EU, Sweden should promote adding commitments for minimum emissions prices to the Paris Agreement. We should also try to influence the WTO to permit climate clubs under international trade regulations, through clear acceptance of the principle that concern for the world's climate is a good enough reason for tariffs on countries without an acceptable level of emissions pricing.

1.4 Part III

In Part 3, we answer seven questions:

1. Can the climate targets of municipalities and businesses contribute to an effective climate policy? If so, how should they be designed?
2. Should climate targets be set separately for different economic sectors, or should all sectors have the same cost pressure on transformation?
3. How effective is climate aid as a climate policy?
4. Is buying emissions allowances and not using them good climate policy?
5. Should Sweden strive to create a surplus of fossil-free electricity for export?
6. Should nuclear power be kept for climate reasons?
7. Should Sweden provide funding for investments in carbon dioxide separation and storage?

CHAPTER 1

Introduction: Why do we need (a report about) climate policy?

THE REPORT IS not concerned with *whether* climate action is necessary, as there is no debate about whether action is necessary, at least not in Sweden and Europe. Nor does the report focus on *how much* less carbon dioxide should be emitted, globally, nationally, locally, or individually. Instead, our aim in this report is to address the question of *how* policy can achieve the desired reductions in carbon dioxide emissions.

The question of *how* cannot be answered by natural science alone. Instead, the answer must involve how to influence the decisions about consumption, production, technical development and investment that are taken by billions of people around the globe, so they are compatible with sustainable development. Through its reports, including those published by the UN climate panel, the Intergovernmental Panel on Climate Change (IPCC), scientific research has convinced us that this requires ending the use of fossil fuels; these reports do not deal with *how*, but rather with what reductions are necessary and why. The "Summary for Policymakers" in the IPCC report on the 1.5-degree objective (IPCC, 2018) does not mention carbon taxes, emissions trading, government subsidies for technology or any other ways in which decision-makers—the report's target audience—can influence society.

However, the question of *how* must be answered. This requires social science-based analysis, but social science research on climate issues has not kept up with that within the natural sciences. Social scientists, particularly macroeconomists, have been too content to stand and watch. Nonetheless, knowledge from the social sciences is necessary if we are to understand how we can change society. This knowledge must be combined with that from the natural sciences if we, as a society, are to deal with the climate issue.

Economists analyze how policy can be used to influence the decisions of individuals and businesses on given markets, such as on the use of fossil fuels. This, along with the fact that many—but not all—of us on the Economic Policy Council 2020 are economists, has meant that our answers to *how* generally use economic methods, although we do not reject other approaches. It is obvious to us that the research methods employed in other social sciences also provide important knowledge that can be used to shape policy reforms and functional societal governance. For example, political science's perspectives on managing environmental policy through objectives are of interest when discussing the efficacy of climate goals and, in this context, analyses of political processes and means of influencing people's willingness to accept change are essential. The humanities are also clearly relevant; analyses of ethical issues in the distribution of transition costs and the emphasis that should be put on individual welfare are vital when responding to questions of how to design climate policy. Despite our best attempts to consider these perspectives, the group's composition has meant they are largely outside our analyses in this report.

Climate policy and, more generally, environmental policy, deals with creating the right conditions for sustainable development. i.e. development that satisfies human needs without undermining the ability of natural systems to provide the natural resources and ecosystem services that underpin society and the economy. In order for future generations to be able to provide for themselves, it is important for present generations to pass down adequate capital in a broad sense: physical capital such as machines and infrastructure; intellectual capital such as knowledge and technology; and natural capital, which includes the amount and quality of natural resources.

The biosphere—with its ecosystems and natural resources—provides us with the essential prerequisites for life, such as fresh water, food, and raw materials in the form of timber, metals, and oil. Technological progress and increased international trade have resulted in many years of rising global production. This has radically changed living conditions for the majority of people on Earth and lifted billions of people out of poverty and misery. At the same time, the use and exploitation of our natural resources has increased, particularly since World War II. This has had a significant impact on the biosphere—our natural capital—much of which has been negative, and includes eutrophication, deforestation, and declining biodiversity.

The best-known example of this impact is global warming. If emissions of greenhouse gases continue at current levels—or increase—we risk an overall level of global warming that could entail very serious consequences for humanity, including impact on our life-sustaining ecosystems. The climate issue is thus central to sustainability.

The natural sciences provide quantitative estimations of the relationship between emissions and climate change, while other researchers can describe the socioeconomic consequences of climate change. Describing these research results is a vital element of this report. This type of systems understanding is necessary to help us determine which policies influence global emissions, and their consequences for climate and human welfare. However, as we stated initially, establishing a target for emissions or the maximum level of global warming is not enough; it is unreasonable for a supranational authority to determine how much carbon dioxide each person and business on the planet may emit. Nor is this approach realistic at a national level, as a system in which a national authority decides, for example, how much steel and cement each company can use is not viable, and the same applies to the use of fossil fuels and other sources of greenhouse gas emissions.

Instead, the council's discussions on climate policy are based upon the fact that the majority of nations are market economies. The decisions that lead to carbon dioxide emissions and the development of fossil-free technology are largely made by individuals and business acting on markets—locally, regionally, or globally. It is reasonable to assume this will continue to be the case, so climate policy must be designed to influence these markets in the right direction. This report therefore emphasizes the economic sciences, but we are fully aware that other research efforts—both inside and outside the social sciences—are vital to understanding human behavior.

Why are markets unable to create sustainable development without climate policy? To understand this, we must realize that markets cannot work without clearly defined rights of ownership. Without functioning rights of ownership there are no incentives—or at best poor incentives—to economize on resources and invest in their preservation.

When we talk about ownership rights, we often think about private property, but the problems that arise if these rights are not upheld also apply to natural resources. The past and the present are full of examples of natural resources being over-utilized and exploited in an unsustainable manner, simply because there is no owner. If there was a single owner, it would be in that owner's interest to use the resource responsibly and safeguard its long-term use. For example, a private forest owner ensures the future growth of the forest, but when it comes to our planet and many of its vital ecosystems, there is no single owner. No one—and everyone—has shared rights of ownership, which also means that no one can be excluded from their use.

If there is no owner to ensure that ownership rights are respected, then actors who over-exploit these resources cannot be held to account. On an unregulated market, they do not consider how their decisions about production or consumption affect other actors, directly or indirectly, through their negative impact on natural capital. They do not need to reflect on any of the societal costs caused by their carbon dioxide emissions into the atmosphere. Economists call these negative effects, ones for which an individual emitter does not need to compensate others, *negative externalities*. To achieve sustainable development, actors who make decisions about individual emissions must take all the negative externalities into account; they must be part of decision-makers' calculations—they must become internalized. This report will discuss how to make this happen.

In this debate, it is often argued that natural resources are over-exploited because of technological development and economic growth. Indeed, it cannot be denied that problems caused by the lack of well-defined ownership rights for natural resources are often exacerbated by economic growth and technological development. The lack of well-defined rights to fish in the world's oceans was not a problem for sustainability when fishing was done from canoes using traditional fishing equipment, but industrial fishing needs regulation to prevent the oceans from being overfished. However, it is important to note that the fundamental cause of the problem of overfishing is not technological development or economic growth, but a lack of well-defined rights to pelagic resources. The solution is not, therefore, to return to fishing from canoes. Similarly, technological development, economic expansion, and population growth have had the effect of reducing the atmosphere's ability to absorb carbon dioxide from a practically infinite resource down to a scarce one. Another question, one we will not try to answer in this report, is that of whether more efficient use of limited resources allows economic growth in the extended long term.

Elinor Ostrom, recipient of the 2009 Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel, demonstrated that humanity has often managed to deal with the abovementioned problems throughout history, long before the existence of the modern market economy. This was done through explicit or implicit agreements on how natural resources, such as a local water source, could be used. The modern nation state has also developed ways of defining ownership rights and other methods for regulating how natural resources are used within national boundaries. However, ownership rights to the climate or, more precisely, to the atmosphere's capacity to absorb emissions of carbon dioxide and other greenhouse gases, cannot be defined at a national level. Carbon dioxide emissions spread rapidly throughout the atmosphere and affect the climate of the entire Earth. These emissions are determined by decisions made by billions of individuals and companies acting on different markets around the world, so old ways of managing rights of ownership over natural resources are no longer adequate.

Understanding the global system is necessary to design good climate policy, and this also applies to the design of national, regional, or local climate policy. This means understanding how the global climate system works and is affected by the concentration of greenhouse gases in the atmosphere. It means understanding how carbon circulates between different reservoirs, such as the atmosphere, biosphere, and the oceans. It also means understanding how the global economy works—especially the markets for fossil fuels and other fuels. Finally, we need to understand how international agreements can arise and be maintained. Our aim in this report is to contribute to increasing the understanding of these complicated and interlinked systems.

We, the authors, have all conducted research on climate issues. Our backgrounds are mixed; we represent different disciplines in the social sciences, law, and natural sciences. Our primary ambition has been to clearly and unambiguously describe what we perceive to be the current situation for research in the areas we represent. If we had each written separate reports, our separate backgrounds could have resulted in different emphases on various aspects of the global climate-economic system, but we have arrived at an overarching description of the current research situation that we can all stand behind. We believe that this may be our most important contribution.

Using our description of the research, we have then attempted to draw conclusions about how climate policy should be designed, both globally and in Sweden. Designing policy is not research, so it is not possible to argue that one is correct in one's own proposals while others are not; it also means that you should not survey the research community for consensus about the "correct" policy. Despite this, within our group we have agreed on many recommendations for climate policy and we believe this can be a constructive contribution to discussions about climate policy. In a few cases we have not reached complete agreement, so this is clearly noted where applicable.

JOHN HASSLER, chair (professor of economics, IIES, Stockholm University)
BJÖRN CARLÉN (PhD in economics, National Institute of Economic Research)
JONAS ELIASSON (visiting professor of transport systems, Linköping University)
FILIP JOHNSSON (professor of energy technology, Chalmers University of Technology)
PER KRUSELL, chair (professor of economics, IIES, Stockholm University)
THERESE LINDAHL (PhD in economics, Beijer Institute of Ecological Economics)
JONAS NYCANDER (professor of geophysical fluid dynamics, Department of Meteorology, Stockholm University)
ÅSA ROMSON (PhD in environmental law, IVL Swedish Environmental Research Institute)
THOMAS STERNER (professor of environmental economics, School of Business, Economics and Law, University of Gothenburg)
MATTIAS SCHAIN, secretary (LLM)

The report consists of three parts.

PART I · Systems understanding. In this section we aim to provide a basic understanding of selected global systems that are relevant to climate change. These systems are complex and require insights from the natural sciences, social sciences, and law.

PART II · Summarizing analysis of Swedish climate policy. This describes Swedish climate policy, analyzing it on the foundation of the systems' description provided in Part I, and providing some summarized recommendations to Swedish decision-makers.

PART III · Questions. Here, we provide answers to various questions currently being discussed in Sweden. Our aim is not to present our answers, but to offer examples of how the systems understanding we attempt to describe in parts I and II can be used to answer concrete questions about climate policy.

PART I

SYSTEMS UNDERSTANDING

CHAPTER 2

What causes climate change?

2.1 Chapter summary

For the Earth's climate to be in equilibrium, the incoming energy radiation from the sun must be balanced by an equal amount of outgoing radiation from Earth to space. Incoming radiation primarily consists of visible light that passes easily through the atmosphere, while the outgoing radiation, besides direct reflection, consists of thermal radiation. The latter is efficiently absorbed by carbon dioxide and other greenhouse gases, and is then reradiated out at greater altitudes. More carbon dioxide in the atmosphere displaces upwards the level from which heat radiates directly to space, which reduces the intensity of this radiation. There is thus an imbalance between the inward and outward energy flows, leading to increases in the Earth's average temperature until balance is eventually regained. How much the temperature needs to rise before this balance is achieved is not known with certainty because it is very difficult to assess the strength of various feedback mechanisms, particularly cloud formation. Using models and historical observations, the IPCC (2013, SPM) estimates that the uncertainty interval for the effect of a doubling of carbon dioxide is 1.5–4.5 degrees Celsius, relative to pre-industrial levels.

The most commonly used coupled global climate and carbon system models show that the global mean temperature increases by an approximately constant number of degrees for every additional emitted unit of carbon dioxide. This means that the increase in the global mean temperature since the start of industrialization is, in principle, proportional to the total amount of carbon dioxide emitted since then. However, there is great uncertainty here, too, because the models give different results. The IPCC (2013, SPM) states an interval of 0.8–2.5 degrees Celsius per 1 trillion tons of carbon.[1] So far, globally, we have emitted almost 600 billion tons. If sensitivity is as low as 0.8 degrees, we can release three times as much again, which would take a couple of hundred years at current emission rates, and still not exceed 2 degrees of warming. If the sensitivity is 2.5 degrees, we can only emit another 200 billion tons (which would take 20 years at current rates) and emissions must cease immediately and entirely to keep the world below 1.5 degrees of warming.

Using model simulations, research has tried to identify the risk of "tipping points". These are self-reinforcing mechanisms that may cause irreversible change in some parts of the climate system once a critical level of climate change has been reached. Reduced vertical circulation in the North Atlantic[2] and the release of carbon dioxide from rapidly thawing permafrost have been suggested as

1. Carbon is the element C. Emissions are often measured as tons of carbon dioxide. When carbon is combusted, each carbon atom reacts with the two oxygen atoms. One ton of carbon then forms 3.67 tons of carbon dioxide.

2. This is sometimes confused with the Gulf Stream collapsing, something that is extremely unlikely.

examples of these tipping points. Assessing the risks of such mechanisms occurring is genuinely difficult, not least because they typically cannot be calibrated against historical observations. However, the IPCC's assessment (2013, chap. 12) is that it is "very unlikely" that these two mechanisms would lead to a rapidly changing climate in this century. With the words "very unlikely", the IPCC means that the probability is less than 10 percent.

Other examples of irreversible changes include melting ice sheets, primarily in Greenland and Antarctica. For example, if the Greenland ice sheet melts, a return to pre-industrial climate will not bring it back: its disappearance is irreversible because as the ice melts, its surface is at a lower, and thus warmer, altitude. It has been established that the Greenland ice sheet is now melting at an accelerating rate. However, this is a very slow process, and at the current rate, it would take about 14,000 years for the ice to completely disappear. The IPCC (2013, chap. 13) assesses that if heating follows the most rapid scenario, the meltwater from Greenland will contribute 10–20 centimeters to the global sea level rise by 2100.

The ice in Antarctica will not melt from the top, but it may melt more rapidly where it is in contact with seawater. The speed of this process could be considerably faster than for Greenland. There is no certainty that it will occur, but if it does, the IPCC (2013, chap. 13) judges that it could contribute tens of centimeters to the global sea level rise by 2100. Some studies show that it could contribute as much as 1–2 meters over the next 200 years.

Another irreversible change is that the seabed in the Arctic could start leaking methane from the large reservoirs of methane clathrate. According to the IPCC (2013, chap. 12), the release of methane clathrates is a slow process and it is "very unlikely" that it would occur rapidly.

There is very limited scientific support for the idea that soon it will be "too late" to act, since we are approaching a situation in which climate change will accelerate out of control. Equally, there is very limited scientific support for the idea that the warming now being observed is not linked to emissions produced by humans. Based on scientific evidence, we cannot rule out climate sensitivity being so small that there is no urgency to reduce emissions, nor can we rule out climate sensitivity being so great that we have already exceeded the emissions level that would keep us below 1.5 degrees Celsius of warming. This uncertainty is vital to the evaluation of which policy should be recommended.

2.2 Two relevant systems

The scientific basis for understanding climate change has two components. The first one is the description of the climate system: how solar radiation is absorbed on the Earth, how the heat is then redistributed between the different parts of the system, and how it finally disappears into space as thermal radiation. A small but important element of this system is the carbon dioxide in the atmosphere, which reduces outgoing thermal radiation. The second component is the carbon cycle, which describes how the carbon dioxide emitted by humankind over time is redistributed among the atmosphere, oceans, and vegetation.

2.3 The climate system

The Earth is heated by solar radiation and cooled by thermal radiation from Earth to space. If the climate is to remain constant, the heating must be balanced by the cooling. More carbon dioxide in the atmosphere tends to reduce the cooling and therefore creates an imbalance between the two effects. To understand this, we must realize that the solar radiation and the Earth's thermal radiation to space are two forms of electromagnetic radiation that have very different frequencies and wavelengths. These differences are because the temperatures of the Earth and the sun are very different.

2.3.1 The atmosphere's effect on solar radiation and thermal radiation

All bodies (such as the sun and the Earth) emit electromagnetic radiation, and the character of this radiation depends on the body's surface temperature. This radiation is described by Planck's law. Figure 1 shows that the intensity of the radiation increases rapidly with temperature,[3] and that the frequency of the radiation increases with increasing temperature. If electromagnetic radiation has a higher frequency, this is the same thing as the radiation having a shorter wavelength. One everyday example of this is halogen lamps that have dimmers. When the dimmer is turned up, the filament gets hotter, which gives a more intense light. It also means that the light is whiter, that the frequency of the light has increased, i.e., that its wavelength has decreased. The surface temperature of the sun is around 5,500 degrees Celsius and the frequency of its radiation is

3. The radiation's intensity is proportional to the temperature measured in Kelvin to the fourth power.

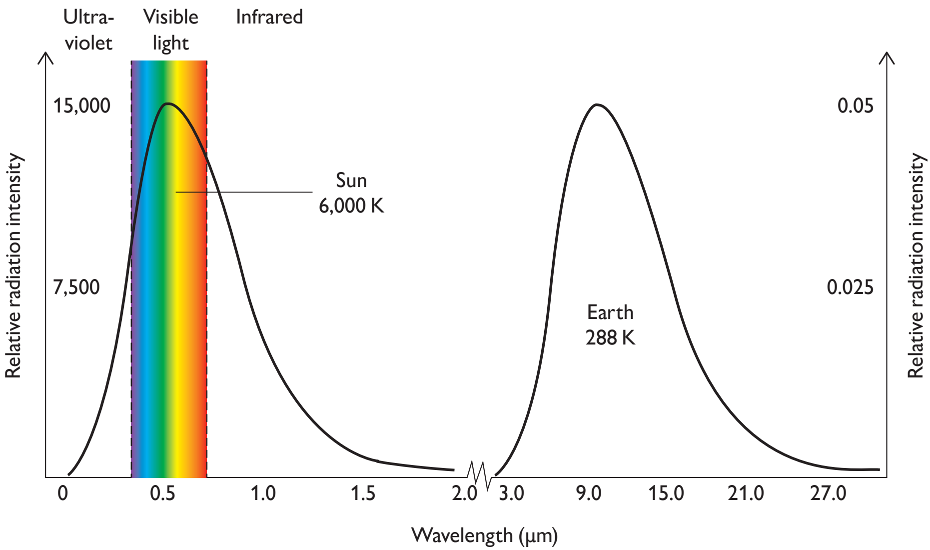

Figure 1 The intensity for different wavelengths of solar radiation (the left curve) and the Earth (to the right).

Source: http://www.faculty.virginia.edu/ASTR5110/lectures/photometry/emissionspec.gif.

mostly in the visible range. The surface temperature of the Earth is obviously much lower, around 15 degrees Celsius on average. The Earth's thermal radiation to space therefore has a much lower frequency and is not visible to the human eye (although it is to thermal cameras, for example).

As the electromagnetic radiation passes through the atmosphere, some of its energy is absorbed by the molecules in the air. How this happens and how much is absorbed depend on the wavelength of the radiation. One way in which the radiation can be absorbed is through ionization, which means that collisions lead to electrons being released from atoms in the molecules in the atmosphere. However, this only happens to radiation with a very short wavelength, shorter than visible light. The part of solar radiation with the shortest wavelengths, ultraviolet radiation, is absorbed in this way in the stratosphere, at altitudes above 10–15 kilometers. However, visible light passes unobstructed all the way down to the surface of the Earth—unless it is cloudy. Some of the light is reflected by the clouds and the surface of the Earth, especially if it is covered by snow or ice. The reflected light disappears into space.

The other way in which electromagnetic radiation can be absorbed by the atmosphere is that it can make molecules in the air vibrate. For this to happen, the molecules must be able to vibrate at the same frequency as the radiation. An everyday example of a similar phenomenon is when a bass note from a loudspeaker makes cups and saucers in a room vibrate and absorb some of the sound's energy, while treble notes, higher up the scale, do not create any vibrations in these objects.

The atmosphere consists of 99 percent oxygen and nitrogen, both of which have molecules with two atoms. When such molecules vibrate the two atoms move straight towards or away from one another. The frequency of this vibration is much higher than the frequency of the Earth's thermal radiation but considerably lower than the frequency of the solar radiation, so these molecules are unable to absorb either thermal radiation or visible light by vibrating.

Molecules with more than two atoms can also vibrate in other ways. A carbon dioxide molecule consists of a carbon atom between two oxygen atoms and can vibrate by bending back and forth. This type of vibration is slower, and the vibration frequency of carbon dioxide molecules is in the middle of the frequency range for thermal radiation. Carbon dioxide in the atmosphere therefore means it can absorb large amounts of thermal radiation. Other gases that consist of molecules with more than one atom can also absorb thermal radiation. The most important ones are water vapor and methane, which absorb in different frequency ranges. Gases that can absorb thermal radiation in this way are called *greenhouse gases*.

When thermal radiation is absorbed by the greenhouse gases at a particular altitude, the atmosphere there is warmed. This warmed atmosphere then releases new thermal radiation. This reradiation is directed both upwards and downwards. The effect of greenhouse gases is therefore not that thermal radiation is completely locked in but that it is absorbed and recreated in small steps. At each new level, more is sent upwards than is received from above, and this continues to an altitude at which the atmosphere is so thin that the thermal radiation has no time to be absorbed by the molecules higher up before it disappears into space. This level is called the *emission level*. If you look at the Earth from space using a thermal camera—which is done from satellites—you see the thermal radiation from this level.

Previously, we described how Planck's law shows that the intensity of the radiation increases with temperature, which means that the amount of energy that radiates out from the Earth depends on the temperature at the emission level. When the Earth's climate is in equilibrium, this energy flow must be as great as the energy flow due to solar radiation that is absorbed by the Earth. This determines the temperature at the emission level. The temperature profile below this, i.e., how the temperature changes with altitude, will adjust automatically so the upward transfer of energy is equal to the outgoing thermal radiation at the emission level. This temperature profile is what decides the temperature at ground level, and we will now look more closely at how this is determined.

2.3.2 Energy transfer in the atmosphere

We have already described how heat is transferred upward in the atmosphere through stepwise absorption and reradiation. In order for the energy to be transferred upwards in this way, the temperature must decrease with altitude. The greater the energy flow, and the more radiation that is absorbed at each level, i.e., the higher the concentration of greenhouse gases, the faster the temperature drops with increasing altitude. There is strong absorption in the lower part of the atmosphere—particularly due to water vapor—and if this radiative transfer were the only way of transporting heat upwards, the temperature would have to drop very quickly.

In practice, the temperature will not be able to fall this rapidly, since such a quick fall in temperature would lead to instability in the atmosphere. To understand this, first, recall the well-known fact that hot air rises. As it does so, its temperature drops by around one degree Celsius per 100 meters of altitude.[4] If the temperature of the surrounding air falls more quickly, then the rising air will continue to be warmer than that around it even at higher altitudes and will thus continue rising, which means that the layers of air are mixed: warmer air rises and colder air falls. This mixing is called convection and is a powerful process for transporting energy. This means that if the temperature were to fall so rapidly with increasing altitude that the layers became unstable, convection could quickly transport hot air upwards so that the temperature increased at higher altitudes and decreased at lower ones until the layering regained stability. However, if the temperature were to decrease more slowly with altitude, the temperature lower down would increase due to

4. As air rises, air pressure falls and the air expands. The expansion requires energy. This is taken from the heat in the air, so the temperature drops.

the low effectiveness of radiative transfer, until the temperature profile became unstable again. The result is that the rate at which temperature declines with increasing altitude is normally close to the threshold for convective instability.[5]

We can now follow the energy's path through the atmosphere. The ultraviolet segment of the incoming solar radiation is absorbed at very high altitudes. The rest is visible light. Some of this light is reflected by clouds, but most of it reaches the ground or the surface of the ocean. Another small part of the light is then reflected, while the rest is absorbed. This absorbed energy heats the air closest to the ground. The heat is then transferred upwards and finally reaches the emission level, from where it radiates out into space.

Let us now analyze what happens if the concentration of greenhouse gases increases. The altitude from which thermal radiation can leave the atmosphere, i.e., the emission level, will be shifted upward. The temperature is lower at this greater altitude, so that the thermal radiation is reduced. If, before the increase in the concentration of greenhouse gases, there was equilibrium between the inflow of solar energy and outflow through thermal radiation, we now have an excess. This means that the climate system starts to accumulate heat, so the temperature rises. This continues until the temperature at the new emission level is once again the same as it was at the original emission level, before the concentration increased. The climate system is once again in equilibrium, with a new temperature profile and higher ground temperature.

---

5. Here, the reasoning is based upon dry air. If the air is instead moist, some of this moisture will condense as the air rises and cools. This condensation releases heat, so the temperature does not drop as much in the rising air. For moist air to be stable, the temperature in the surrounding layers of air must therefore fall more slowly than 1 degree per 100 meters.

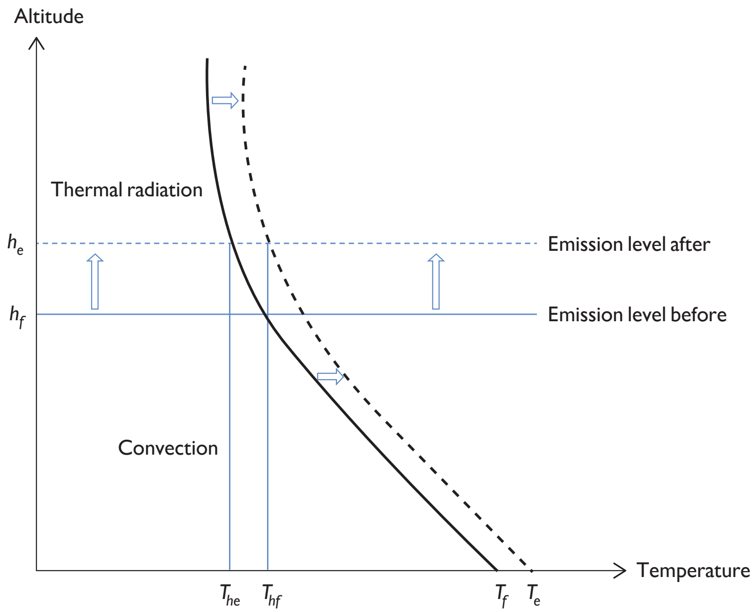

Figure 2 An illustration of the greenhouse effect. The curves show how the temperature in the atmosphere depends on altitude. The shape of the temperature curve is decided by the mechanisms for heat transport up from ground level, while its position when the climate is in equilibrium is decided by the condition that upward thermal radiation from the emission level must be equal to the incoming solar radiation. This determines the temperature at the emission level, T_{hf}. If the concentration of greenhouse gases increases, then the emission level shifts upwards, and the requirement for equilibrium means that the temperature curve shifts to the right, from the solid to the dashed curve, according to the arrows. The temperature at ground level then increases from T_f to T_e.

We illustrate the consequences of a higher concentration of greenhouse gases in figure 2. The horizontal axis shows the atmosphere's temperature, and the vertical axis shows the height above ground level. The solid line shows the relation between height and temperature before the concentration increases. The curve has a negative slope because the temperature falls with height, as explained above. At ground level, the temperature is T_f, and at the emission level, it is T_{hf}. A higher concentration of greenhouse gases shifts the emission level upwards (from hf to he). For an unchanged temperature curve (the solid line), the temperature at the new emission level is lower ($T_{he} < T_{hf}$). The thermal radiation is thus lower, so heat accumulates and the temperature rises, which shifts the temperature curve to the right. This process continues until the temperature at the new emission level has risen to that of the old emission level, i.e., before the concentration of greenhouse gases increased. The temperature at ground level has then risen from T_f to T_e.

Relatively little heat can be stored in the air and ground. If this were the only storage, equilibrium would quickly be restored, but because oceans can store large amounts of energy with little increase in temperature, it takes several centuries to regain a balance. Even if the concentration of carbon dioxide stopped increasing today, the climate would therefore continue to gradually become warmer for a very long time. There is no certainty about how long this would take and how much warmer it would be, and this is one of the questions that climate scientists are working on.

Naturally, the above description is simplified. Primarily, we have chosen to disregard that solar heating is stronger in the tropics than at higher latitudes, which means that the absorbed heat is not only transported upward through the atmosphere but also horizontally toward the poles, to then disappear as thermal radiation to space at higher latitudes. This horizontal heat transfer takes place through winds and ocean currents, but because they are irregular and fluctuate, there can be great variations in temperature. The description is therefore inadequate for determining the ground temperature on a

A MATHEMATICAL DESCRIPTION

It is worth formulating what we have described above mathematically, as this makes it possible to provide quantitative answers to questions of how much and how fast our climate is changing.

Let S represent absorbed solar radiation and L thermal radiation to space. Both are measured in W/m^2 and should be interpreted as an average across the Earth and over one or more years.

The Earth's net absorption N of energy is then:

$$N = S - L \quad (1)$$

If the inward energy flux is equal to the outward flux, the climate system is in equilibrium. We have $N = 0$ and the climate is stable. We assume that the climate was in balance before humans started emitting carbon dioxide. We call the absorbed solar radiation at this time S_0 and the thermal radiation from Earth L_0. Given that the climate system was in balance at that time, i.e. $N_0 = 0$, it must be true that $S_0 = L_0$.

When the concentration of carbon dioxide subsequently increased, the outward energy flux decreased, as we described above. This decrease is called CO_2 *forcing* (represented by f_{CO_2}). It is defined as the decrease in thermal radiation at the initial global average temperature, i.e. before emissions of carbon dioxide began. We call this initial temperature T_0. Including CO_2 *forcing*, the outflow of energy is $L = L_0 - f_{CO_2}$. Unless S changes, we get a positive net absorption of energy $N = f_{CO_2}$ and Earth's average temperature T consequently starts to increase.

As the Earth's average temperature increases, the outward energy flux of heat is affected in several ways. The most obvious effect is that the outward flux of thermal energy increases, as we described above. Let us assume that, at a certain time t, the temperature has increased from T_0 to $T_0 + T_t$. If the temperature increase is not too great, we can make an approximate assumption that the increase in thermal radiation is proportional to the temperature increase, and therefore add a term $k_{Planck}T_t$ to L. Here, k_{Planck} is a constant coefficient that can be determined from Planck's law.

Thermal radiation from the Earth is also affected in other more indirect ways by the temperature increase. Warmer air usually contains more water vapor and, as this is a greenhouse gas, it reduces the outflow of heat. Cloud cover may change on account of the temperature increase, and clouds efficiently absorb thermal radiation. If we again make an approximate assumption that all these effects on thermal radiation are proportional to the temperature increase, we can summarize them as a term $k_{other}T_t$, where k_{other} is a constant coefficient that summarizes other feedback mechanisms acting on thermal radiation. This gives us:

$$L = L_0 - f_{CO_2} + k_{Planck}T_t - k_{other}T_t \qquad (2)$$

The Earth's absorption of sunlight is also affected by the temperature increase. A change in cloud cover may change the reflection of sunlight, and the decreased amount of snow and ice causes less sunlight to be reflected and more to be absorbed. We assume that these effects are also approximately proportional to the temperature increase, and summarize them as a term $k_{refl}T_t$. This gives us:

$$S = S_0 + k_{refl}T_t \qquad (3)$$

We can now calculate the Earth's net absorption of energy and how it is affected by changes in global average temperature. If we insert (2) and (3) in (1), and consider that $S_0 = L_0$, net absorption becomes:

$$N = f_{CO2} - (k_{Planck} - k_{other} - k_{refl})T_t \qquad (4)$$

As long as net absorption remains positive, the temperature increases. Given that $(k_{Planck} - k_{other} - k_{refl})$ is greater than zero, we see from (4) that a higher global average temperature has a negative effect on net absorption. This means that an increase in temperature reduces net absorption. An increase in temperature then ultimately results in $N = 0$, at which time the climate system is in balance again (unless f_{CO_2} changes). Until that time, the Earth heats up and energy is stored in the oceans.

We can easily work out how much the global average temperature must increase to balance CO_2 forcing so that we regain equilibrium. Let us call this temperature increase T_{equ}. If we replace T_t with T_{equ} in equation (4), set N to zero and solve it for T_{equ}, we get this temperature:

$$T_{equ} = \frac{f_{CO_2}}{k_{Planck} - k_{refl} - k_{other}} \qquad (5)$$

The next step is to describe how much CO_2 forcing is produced by a given increase in the carbon dioxide concentration in the atmosphere. Suppose the carbon dioxide concentration were to double, from the preindustrial value of 280 ppm to 560 ppm. We can call the resulting CO_2 forcing value $f_{2\times}$. It may be determined with physical radiation calculations and is roughly $f_{2\times} = 3.7\ \mathrm{W/m^2}$. The temperature increase required to balance this is called equilibrium climate sensitivity, ECS. From (5) we get:

$$ECS = \frac{f_{2\times}}{k_{Planck} - k_{other} - k_{refl}} \qquad (6)$$

ECS is a central concept that describes how much the temperature increases in the long term if the carbon dioxide concentration doubles.

Radiation calculations also show that if the carbon dioxide concentration doubles again, to 1,120 ppm, four times the original concentration, then CO_2 forcing is roughly twice as strong, i.e. $f_{4\times} = 7.4\ \mathrm{W/m^2}$. It is more generally true that CO_2 forcing at the margin is proportional to the percentage increase in the concentration of carbon dioxide. Every percentage point increase in the carbon dioxide concentration increases CO_2 forcing by 0.053 $\mathrm{W/m^2}$. If we knew the climate sensitivity, we would therefore be able to predict the equilibrium temperature for each carbon dioxide concentration.*

ECS may be determined from (6) by adding up the various

---

* Expressed mathematically, $f_{CO_2} = 3{,}7 \cdot \ln(S_t / S_0) / \ln(2)$ where S_t is current and S_0 is the preindustrial level of carbon dioxide in the atmosphere.

feedback factors in the denominator, i.e. $k_{Planck} - k_{other} - k_{refl}$. A more advanced but in principle similar method is to use a climate model. This is a mathematical three-dimensional simulation model of the atmosphere and the ocean that describes winds, ocean currents and all the other processes mentioned above.

As noted above, it is possible to calculate $f_{2\times}$ and k_{Planck} fairly precisely with an accuracy of roughly 20%. If we could ignore k_{other} *and* k_{refl}, ECS would be just over one degree, which is almost certainly too low since $k_{other} + k_{refl}$ is highly likely to have a positive value. This means that the temperature needs to increase more to balance a given CO_2 forcing value.

There is widespread agreement among climate scientists that $k_{other} + k_{refl}$ is probably a positive number, but there is no such agreement on the actual value of this number. This is because it is much more difficult to determine k_{other} and k_{refl} than to determine $f_{2\times}$ and k_{Planck}. Clouds are of particular significance for the radiation balance, both because they reflect incoming solar radiation (which you can feel on a summer day with varying cloud cover) and because they absorb thermal radiation to space (which you notice in the difference between clear and cloudy winter nights).

When, where and at what height changes in clouds occur all have a great influence on the radiation balance. However, it is difficult to know how clouds are affected by the increasing temperature, because clouds are affected by large-scale wind patterns, by small-scale turbulence and by microscopic processes that control the formation of water drops and ice crystals. This also means that the description of cloud processes in climate models is very uncertain. Reasonable changes in this description change the models' ECS by several degrees. Consequently, it has proven difficult to determine ECS using a detailed calculation of the various specific effects, whether you use (6) or climate models.

The empirical method is another way to determine ECS. This involves determining the denominator in (5), i.e. the total of the feedback factors, from the observed temperature increase since the start of industrialization. There are two complications with this method. The first is that the climate system is not yet in equilibrium, i.e. we cannot neglect N (net absorption of energy) in (4). However, there are measurements of the ocean temperature going back roughly 50 years that show that heat is absorbed by the ocean at a rate equivalent to $N = 0.7\ \mathrm{W/m^2}$.

The second difficulty is that the climate has been affected not only by human emissions of carbon dioxide and other greenhouse gases, but also by emissions of aerosols, small particles that are suspended in the atmosphere. They can reflect sunlight and also function as nuclei for cloud drops, which may also make an indirect contribution to increased reflection. As the aerosols increase the reflection of sunlight, they make the climate colder.

Emissions of aerosols are primarily associated with the combustion of fossil fuels. One major source is sulfur dioxide, but there are also other sources. Aerosols disappear from the atmosphere after a few weeks, unlike carbon dioxide, which remains for centuries. The concentration of aerosols therefore depends on ongoing emissions, while the concentration of carbon dioxide depends on accumulated emissions. The concentration of aerosols has decreased in the West in recent decades as a result of better flue gas purification. However, it has increased in Asia. Nevertheless, most people believe that it will also decrease there in the future as countries are forced to purify flue gases to deal with health problems and local environmental damage.

The size of the cooling effect of human emissions of aerosols is very uncertain. Nor is it entirely certain whether their impact is positive or negative, as there are also aerosols (black carbon) that absorb sunlight and heat the climate. The IPCC (2013, SPM) indicates the uncertainty interval as approximately 0–2 W/m^2 for the effect of aerosols. The uncertainty interval is roughly as high as the direct effect of a 50% increase in the carbon dioxide concentration, i.e. roughly as much as it has already increased.

The observed temperature increase is a result of both carbon dioxide and aerosols. The empirical method therefore also only provides an uncertain estimate of climate sensitivity, which is, of course, a measure of the effect of carbon dioxide alone. If the effect of aerosols is at the lower end of the interval (i.e. 0), the result is climate sensitivity of less than two degrees each time the carbon dioxide concentration doubles. If we assume instead that the aerosols have a strong cooling effect, the result is high climate sensitivity. This would mean that the cooling effect of the aerosols conceals a large part of the heating effect of the carbon dioxide and that heating will accelerate when the concentration of aerosols decreases in the future.

A variant of the empirical method is based on what we know about changes in carbon dioxide concentration and the climate in the past (paleoclimate), for example the last ice age. This method also involves great uncertainty.

The IPCC (2013, SPM) uses all the methods above to estimate ECS. After pooling the results, it indicates that ECS is likely in the interval of 1.5°C–4.5°C.* This is a large uncertainty interval, which is illustrated by the following mathematical example. Let us assume first that ECS is 4.5°C. This would be consistent with the heating we observe if a large part of the heating effect of carbon dioxide is masked by the cooling effect of aerosols. Let us also assume that this cooling effect ceases in the future as a result of better flue gas purification, that the heating effect of greenhouse gases other than carbon dioxide (primarily methane) also ceases, and that we could somehow keep the carbon dioxide concentration constant at the current value of 410 ppm until the climate system were in equilibrium again. The temperature would then be stabilized at an increase of approximately 2.5°C, which is clearly higher than the two-degree target.

Let us assume instead that ECS is 1.5°C. For this to be in line with what we observe, we need to assume that the cooling effect of the aerosols is insignificant. If we assume that the heating effect of greenhouse gases other than carbon dioxide disappears in the long term, the carbon dioxide concentration would need to increase to just over 700 ppm for the temperature increase to be two degrees, i.e. nearly 300 ppm more than the current 410 ppm. This increase is considerably more than the approximately 130 ppm by which the carbon dioxide concentration has increased so far throughout the indus-

* Here, the IPCC state that the term "likely" should here be interpreted as 66–100 percent probability, i.e. it is not possible to rule out that climate sensitivity is below 1.5°C or above 4.5°C.

particular day in a particular place, but it is still generally correct for determining the Earth's average temperature and for understanding the greenhouse effect.

Uncertainty about climate sensitivity has not decreased in recent decades, but we can hope that it will in the future. The most promising route should be to integrate the various methods mentioned in the mathematical description, demanding that climate models should include a reasonable description of the detailed processes and reproduce heating since the start of the industrial era and what we know of the climate in previous epochs—and also correspond to the increasingly detailed measurements of the subprocesses that are now being conducted by satellites. However, it is hardly realistic to believe that uncertainty will soon be a thing of the past. This is of great significance for the choice of good climate policy.

trial era. Even if we assume that the heating effect of the other greenhouse gases remains at the current level, the carbon dioxide concentration would need to increase to just over 550 ppm for the temperature increase by two degrees, i.e. increase by roughly as much again as it has increased so far during the period in which we have been using fossil fuels.

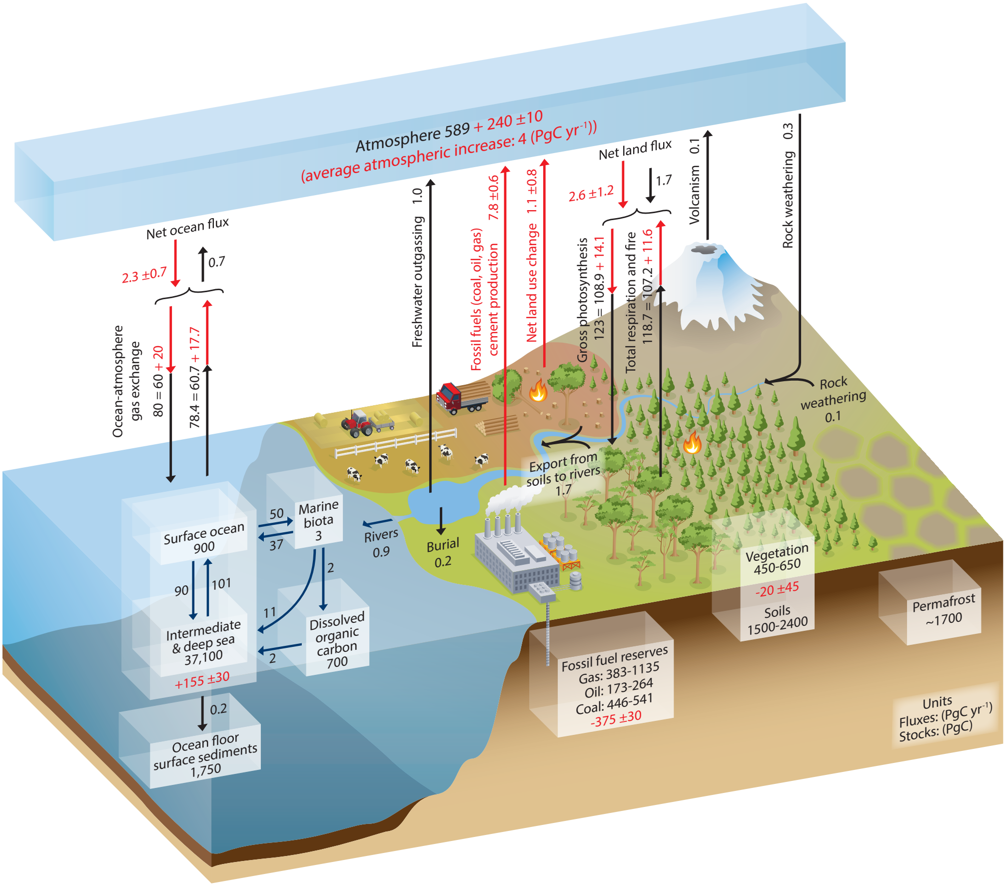

Figure 3 Illustration of the carbon system. The figures in the boxes are the amount of carbon in the reservoirs, measured in GtC. The arrows are the annual flows (fluxes), measured in GtC per year. The red figures are the changes caused by anthropogenic carbon dioxide emissions.

Source: J. Rogelj, D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, and M. V. Vilariño: "Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development". Chapter 2, figure 2.3 in IPCC (2018).

2.4 The carbon system

As stated, the inflow of carbon dioxide to the atmosphere is a decisive factor in the greenhouse effect, and to understand this, it is necessary to understand the carbon system.

In the climate system, carbon atoms primarily circulate between three different reservoirs: the atmosphere, the oceans, and land surfaces. Chemically, there are two forms of carbon: organic carbon and inorganic carbon. Organic carbon is mainly found on land, in living and dead plants, and buried in the ground (terrestrial carbon). Inorganic carbon exists both in the atmosphere in the form of carbon dioxide and in the oceans in the form of dissolved carbon dioxide, bicarbonate ions, and carbonate ions. The different forms of inorganic carbon in the oceans comprise a chemical buffer system that regulates the water's pH (i.e. its acidity), and they can easily transform from one to the other in reactions to achieve chemical equilibrium. The oceans also contain organic carbon, but the amount here is insignificant compared to the amount on land because dead organic material in the oceans is decomposed into inorganic carbon much more quickly than dead trees on land.

The oceans are by far the largest reservoir, containing 38,000 GtC (the amount of carbon in each reservoir is measured in GtC, or gigatons of carbon [1 gigaton is equivalent to 1 billion tons of carbon]). This can be compared to the more than 800 GtC in the atmosphere and the 2,000–3,000 GtC on the land surface (figure 3).

There are large flows moving continually between these reservoirs. Plants absorb carbon dioxide from the air and transform it into organic carbon using sunlight, in a process called photosynthesis. At the same time, plants decompose some of their organic carbon into carbon dioxide, and microorganisms, fungi, and animals also break down the organic carbon in living and dead plants to produce carbon dioxide. These flows to and from the atmosphere are almost equally sized and, over a year, amount to almost one-sixth of the amount of carbon dioxide in the atmosphere. Similarly, the oceans dissolve large volumes of atmospheric carbon dioxide in some areas, while almost the same amount is released to the atmosphere in other areas.

Since the start of the industrial era, carbon dioxide produced by combusting fossil carbon has been added, releasing around 10 GtC into the atmosphere every year,[6] with deforestation also resulting in the additional release of more than 1 GtC to the atmosphere. This has led to carbon dioxide levels increasing from 280 ppm to 410 ppm, and the increase continues at an accelerating rate (figure 4).[7]

This increase means that the carbon system is far from a state of equilibrium. The higher concentration means that more carbon dioxide from the atmosphere is dissolved in the oceans, while less is released from them. There is thus a net flow from the atmosphere to the oceans. Higher concentrations of carbon dioxide also boost plants' photosynthesis, so they absorb more carbon dioxide. Much of this carbon rapidly returns to the atmosphere when the plants decompose, but the result is still that the total amount of organic carbon on land is increasing, at the cost of atmospheric carbon dioxide. Increased tree cover due to a warming climate at higher latitudes has the same effect.

The net flow of carbon from the atmosphere is now estimated

---

6. Emissions are often measured as carbon dioxide instead. A unit of mass of carbon can be multiplied by 3.67 to obtain the mass of carbon dioxide.

7. The amount of carbon in the atmosphere is often measured in ppm, parts per million volume, of carbon dioxide. Multiplying the concentration in ppm by 2.13 gives the amount of carbon in the atmosphere measured in GtC.

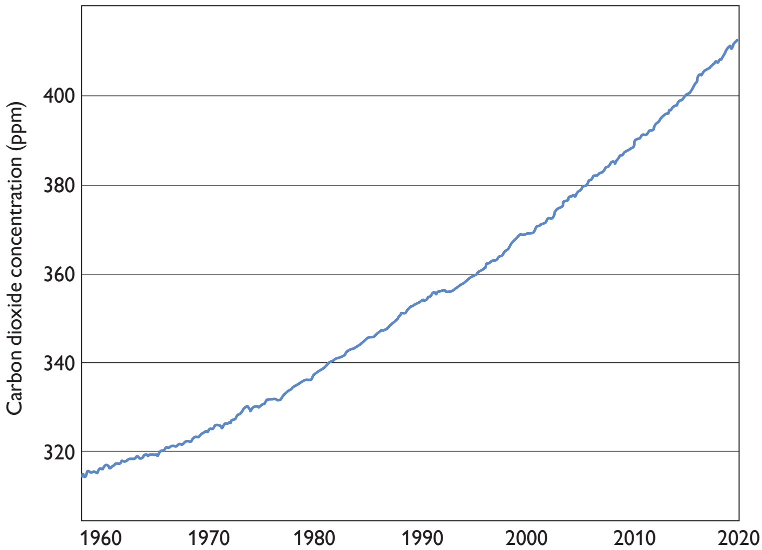

Figure 4 The increase in the concentration of atmospheric carbon dioxide in recent decades.

Source: https://www.esrl.noaa.gov/gmd/ccgg/trends/.

to be 3.0 Gt per year to the land reservoir and 2.4 Gt to the oceans. Together, this is a little over half the amount added every year through the combustion of fossil fuels. What will happen to these carbon flows in the future?

The flow to the oceans and the flow to land can be regarded as adaptations to a new equilibrium, with a higher concentration of carbon dioxide and higher temperatures than the equilibrium that existed prior to the industrial era. If we were to stop combusting fossil fuels, these flows would gradually reduce and the system would approach a new state of equilibrium. For the land reservoir, we can expect this adaptation to the climate and carbon dioxide concentration to take about 50 years; this is the average lifespan of trees, which contain most of the biomass. For the oceans, it will take much longer: many centuries, which is the time it takes for the water to circulate between the oceans' depths and their surface, so that it enters equilibrium with the atmosphere. Even if the carbon flow to land is now greater than that to the oceans, it is the latter flow that is decisive in the long term because the oceanic carbon reservoir has a much greater capacity than the land reservoir.

Equilibrium with the oceans is primarily governed by a condition for chemical equilibrium that states that the partial pressure of carbon dioxide must be as great in the water as in the atmosphere. If the atmospheric partial pressure is higher, carbon dioxide will flow to the water, and vice versa. The amount of carbon contained by the water at this saturation pressure (solubility) depends on both the temperature of the water and its acidity (its pH). If you could maintain a constant temperature and pH, doubling the concentration of carbon dioxide would lead to twice the amount of carbon dioxide being dissolved in the water in a state of equilibrium. Because the oceans contain 50 times more carbon than the atmosphere, this would mean that 98 percent of the carbon dioxide released into the atmosphere would be absorbed by the oceans when equilibrium is achieved in a few centuries.

However, in reality, neither temperature nor pH is constant. The temperature in the oceans increases, and as more carbon dioxide is dissolved in them, the water becomes more acidic. This reduces the oceans' capacity for absorbing carbon dioxide, so considerably less than 98 percent of the carbon dioxide will be absorbed at equilibrium. If the amount of carbon dioxide that is emitted corresponds to those IPCC scenarios in which the average global temperature does not increase more than 1.5 or 2 degrees Celsius, around one-quarter will remain in the atmosphere for thousands of years. If emissions are much greater, this proportion increases. For example, if the total accumulated emissions are 2,000 GtC, it is probable that over 40 percent will remain in the atmosphere. To the present day, accumulated emissions are close to 600 GtC, of which almost half have been released in the past 30 years.

2.5 The combined effect of the climate system and the carbon system

From the above description, we can note two properties of the climate system:

1. The oceans' capacity to store heat delays warming. This means that if the concentration of carbon dioxide rapidly increases to a certain value and then remains constant, the average global temperature will continue to increase long after the concentration has stopped increasing. The temperature lags behind the carbon dioxide concentration.
2. The heating effect of carbon dioxide depends on the margin on the *relative* increase of its concentration in the atmosphere. This means that an increase from 700 ppm to 701 ppm causes half as much heating as an increase from 350 ppm to 351 ppm. The marginal effect of additional carbon dioxide therefore falls with increasing concentration.

On the other hand, the carbon system has the following two properties:

3. Oceans and terrestrial vegetation continually absorb carbon from the atmosphere (just over half as much as humankind re-

leases). Even if humanity's emissions ceased entirely, these flows of carbon would continue at a gradually decreasing rate.

4. In the long term, the oceans have a much greater capacity than the terrestrial plants for sequestering carbon, but the capacity of this buffer system is limited. This means that, in the long term, the greater the total accumulated emissions, the smaller the proportion of emissions that are absorbed in the oceans. Thus, the larger the total accumulated emissions, the greater the part of an emitted unit that remains in the atmosphere for the foreseeable future (thousands of years).

The properties of the two systems counteract each other in two ways:

If emissions of carbon dioxide were to suddenly cease, the lag caused by the oceans' capacity to store energy has the effect of making the temperature continue to rise (property 1), while the oceans' continued absorption of carbon dioxide would reduce the concentration of carbon dioxide in the atmosphere over time, having an effect in the opposite direction, i.e., causing the temperature to fall over time (property 3).

The heating effect of additional carbon dioxide declines with increasing concentration (property 2), which decreases the marginal effect on the energy balance the more has been emitted (property 2). On the other hand, the more has been emitted, the greater the proportion of marginal emissions that remain in the atmosphere (property 4).

Simulations performed by researchers using models that include both the climate and carbon circulation show that both types of contradictory properties (1 and 3, and 2 and 4) largely balance each other out. Because properties 1 and 3 balance each other out, if carbon dioxide emissions suddenly cease, the global average temperature will remain about constant. Because properties 2 and 4 balance each other out, the effect on the climate of an additional unit of emissions is fairly independent of how much has previously been emitted. Because each unit of emissions increases heating by the same amount (the balance of 2 and 4) in both the short and long term (the balance of 1 and 3), global warming is proportional to accumulated historical emissions. The proportionality coefficient is called TCRE (transient climate response to cumulative carbon emissions). There are no fundamental reasons why the effects of the climate and carbon systems compensate for each other in these ways; it is a coincidence.

Figure 5, from the IPCC (2018), illustrates this result. The figure shows the relationship between accumulated emissions—measured here in billion tons of carbon dioxide—on the horizontal axis, and the global average temperature on the vertical axis, for different emissions curves. As we can see, the relationship is approximately linear, i.e. the temperature is proportional to accumulated emissions. The slope of the relationship is given by the TCRE proportionality coefficient.

In practice, this means that if, in an Earth system model, emissions were suddenly turned off, the temperature would generally then remain about constant and that this temperature is independent of how rapid the emissions were prior to this. This also means that if the emissions are twice as great in one simulation as in another one using the same model, the temperature also increases twice as much.

The proportionality result also means that it is possible to determine a *carbon budget*. Given that a particular global average temperature should not be exceeded, with an assumed value for the TCRE proportionality coefficient, it is possible to calculate how

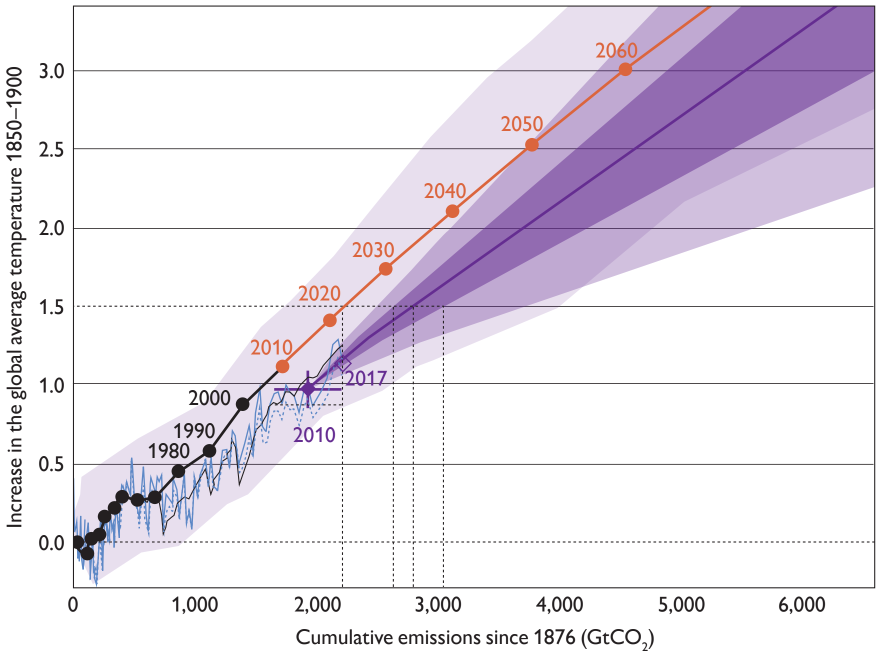

Figure 5 Global average temperature and accumulated carbon dioxide emissions. The temperature should be approximately proportional to the accumulated emissions for the various emissions pathways. The colored fields show the uncertainty in the calculations. The dashes lines show how much carbon dioxide remains to be used to stay within the 1.5-degree target.

Source: P. Ciais, C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J. Galloway, M. Heimann, C. Jones, C. Le Quéré, R. B. Myneni, S. Piao and P. Thornton:"Carbon and Other Biogeochemical Cycles". Chapter 6, figure 6.1 in IPCC (2013).

much more carbon can be emitted. For example, assuming we do not want to exceed 2 degrees of global warming and that the TCRE is 2 degrees per 1,000 GtC, we can emit 1,000 GtC; because we have already emitted 600 GtC, 400 GtC remain. According to the proportionality result, the time profile for the emission of these 400 GtC is irrelevant. The IPCC (2013, SPM) states that for it to be probable that the increase in temperature stays below 2 degrees, accumulated emissions must not exceed 1,000 GtC. At the current rate, we will reach this level of accumulated emissions in around 40 years.[8]

We must make several qualifications when using the proportionality result; arguably the most important one is that there is great uncertainty about the value of the TCRE proportionality coefficient, as different models give different values. The IPCC (2013, SPM) states that it is in the interval of 0.8–2.5 degrees per 1,000 GtC. This great uncertainty rests primarily on the uncertainty of climate sensitivity, i.e. how sensitive the climate is to the carbon dioxide concentration in the atmosphere. Some simple calculations can illustrate what this means.

For simplicity's sake, in these illustrations we disregard the contribution to global warming from aerosols and greenhouse gases other than carbon dioxide. If TCRE = 0.8 degrees, we can emit a total of 2,500 GtC and still achieve the 2-degree target. Accumulated emissions are currently close to 600 GtC, so we could thus emit three times as much again. If we instead assume that TCRE = 2.5 degrees, we can emit a total of 800 GtC, i.e. just another 200 Gt, which will take 20 years at the present rate. In the latter scenario there is an implicit assumption that aerosols now have a powerful cooling effect—so that although climate sensitivity is high, it is masked by the aerosols—and that this cooling disappears before the temperature has increased by 2 degrees.

Furthermore, the proportional relationship between accumu-

8. Because one ton generates 3.67 tons of carbon dioxide when it is combusted, these carbon budgets are stated in $GtCO_2$ (billions of tons of carbon dioxide) by multiplying them by 3.67.

lated emissions and temperature is just an approximation within certain boundaries. It only applies to reasonable emissions paths, and not if the temperature increase is slowed by negative emissions long after the emissions have occurred, for example. Nor does it apply after the temperature has reached its maximum or if the accumulated emissions are very large, in excess of 2,000 GtC.

Finally, we should note that proportionality applies to the relationship between accumulated emissions of carbon dioxide and the global average temperature without considering emissions other than carbon dioxide, although they currently have a considerable impact. These are other greenhouse gases that contribute to warming—particularly methane—and aerosols that cool the climate. What most of them have in common is that they have a much shorter life in the atmosphere than carbon dioxide, from a few weeks for aerosols to 10–15 years for methane.[9] This means that the accumulated emissions of these are not relevant, as their effect on the climate is due to the current emissions. The same applies to the high altitude effects of aviation. The warming caused by aviation's carbon dioxide emissions is generally permanent, while that caused by high altitude effects disappears immediately if aviation ceases.

2.5.1 Tipping points

One concern that has been presented is that if global warming exceeds a certain level, a tipping point will be passed. Usually, this means that a self-reinforcing mechanism starts at a particular temperature, so that climate change, or some of its effects, can no longer be stopped. The process may be rapid, but it can also be slow and yet irreversible.

---

9. Nitrous oxide and many industrial gases are greenhouse gases that are persistent in the atmosphere.

Of course, it is impossible to say anything about this from empirical observations of the climate since the preindustrial era, but the IPCC has tried to estimate the risk of the processes that have been suggested; these estimations largely rest on model simulations. According to the probability terminology that is used, "very likely" is a probability of at least 90 percent and "likely" at least 66 percent, while "unlikely" means a maximum of 33 percent and "very unlikely" a maximum of 10 percent. Here, we discuss some of the proposed tipping points.

Collapse of vertical circulation the in the Atlantic. This phenomenon is often equated with the phenomenon of the Gulf Stream disappearing, but they are not identical. Since the Gulf Stream is driven by the most fundamental wind patterns in the atmosphere, it is extremely unlikely that it will stop. In simplified models of the ocean, a rapid melting of the Greenland ice sheet could lead to permanent changes in the vertical circulation in the Atlantic, so that deep water is no longer formed in the North Atlantic. However, according to more complete simulation models, the formation of deep water and the vertical circulation in the North Atlantic will temporarily weaken due to climate change and then recover. According to the IPCC (2013, chap. 12), it is "very unlikely"—i.e. a probability less than 10 percent—that the Atlantic's vertical circulation will collapse in the 22nd century and "unlikely"—less than 33 percent probability—after that.

- *Carbon dioxide from thawing permafrost*. Large amounts of organic carbon are held in the tundra permafrost in Siberia and North America, more than twice as much as atmospheric carbon dioxide. If this thaws, organic material could decompose and emit carbon dioxide. There is no evidence that this is currently a considerable source of carbon dioxide—quite the opposite, the Arctic is a carbon dioxide sink. According to the IPCC (2013, chap. 12), it is possible that the permafrost will be a small net source of carbon dioxide before 2100, with more recent research presented by the IPCC (2019b) indicating an increased risk of this. Permafrost thaws slowly, illustrated by the deeper areas dating from the ice age. If the carbon dioxide is released in this way, it is an irreversible process.

- *Methane clathrate on the ocean floor*. A great deal of carbon is stored as methane clathrate on the ocean floor, particularly in the Arctic. (Methane is a strong greenhouse gas, but in the atmosphere, it is oxidized into carbon dioxide with much less greenhouse potential in about 10 years.) If the ocean heats up, this methane could be released. This is not currently a considerable source of methane, and as it is released from the ocean bed, most of it is oxidized to form carbon dioxide in the water. According to the IPCC (2013, chap. 12), the release of methane clathrates is a slow process—that it would occur rapidly is "very unlikely"—and it is "unlikely" that large amounts will be released prior to 2100. If it does happen, the process is irreversible.
- *Melting ice sheets*. Because the atmospheric temperature drops with increasing altitude, an ice sheet must be at a critical height to remain stable. If it melts and no longer reaches this height at any point, it will probably melt entirely. This change is irreversible. Greenland's ice sheet is more than 2,000 meters deep, and if it were to melt, sea levels would rise by an average of 7 meters. It has been established that it has started to melt at an accelerating rate, but this is a very slow process, and at the current rate, it would take about 14,000 years for the ice to completely disappear. The IPCC (2013, chap. 13) assesses that if heating follows the most rapid scenario (RCP8.5), then meltwater from Greenland will

contribute 10–20 centimeters to the global sea level rise by 2100.

The other large ice sheet is in Antarctica. It is colder there than in Greenland, so it is unlikely to melt from the top, but it can lose mass where it is in contact with the ocean. This is particularly true of western Antarctica, where the ice rests on ground that is below sea level, which may make it unstable if the water heats up. This process could occur considerably faster than that in Greenland. The IPCC (2013, chap. 13) judges that if this occurs, which is very uncertain, it could contribute tens of centimeters to the global sea level rise by 2100. Otherwise, their assessment is that the contribution from Antarctica will be less than 10 centimeters and that the total sea level rise by 2100 will probably be between 50 and 100 centimeters if global warming follows the fastest scenario. In its latest report, the IPCC (2019b) has made an upward adjustment to sea level rise by 2100 in scenario RCP8.5 by 10 centimeters, due to a greater contribution from Antarctica. It is now stated as probably being between 0.61 and 1.10 meters, with continued increases in coming centuries.

- *Drying of the Amazon.* Trees in the rainforest absorb large amounts of water, which then evaporates into the atmosphere and contributes to precipitation. The forest thus "recycles" the water, so there is concern that if the forest is felled or dies due to a drier climate, the climate would become even drier and prevent the forest from regenerating. According to model simulations, this scenario is most probable in the Amazon. However, the risk is counteracted by the positive effect on vegetation of increasing levels of carbon dioxide. The risk is difficult to estimate, but according to the IPCC (2018), it could occur at global warming of 3–4 degrees or 40 percent deforestation.

CHAPTER 3

What is the impact of climate change?

3.1 Chapter summary

The magnitude of forecasted climate change and its effects naturally depends on the amount of emissions. The IPCC (2013) uses a range of emissions scenarios. In one of these, where emissions peak in 2040 and then fall, the forecast global average temperature increases by 2.4 degrees toward the end of the century compared to the average for 1850–1900. The uncertainty interval is large: 1.7–3.2 degrees. The commitments established under the Paris Agreement are estimated to lead to global warming of around 3 degrees.[1] A more pessimistic scenario, in which emissions continue to increase through-

1. In the "Emissions Gap Report 2018", the UN's global environment programme, UNEP (2018) states that the current commitments in the Paris Agreement will lead to a 3-degree rise in the global average temperature by 2100. They also state an uncertainty interval of 2.7–3.2 degrees. In a report from December 2018, Climate Action Tracker, an independent research partnership, also forecast 3 degrees of heating by 2100, with an uncertainty interval 2.4–3.8 degrees. The increases are relative to the pre-industrial temperature, which is often stated as an average for the period 1850–1900.

out this century, leads to a predicted warming of 4.3 degrees, with a 90 percent uncertainty interval of 3.2–5.4 degrees.

Climate change is often summarized as the change to the global average temperature, but it is of course multifaceted. Sea levels are estimated to rise by .5 to 1 meter over this century. Even if the number of tropical storms does not increase, it is likely that the very strongest ones will be more frequent. However, model simulations reported by the IPCC (2013) do not indicate that storms at northern latitudes will increase in either number or strength. There is uncertainty about effects on agriculture because carbon dioxide in itself boosts plant growth, but climate change could have negative consequences. The overall effect varies between different crops and regions. The frequency of extreme heatwaves is expected to increase in many parts of the world. Densely populated areas, including parts of Asia, may experience heat waves during which it is physiologically impossible to work outdoors.

Depending on the region and the ability to adapt, climate change's impact on economies and people's well-being will vary greatly. One summary of studies that review the global consequences shows damage at about 5 percent of GDP at 2 degrees of warming, with 10 percent at 3 degrees, although there is wide variation in the studies' results. Climate change does not threaten the survival of humanity, but it may have catastrophic consequences for some countries.

Our assessment is that the direct effects in Sweden will be small compared to our GDP. In this century, negative and positive direct effects are estimated to be fractions of a percent of GDP. In addition to the direct effects, there are indirect effects caused by climate change in the rest of the world. These effects could arise due to trade, migration, international conflicts, and an increased need for international aid. They are varied and very difficult to evaluate.

3.2 The effects of climate change

The effects of climate change vary greatly between different areas, and because the climate is more difficult to predict at a regional level than at a global level, the effects of climate change are difficult to predict at a regional level. The empirical method that is used to determine global climate sensitivity functions less well at a regional level, because natural climate variations are greater there than when considering the Earth's average temperature. Predictions of the effects of climate change are therefore largely based on model simulations.

Naturally, forecasts of the magnitude of climate change depend on the amount of emissions. Reports from the IPCC often use four scenarios, called RCPs (Representative Concentration Pathways): RCP2.6, RCP4.5, RCP6.0, and RCP8.5. The numbers indicate estimated radiative forcing in 2100, the reduction in energy outflow from the Earth to space caused by carbon dioxide in an unchanged climate; see section 2.3. In the first scenario, emissions start to fall now. In the second and third scenarios, emissions peak around 2040 and 2080, and in the last one, they increase throughout this century. These scenarios generate different trajectories for the concentration of atmospheric carbon dioxide, which are shown in figure 6.

In turn, these scenarios also generate different forecasts for the increase in the global average temperature. These are shown in table 1. When you look at the table, it is important to note that RCP2.6 and RCP4.5 require a considerably more forceful climate policy than that which is currently implemented. According to the nationally determined contributions (NDC) made under the Paris Agreement thus far, global warming is estimated to be about 3 degrees toward the end of this century. However, the Paris Agreement contains a clear ambition to gradually tighten up these obligations. All sce-

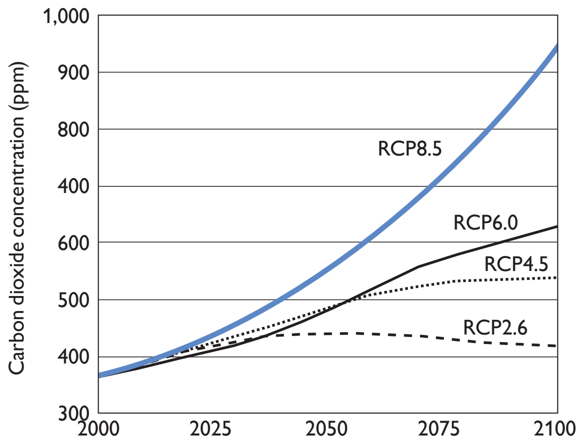

Figure 6 The IPCC's four scenarios for the trend in carbon dioxide concentration to 2100.

Source: van Vuuren et al. (2011).

narios, except for RCP8.5, lead to a predicted temperature increase below 3 degrees and would thus require more measures than those to which countries have already committed.

3.2.1 Sea level rise

Numerous factors cause rising sea levels through global warming. The IPCC's estimates for sea level rise by 2100 are primarily based on model simulations. In these, the largest contribution is from thermal expansion of the seawater, followed by melting glaciers and then from the melting ice sheets on Greenland and Antarctica. In the long term, the largest contribution will probably be from Greenland. For the RCP8.5 scenario—the one with the fastest heating—the IPCC (2013, SPM) states that the sea level rise by 2100 will probably be

Table 1 Forecast increases in the global average temperature. The IPCC states that the uncertainty interval is such that the risk is one third or less that the temperature will be outside the interval. The table in the source shows the temperature increase relative to the period 1986–2005. To show the increase relative to 1850–1900, 0.6 degrees have been added to all temperatures.

Scenario	*Temperature increase above the average 1850–1900*			
	2046–2065		*2081–2100*	
	Forecast	*Uncertainty*	*Forecast*	*Uncertainty*
RCP2.6	1.6	1.0–2.2	1.6	0.9–2.3
RCP4.5	2.0	1.5–2.6	2.4	1.7–3.2
RCP6.0	1.9	1.4–2.4	2.8	2.0–3.7
RCP8.5	2.6	2.0–3.2	4.3	3.2–5.4

Source: IPCC (2013, table SPM.2).

0.5–1 meter. In its latest report, the IPCC (2019b) has increased this estimate by 0.1 meter. It is likely that the sea level will then continue to rise for several centuries, even if the concentration of atmospheric carbon dioxide stops increasing. There is also a risk that sea levels will rise faster if western Antarctica's ice sheet were to collapse, but there is a great deal of uncertainty about such a scenario.

3.2.2 Precipitation

Even if climate models give different results in many ways, they agree on one point: that the atmosphere's relative humidity will remain about the same, on average, in a warmer climate. Relative humidity is measured in relation to the maximum amount of water vapor the atmosphere can contain. This maximum increases with temperature by about 7 percent per degree Celsius, according to the Clausius-Clapeyron relation. Therefore, if relative humidity is constant, the amount of water vapor—the absolute humidity—will also increase by 7 percent for every degree of increased temperature. This corresponds well with observations of the trend in humidity since the mid-1970s. That absolute humidity follows temperature in this way is important for understanding changes in precipitation—and other aspects of climate change.

Even if relative humidity remains constant, precipitation will not be unchanged. As the previous chapter described, the energy that reaches the surface of the Earth is transported back up through the atmosphere as thermal radiation, thermal energy in the air, and the latent heat of water vapor. In a warmer climate, with greater absolute air humidity, a larger proportion of the energy transport will occur through latent heat, i.e. the water evaporates at the surface of the Earth and condenses at a higher altitude. As this energy transport becomes more significant, evaporation increases, as does precipitation. The IPCC (2013, chap. 12) estimates that global precipitation will increase by 1–3 percent per degree, based on model simulations. Measuring global precipitation is difficult. There are large local variations, precipitation fluctuates a lot from one year to another, and there are few measurements over oceans, so it has not been possible to confirm these results using historical observations.

Unlike average precipitation, the precipitation in a heavy downpour depends on how much water vapor is held in the atmosphere. The IPCC (2013, chap. 12) therefore finds it very likely that precipitation in extreme weather events will increase more than average precipitation as the climate gets warmer and that this increase is probably in the interval of 5–10 percent per degree. For statistical reasons, it is difficult to confirm such a trend through observations because extreme events rarely occur. Rapidly increased precipitation in extreme weather events due to increasing temperature also entails an increased risk of flooding.

A global increase in precipitation does not mean it increases everywhere. There are significant regional differences, and the generally expected patterns are that precipitation will increase most in the areas where it is now plentiful, i.e. in the tropics and at high latitudes, while it will increase less or decline where the climate is already dry, in subtropical areas. The details are difficult to predict, but most climate models predict that it will become drier in the Mediterranean region in particular.

3.2.3 Storms

The mechanisms responsible for tropical storms and storms at higher latitudes are different; while tropical storms are driven by evaporation from the surface of a warm ocean, storms at higher latitudes are caused by temperature differences between lower and higher latitudes. There are no clear observational indications that the number of either kind of storm has increased over the last century. Observations do show that the number of very powerful tropical storms in the North Atlantic has increased since the 1970s, but it is unclear why. Reductions in aerosol emissions in this region may have been significant, as may the warmer climate (IPCC, 2013, chap. 14).

Model simulations show that global warming will probably not lead to more tropical storms but that the strongest storms may increase in strength. However, the simulations do not indicate that storms at higher latitudes will increase in either number or strength. Even if wind speeds do not increase, the precipitation that falls during the storms will probably increase for both types of storms.

3.2.4 Health effects

Climate has a direct effect on human health, with many deaths being caused by heat and by cold every year. A current statistical calculation for the USA shows an excess mortality of 2–5 percent in both heatwaves and cold spells (Anderson and Bell, 2009). A statistical calculation for India shows greater excess mortality in cold rather than hot weather (Fu et al., 2018). Global warming means that heatwaves will be hotter and cold spells milder. Some attempts have been made to apply current statistical relationships between temperature and excess mortality to the future climate, but such methods do not consider the population's capacity for adaptation. Nor do they take account of the absolute physiological limit to the temperature humans can withstand, which is highly dependent on humidity. If it is dry, sweating is an effective method of cooling and dealing with very high temperatures, but it is ineffective in high humidity.

The wet bulb temperature (TW) is therefore a relevant measure of how heat affects humans; this is the temperature of a wet object in the shade. Due to evaporation, a wet object, such as a sweaty body, is colder than the surrounding air, but the difference decreases with the air's relative humidity. On land, TW tends to be highest close to the coast and in moist areas, such as rainforests and areas with extensive irrigation. It has a close relationship with the surface temperature of the ocean and normally decreases with height by about 2 degrees per 100 meters. In association with global warming, TW in the tropics generally increases as much as the global average temperature.

People's capacity for physical activity declines rapidly when TW approaches 30 degrees, and at 32–33 degrees, even young and healthy people are incapable of even light physical work. At a TW above 35 degrees, it is impossible to maintain a body temperature of 37 degrees, causing a significant risk of heatstroke. Currently, TW rarely exceeds 31 degrees anywhere on Earth. Toward the end of the 2100s, TW may approach 35 degrees in extreme heatwaves, first on the coast of the Persian Gulf and then in the densely populated areas around the Indus in Pakistan and the Ganges in India, as shown in model simulations where the global average temperature in the period 2071–2100 is 4.5 degrees higher than preindustrialization (Im, Pal, and Eltahir, 2017).

According to these simulations, over these 30 years, 4 percent of the South Asian population will be exposed to a TW of at least 35 degrees during a heatwave, and 20 percent to a TW of at least 34 degrees. Other simulation models have estimated the loss of work capacity based on the monthly average TW (Dunne, Stauffer, and John, 2013), calculating that the global reduction in work capacity due to heat is 6–10 percent during the hottest month of the year in the current climate. Toward the end of this century, the equivalent reduction will be 27 percent if global warming is then 3.4 degrees. In the same simulations, warming will be 6.2 degrees by 2200, reducing the global work capacity by 61 percent in the hottest month of the year and by at least 12 percent in all months of the year. The assumption has been that the population has the same geographic distribution as today.

3.2.5 Plant life and nature

Global warming is shifting climate zones toward the poles and higher altitudes. According to the IPCC (2014, chap. 4), this is now happening at an average speed of about 1 kilometer per year and up to four times as quickly on plains; these figures will double in the fastest scenarios for global warming. However, all these figures are uncertain. Many animals can relocate quickly enough to follow these shifts, but most plants cannot. For example, it is estimated that trees can spread around 100 meters to 1 kilometer each year. This spread is made more difficult if areas of nature are cut off by areas that are exploited by humans, which can lead to species becoming extinct. Climate change has only had a marginal role in documented cases of extinction, and during the rest of this century, it is likely that changes in land use—such as deforestation—will play a greater role in extinctions.

Coral reefs are one of the ecosystems that are most sensitive to climate change, and there have been numerous observations of high water temperatures causing extensive coral bleaching. Because of this and other factors—such as ocean acidification and fishing—the number of coral reefs is declining. The IPCC (2014, Cross-Chapter Box) estimates that around one-third—with an uncertainty interval of 9–60 percent—of all coral reefs risk being destroyed in coming decades and that this proportion will increase to two-thirds—uncertainty interval of 30–88 percent—even if the increase in the global average temperature is limited to 2 degrees.

Plants are not only affected by changes to the climate but are also directly affected by the increasing concentration of carbon dioxide because it is necessary for photosynthesis. This is often called the carbon dioxide fertilization, and it is particularly strong in dry climates. This is because the plants lose water via the transpiration of water vapor through the same pores—stomata—that they use for absorbing carbon dioxide. The plants can regulate the size of these pores efficiently, so if the level of carbon dioxide doubles, the plants could, in principle, halve these openings, and thus also their water consumption, while still absorbing as much carbon dioxide as previously. On the other hand, higher temperatures increase the loss of water vapor through a pore of a given size, and thus the plants' water consumption, but this effect is considerably weaker than that of the increased concentration of carbon dioxide. Global satellite observations have shown that vegetation is increasing in most dry areas (IPCC, 2019a). During the last ice age, both the temperature and carbon dioxide concentration were considerably lower than in the 19th century, and deserts were large, while the extent of tropical rainforests and other types of forest was substantially smaller.

As previously mentioned, plants absorb about 3.0 GtC from the atmosphere every year, which is the difference between photosynthesis and the decomposition of plants to carbon dioxide. Therefore, this does not tell us how much photosynthesis is increasing, since decomposition also increases due to rising temperatures and growing volumes of dead plant matter. The IPPC (2013) did not make a quantitative assessment of the increase in photosynthesis, but numerous studies have subsequently been conducted using different types of observation data. Satellite measurements of the Earth's "greenness" have been conducted since the 1980s, providing a measure of the total area of leafy green vegetation and showing that the Earth is becoming greener. Other data that have been used are the concentration of chemical markers of photosynthesis preserved in the Antarctic ice, the size of the annual variations in the atmosphere's carbon dioxide levels, and direct measurements of plant growth in the field. In many cases, these are combined with model simulations of vegetation by using statistical methods. According to one of these studies, global plant production increased by 31 percent in the 20th century (Campbell et al., 2017) and, according to another, by 18 Gt of carbon annually (15–20 percent) in the same period (Keenan et al., 2016), while in a third study, the increase was 21 percent between 1961 and 2010 (Li et al., 2017). Attempts to explain this increase indicate that considerably more than half of it is caused by carbon dioxide fertilization. The second-most important explanation is that warming extends the growing season in northerly latitudes.

3.2.6 Agriculture

Using statistical studies similar to those used for natural vegetation to measure the effects of climate change and increased carbon dioxide concentration on agricultural production is not possible because agriculture is strongly affected by changes in methods, such as irrigation and artificial fertilizers. Field experiments in which the level of carbon dioxide around growing crops has been increased have shown positive but highly varied results. Typically, growth increases by 20–30 percent when carbon dioxide levels increase by about 200 ppm, while the level of proteins in the crops declines.

The IPCC (2014, chap. 7) describes the effects on harvests from a large number of simulation models for specific crops; according to their mean value, climate change has reduced harvests by around 1 percent per decade in recent decades. This can be compared to the increase of 15–25 percent per decade in global harvests per hectare between 1960 and 2010, thanks to improved agricultural methods. However, most of these climate models did not include the direct effects of carbon dioxide concentration. Looking to the future, the estimation was that the negative effect will be 1–2 percent per decade, with a wide variation across the different models. Later simulations that were conducted for the IPCC using three different agricultural models, all of which included carbon fertilization, showed positive effects at 2 degrees of warming for global harvests of wheat, rice, and soya, and negative effects on maize (Ruane et al., 2018, and Rosenzweig et al., 2018). When carbon fertilization was removed, the effect was negative in all cases, with harvests reduced by 3–7 percent.

3.3 Effects on the economy and human welfare

As we have described, climate change is extremely complex, so the overall effect on the economy and on human welfare is enormously difficult to determine. However, making such an assessment is vital because it is necessary for designing a balanced climate policy and estimating the scale of the damage caused by carbon dioxide emissions. Even though it is not possible to make this kind of assessment without making value judgments, researchers have assumed the task.

Two different approaches have been used. One could be called "bottom up" and can be simply described as follows: first, make a list with all the possible types of mechanisms through which climate change could affect human welfare; then, gather quantitative studies that describe the size of the effects caused by these mechanisms in various parts of the world. After this, summarize all the mechanisms and regions to obtain a global damage function. This is often expressed as the relationship between the change in the global average temperature and climate damage expressed as a percentage of GDP. It is important to note that even if the damage is expressed as a percentage of GDP, values not included in standard calculations of GDP are also included; loss of life and health, the extinction of animal species, and the loss of non-commercialized natural areas are damages that are not measured in GDP but are nonetheless important to account for in the calculation.

William Nordhaus is the pioneer in this field. In his work with the first integrated climate-economy model, he constructed a global climate damage function using the "bottom up" method. The mechanisms that he described were agriculture, sea level rise, other market activities, human health, non-market priced natural values, other ecosystem services and biodiversity, as well as unspecified disasters. He divided the world into thirteen regions and collected studies of these mechanisms for all of them (Nordhaus, 1994).

The second approach instead uses statistical methods to analyze the more overarching link between climate change and economy and well-being. One way of doing this is to study the relationship between natural climate variations and the level and growth of GDP, for example. Dell, Jones, and Olken (2014) use data for GDP and GDP growth in all the countries of the world over a 50-year period. They also use data for the countries' average temperature per decade and study how deviations from a country's normal temperature affect the level and growth of GDP. They found that increasing temperature has strongly negative effects on economic growth—but only in poorer countries.

One variant of the second approach studies the relationship between a country's average temperature and its GDP per surface unit. Nordhaus et al. constructed a database with GDP distributed across the Earth in a grid of 1 x 1 degree.[2] From this, we can establish that there is a clearly inverted U-shaped relationship between average temperature and GDP per square. This is shown in figure 7, where the horizontal axis shows the average temperature and the vertical axis shows GDP. We can see that increasing temperature is correlated with higher GDP up to a temperature of about 11 degrees; for higher temperatures, this relationship is negative. This relationship is robust to the addition of many controls and also applies within countries.

If we assume that the relationship shown in figure 7 also applies to climate change, cold areas would stand to gain from climate change and hot ones would stand to lose. Because the majority of people live in areas with a temperature above 11 degrees, the majority of the global population would lose. Population distribution across areas of different temperatures is shown in figure 8.

The two approaches just described have different advantages and disadvantages. The "bottom up" approach has the benefit that it is explicit about which mechanisms are covered, providing clarity and often reliability for extrapolations, i.e. forecasts of yet unobserved climate change. For example, there is extensive knowledge of how agriculture is affected by changes to the climate. One disadvantage is that the list of mechanisms may be incomplete: For example, Nordhaus' original list did not include costs associated with climate-driven migration.

The approach that measures the effect of natural climate variations on the economy has the advantage of avoiding the need to define a list of mechanisms, but the disadvantage is that it studies relatively short-term variations in the climate. Of course, there is

2. The database is available at https://gecon.yale.edu/.

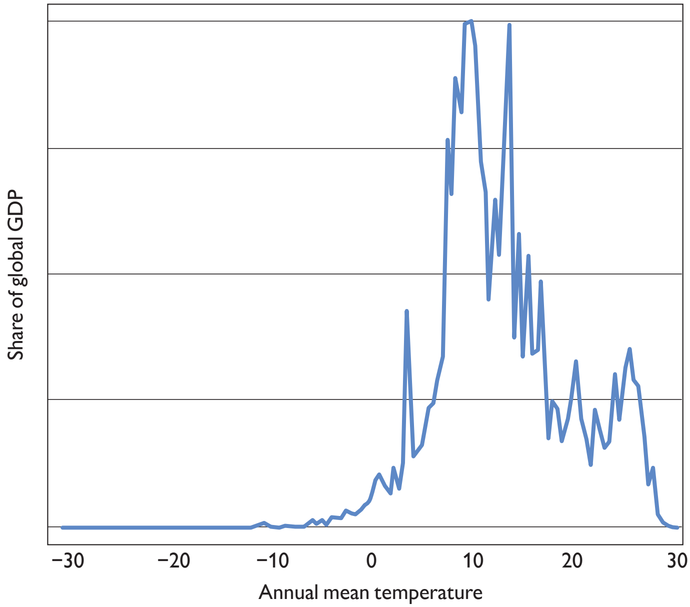

Figure 7 The relationship between annual mean temperature and GDP at a level of 1 x 1 degree for the entire Earth.

Source: Krusell (2019).

no certainty that the effects of a temporarily higher temperature in a specific decade are the same as if the temperature is permanently higher. This disadvantage does not exist for the approach in which the long-term relationship between temperature and GDP is studied, but this method cannot say anything about the adaptation costs that arise if the climate changes.

Given that the various approaches have different strengths and weaknesses, it is reasonable to try to use all of them in quantifying the relationship between climate change and economy/welfare. One way of doing this in a systematic manner is to use meta-analy-

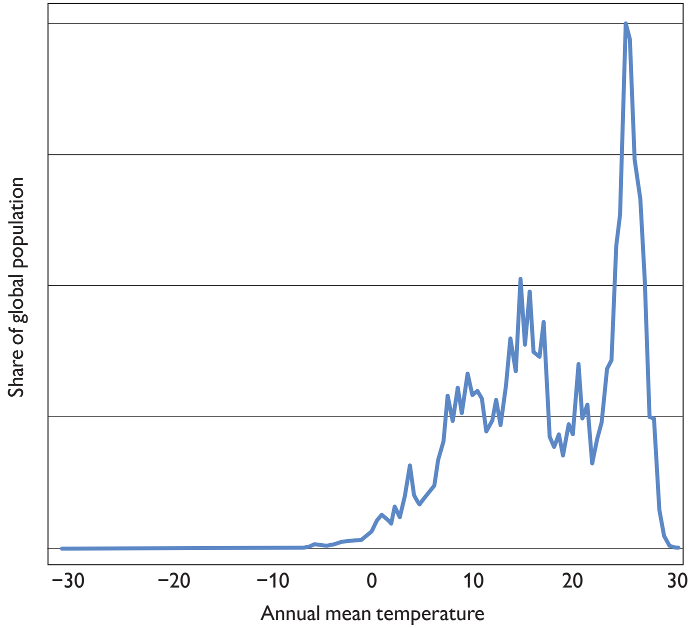

Figure 8 The relationship between annual mean temperature and population at a level of 1 x 1 degree for the entire Earth.

Source: Krusell (2019).

ses that combine information from all the available studies in a statistical analysis. One recently published meta-analysis is that by Howard and Sterner (2017), combining around 50 studies, each of which shows climate damage expressed as a percent of GDP for a set increase in the global average temperature.

Figure 9 shows the studies used by Howard and Sterner,[3] with

3. Studies with temperature increases that were too large have been excluded from the figure. The information value of these studies can be regarded as very limited.

each circle/triangle in the figure representing one study. The triangles show studies that are variations on previous studies and are therefore given less weight in the combined statistics. The articles cover different variants for combining the studies, with the one preferred by the authors given the black line. For a 1.5-degree increase in the global average temperature, it shows damage estimated to be 2.6 percent of global GDP. For 2 and 3 degrees of warming, the global values for damage are 4.6 and 10.3 percent.

There are several things here that are worth noting. Firstly, this shows the combined damage at a global level; there is huge variation for individual countries and regions. For some, the damage is much greater, but combined globally, they are balanced out by less dam-

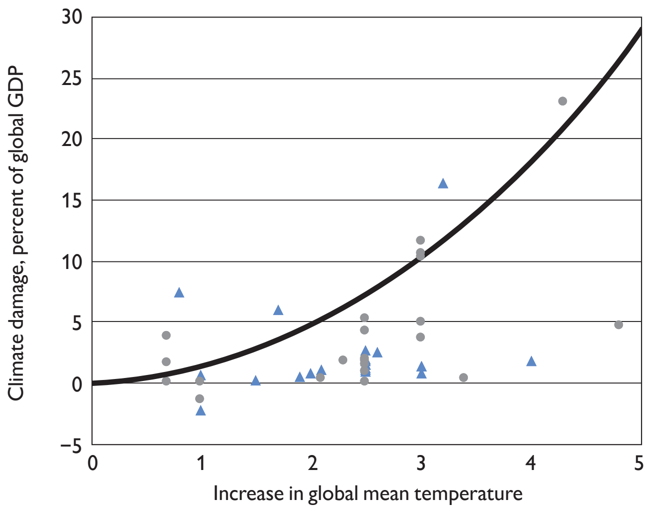

Figure 9 Studies of global climate damage.

Source: Data from Howard and Sterner (2017).

age in other parts of the world. Naturally, in practice, there is nothing that says we can assume that those who are least affected or who benefit compensate for those who are worst affected.

Secondly, there is significant uncertainty. Different studies arrive at different results, and it is not possible to determine which is correct, nor it is possible to rule out all the studies underestimating or overestimating the damage. Section 5.4 demonstrates that the consequences will be much worse if we underestimate the risks—thus taking measures that are too weak to reduce emissions—than the contrary—that we overestimate the risks and take measures that turn out to be unnecessarily stringent. Therefore, in general, when designing climate policy, it is wise to base it on the risk of significant climate damage, even if it is unclear how great the risks are and exactly what the damage will be. This can be compared to it often being wise to buy insurance coverage for accidents that may have a low probability of occurring but very damaging consequences if they do.

3.4 Effects in Sweden

3.4.1 Temperature changes

Naturally, how Sweden is affected by climate change depends on the extent of global climate change. It is likely that the annual average temperature will increase more in Sweden than the world average. The Swedish Meteorological and Hydrological Institute (SMHI) has used nine climate models to calculate how Sweden's climate will change in different global emissions scenarios.[4]

4. The results of SMHI's simulations are available at https://www.smhi.se/klimat/framtidens-klimat/klimatscenarier/.

Table 2 The average increase in temperature according to two scenarios. The table is based on data from SMHI's climate scenarios calculated at the Rossby Centre.

The increase in average temperature for 2081–2100 over the average for 1961–1990. Scenario RCP4.5 and RCP8.5 in parentheses.

	Year	*Winter*	*Summer*
Sweden	3.2 (5.5)	4.1 (6.8)	2.5 (4.4)
Norrbotten	3.9 (6.5)	5.3 (8.7)	2.7 (4.9)
Stockholm	2.8 (4.7)	3.3 (5.4)	2.3 (4.2)
Skåne	2.3 (4.1)	2.6 (4.4)	2.2 (4.0)

Source: https://www.smhi.se/klimat/framtidens-klimat/klimatscenarier/.

Table 2 shows the expected increases in mean temperatures in Sweden by the end of the century, using the RCP4.5 and RCP8.5 scenarios. The table compares the predicted temperature with the average for the period 1961–1990. The expected increase in the global average temperature by the end of the century is 2.1 degrees in scenario RCP4.5 and 4.0 degrees in RCP8.5.[5] SMHI's model predictions state that the temperature will increase more than this in Sweden, particularly in northern Sweden, with an average annual mean temperature for the final two decades, according to the prediction, of 3.2 degrees above the average for 1961–1990 in RCP4.5.

5. In the HadCRUT4 dataset, the global mean temperature is 0.3 degrees higher in 1961–1990 than in 1850–1900. In Table 1, we show that RCP4.5 leads to an expected increase in the global mean temperature towards the end of the century of 1.74 to 3.2 degrees in relation to 1850–1900.

In comparison, the warmest year in the period 1961–2016 occurred in 2014, when the average Swedish temperature was 2.3 degrees above average. Also for comparison, the difference in annual mean temperatures in Gävle and Malmö is about 3 degrees.

For Norrbotten, the prediction states that the average temperature by the end of the century will have risen by 3.9 degrees in scenario RCP4.5. The table also shows that it is particularly the winters that will become warmer.

As we have mentioned, RCP4.5 entails greater reductions in emissions than countries have yet committed to. Therefore, we are also showing the consequences of the more pessimistic scenario, RCP8.5, where emissions continue to increase throughout this century. The temperature in Sweden then increases by 5.5 degrees, which is about the same as the difference in the annual mean temperatures of Umeå and Malmö.

3.4.2 Effects on the economy and welfare in Sweden

The Commission on Climate and Vulnerability (SOU 2007:60) produced a collected assessment of the consequences of a changed climate in Sweden. The model scenarios used by the Commission were that the mean temperature in Sweden increases by 3–5 degrees by the 2080s compared to the years 1960–1990. The winter temperature could increase by 7 degrees in northern Sweden. Even if new knowledge has been added since 2007, it is worth describing the Commission's overall conclusions, as no new analysis using the same broad approach has been conducted in Sweden.[6]

---

6. The National Institute of Economic Research (2017a) has a more recent literature review. Some of the below reasoning is also based on this study.

In Sweden, a warmer climate will lead to a longer growing season, with the growth of pine, spruce, and birch calculated at 20–40 percent higher than at present by the end of the century. This means that felling could increase or that the area of protected forest could significantly increase without reducing the volume of timber extracted from the forest. The Commission's assessment was that this higher growth compensates for increased losses caused by storms, fires, and other damage.

Agricultural returns are expected to increase due to higher levels of carbon dioxide in the atmosphere. The effects of climate change as such, i.e. the temperature change, are more difficult to assess, but the assessment is that positive growth effects and the opportunities for new crops are largely canceled by negative effects in the form of the increased risk of drought in some areas, the increased frequency of extreme weather events, insect attacks, and other diseases.

The amount of precipitation and its pattern will change in Sweden and is expected to increase most in northern Sweden. Naturally, changes in precipitation have numerous consequences: from the increased risk of floods that cause erosion, landslides—primarily in the south of the country –to altered spring floods and increasing hydropower production in the north. The Commission on Climate and Vulnerability's assessment, based on calculations, is that hydropower production can be expected to increase by 15–20 percent by the end of the century. The Commission particularly highlighted a number of negative effects of climate change:

– The risk of flooding, landslides, erosion increases in many places in Sweden.
– The risk of dramatic changes to ecosystems in the Baltic Sea.
– Declining water quality in lakes and waterways.

- Mountain areas will be largely overgrown, affecting reindeer husbandry and tourism.
- Shortened season for winter tourism.
- More deaths due to heatwaves, increased spread of infectious diseases and other negative health effects.

The Commission on Climate and Vulnerability and SMHI (2010) described some effects in detail, as well as the risks due to increased precipitation and sea level rise. Among other things, 200,000 buildings are estimated to be too close to water in areas with an increased risk of landslides due to greater waterflow. One of the more critical areas that was identified is Götaälvdalen, the area around the River Göta Älv. Buildings are exposed to the greatest risks, but more extensive flooding also has consequences for roads, railroads, and other infrastructure. Increased waterflows also bring increased risks for power station and tailings dams, and additional problems caused by cloudbursts and flooding, which are already a problem for drainage and sewerage systems. Also, rising sea levels bring an increased risk of coastal erosion, with negative consequences for buildings in low-lying areas, particularly in the regions of Skåne, Blekinge, and Halland.

In the north, the tree line in the mountains will move upward and open mountainsides become overgrown; this does not necessarily mean less biodiversity but that its composition will change. However, ecosystem collapses can also be expected in some areas. For example, increased drought in parts of the vegetation periods along the coast of Norrland and in southern Sweden may lead to impoverishment and reduced biological activity, with reduced biodiversity as a result.

Regarding the direct health effects due to heatwaves, the Commission on Climate and Vulnerability estimates that the number of deaths per year will increase by 1,000 people toward the end of this century, compared to a case with no climate change. This estimate is primarily based on studies of the relationship between temperature and mortality in the Stockholm region, combined with a climate scenario in which summer temperatures in Stockholm are expected to increase by 3–4 degrees in the period 2071–2100, relative to 1961–1990.

Similar studies show that, in terms of health, the optimal temperature varies between cities and countries depending on the climate. For example, the optimal temperatures in London and Athens are 20 and 25 degrees (Näyhä, 2005), so it appears that the higher the average temperature, the higher the optimal temperature. It reasonable to believe that these differences in the "optimal" temperature are due to humans adapting to the climate, so it is also reasonable to believe that a long-term change in climate will lead to adaptation in the form of changed habits, different building methods, and—not least—protective measures in the form of air conditioning.

Studies in the USA show that the increased use of air conditioning can lead to almost complete adaptation, which has significantly reduced the mortality associated with heatwaves in the southern USA. It is probable that a similar adaptation will take place in Sweden, so the relationship between temperature and mortality shifts toward a higher "bliss point."

Thus far, the Commission on Climate and Vulnerability is the only attempt to estimate the effects in Sweden and express them as a proportion of GDP in a reasonably transparent and coherent manner. Two overarching conclusions from the Commission's results are that the direct costs and benefits of climate change largely cancel each other out and that they are both small: a few tenths of a percent of GDP. The total estimated effects of climate change in Sweden are thus minor when placed in relation to GDP.

Three factors contribute to this result. First, the sectors that can be expected to be most affected by a changed climate are a small part of Sweden's overall production. Second, the importance of these sectors (agriculture, forestry, fishing, and mining) for the Swedish economy appears to be decreasing over time. Third, the importance of producing goods is declining at the cost of service production. Over time, the Swedish economy has generally become less dependent on sectors that produce goods, particularly on sectors with direct links to natural capital (forest, soil, and water). This is not unique to Sweden but is similar in all developed countries, i.e. the agricultural sector represents a decreasing fraction of GDP, while the service sector in particular is increasing. Naturally, this means that even if these sectors are seriously affected by climate change, the economic effects will largely be limited.

Of course, the fact that net costs are small in relation to GDP does not mean that they are insignificant; locally and regionally, they can be of great importance. For example, we can expect that people who live close to coasts and waterways with an increased risk of flooding will be more affected than people who do not live in such areas. Also, we can perhaps expect that the inhabitants of rural areas dominated by agriculture and forestry will make gains.

In summary, our assessment is that the results of the Commission on Climate and Vulnerability remain relevant. The direct effects of climate change will probably be relatively small in Sweden, when placed in relation to the economy. Even if climate change entails a need for adaptation in Sweden, it is hard to believe anything other than that the ability of the Swedish economy to adapt is adequate for dealing with this. Unlike the world as a whole, we also have access to effective transfer mechanisms and insurance systems that facilitate compensation for the people who are worst affected. However, estimations of the consequences of climate change in Sweden are uncertain and, in some cases, based only upon qualitative assessments. Because a systematic overview of the effects of climate change in Sweden has not been conducted since 2007, it would appear reasonable for this to be redone.

We would also like to emphasize that the studies we refer to and our own assessments do not include the indirect effects of climate change. Sweden is not an isolated island in the global economy, which means that events in the world around us are of huge importance to Sweden's inhabitants. Trade, migration, international conflicts, and the need for increased international aid are areas in which global climate change can affect Sweden and where major effects can in no way be excluded. Our conclusion is that climate change will have the most impact in other countries and that this will also have consequences for us. The scale of these indirect effects is very difficult to predict.

CHAPTER 4

The global energy system

4.1 Chapter summary

At national and global levels, the energy system can be divided into four parts: i) the supply of energy from energy sources, e.g. oil and wind; ii) conversion, such as to gasoline and electricity; iii) distribution, e.g. to electricity grids and charging stations; and iv) final use. The transition to climate neutrality touches on all these parts.

Global energy provision is dominated by fossil fuels, which have stood at around 80 percent for many decades. Fossil-based energy sources dominate the supply of energy in the EU as well, but not in Sweden. In 2017, renewable sources of energy represented 39 percent of Sweden's energy supply, with nuclear fuel at 31 percent and fossil fuels at 26 percent.

One important difference between energy sources is whether they are plannable. For example, the supply of energy from wind cannot be planned: it just depends on how much wind there currently is. A larger share of non-plannable power will increase variation in electricity prices, boosting the relative value of plannable forms of power that have enough flexibility.[1] This includes the combustion of gas or biofuels, as well as storage and measures that increase variations in demand. Differences in plannability mean that forms of power with different average costs per supplied unit of energy can be profitable at the same time.

To determine how measures that reduce demand for fossil fuels affect global emissions, we must analyze the market structure. Conventional oil is traded on a global market and is cheap to extract and transport in relation to its price, so reduced demand for oil reduces its price on the world market but not global use. Decreased use in Sweden tends to increase use somewhere else; we say that a drop in domestic oil use leads to *leakage*. The market structure is different for coal, where reduced demand—such as that caused by a price on carbon dioxide emissions—likely does lead to reduced use. Consequently, Swedish exports of fossil-free electricity to countries with a large share of coal power can have a major effect on overall emissions.

The price of renewable energy has fallen over the last few years, and the global use of these energy forms has risen—but without any decline in the use of fossil fuels. Simply lowering the price of green energy is not enough to achieve the transformation to climate neutrality.

---

1. Here, it is important to note that the majority of present-day plannable energy forms are used with a large number of full-load hours and are economically dimensioned accordingly.

4.2 Energy systems in the world and in Sweden

The majority of humanity's greenhouse gas emissions—around 70 percent—are in the form of carbon dioxide from the combustion of fossil fuels, with the remainder primarily comprising methane and nitrogen oxide emissions. In turn, for carbon dioxide emissions, the majority are caused by combusting fossil fuels for their energy. Despite the significant expansion of renewable energy in many regions since the start of this century, the proportion of fossil fuel–based energy has almost constantly remained at 80 percent. This chapter discusses energy systems in the world and in Sweden.

The energy system can be divided into four parts:

1. Supply from energy sources, e.g. oil, coal, hydropower, and wind.
2. Conversion, such as to electricity, hot water, or liquid fuel.
3. Distribution, e.g. to electricity grids, charging stations, and filling stations.
4. Final use.

Transforming the energy system to meet climate targets entails considerable change in all four of these parts, while the degree of these changes and how they are distributed between these parts depend on regional conditions.

Figure 10 is a schematic representation of the various parts of Sweden's energy supply. It is important to realize that the transition to a fossil-free energy system requires change in all four parts. For example, electrifying vehicle traffic not only means changing the final use; the supply of energy must change from oil to something else. Electrical power must be produced—converted—and must distributed to be available in the vehicle when it is needed.

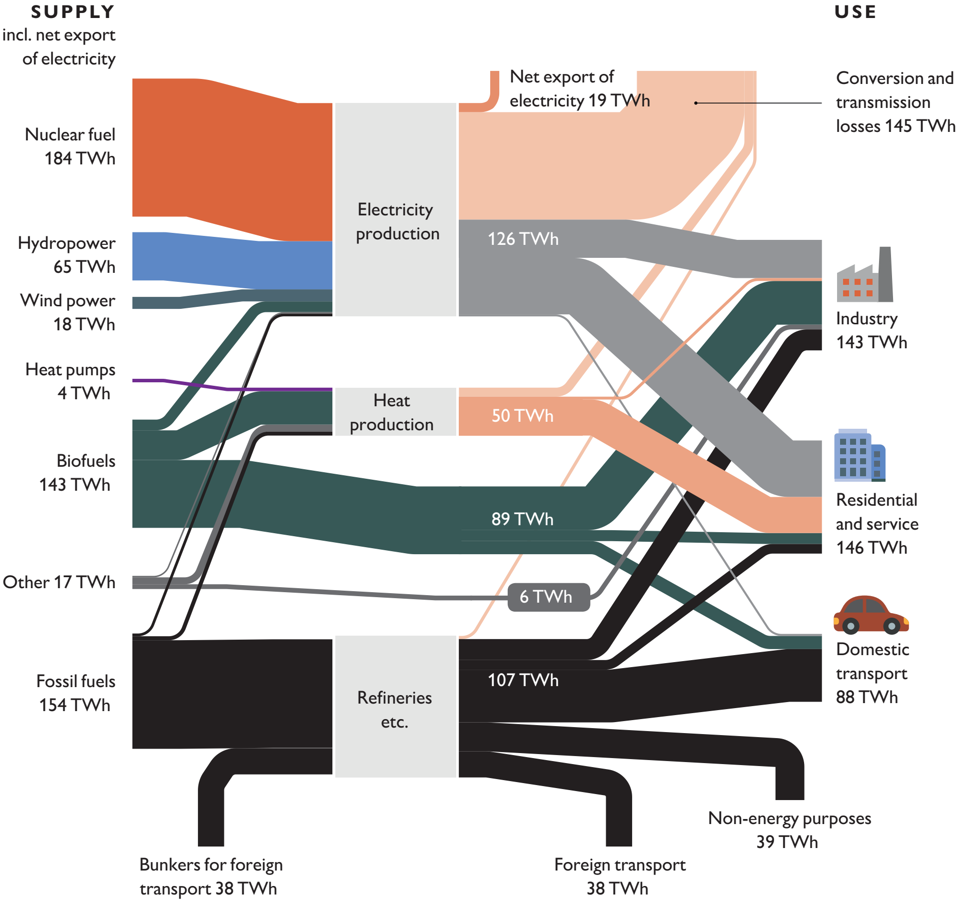

Figure 10 Supply, conversion (distribution) and final use of energy in Sweden, 2017.

Source: Swedish Energy Agency (2019a).

4.2.1 Supply

Supply can come from energy sources that are renewable or non-renewable: non-renewable sources are fossil or nuclear fuels, i.e. fuels that are extracted from deposits in the ground, while renewable sources of energy can be divided into flow resources and critical flow resources. Flow resources will always be available, as they come from the wind, sun, and water. Critical flow resources are biofuels, from forests and fields, which differ from flow resources in at least two important ways. The first is that we must utilize them sustainably so that we do not extract more than can be regenerated—and the regenerated amount depends on how well the resource is managed. Secondly, critical flow resources are a vital part of the carbon circulation that we described in chapter 2. The balanced use of forests and soils can both generate fuel and keep carbon out of the atmosphere.

Figure 11 shows how the proportion of fossil fuels in global energy use has remained constant for several decades. Despite the significant expansion of renewable energy in many regions since the start of this century, the proportion of fossil fuel–based energy has remained almost constantly at 80 percent during this period, so the use of fossil fuels has therefore increased in absolute terms. As a whole, this has also accelerated over the last two years; in other words, it increased more in 2018 than in 2017. The proportion of renewable energy, excluding hydropower, was negligible for the majority of the period shown in the figure but has increased in recent years. However, this proportion is no greater than around 5 percent, about the same as nuclear power. Hydropower is relatively constantly at around 6–7 percent.

We can see a downward trend in the proportion of oil among fos-

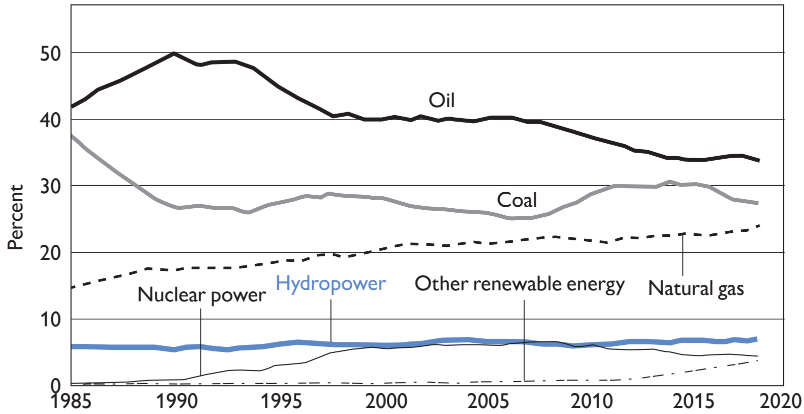

Figure 11 Fossil fuels and renewable energy respectively, as a share of the world's primary energy use.

Source: BP Statistical Review of World Energy 2019.

sil fuels. The proportion of natural gas has increased, while coal has remained relatively constant in recent decades. These trends have resulted in the three types of fossil fuels now having about the same share, with each comprising almost one-third of the energy supply.

The use of fossil fuels in Europe has declined since 1990, but not particularly quickly, whereas the use of renewably produced energy has increased in recent years but is still a small share of the energy supply. Some regions—such as Germany and Denmark—do have a significant share of renewable electricity production, but in terms of the total supply of energy, only a minor amount is renewable. There are considerable challenges in the transition to renewable energy, particularly in transport and industry. Carbon dioxide emissions from Europe's electricity production have declined, while emissions from the transport sector in the EU and in Sweden have remained

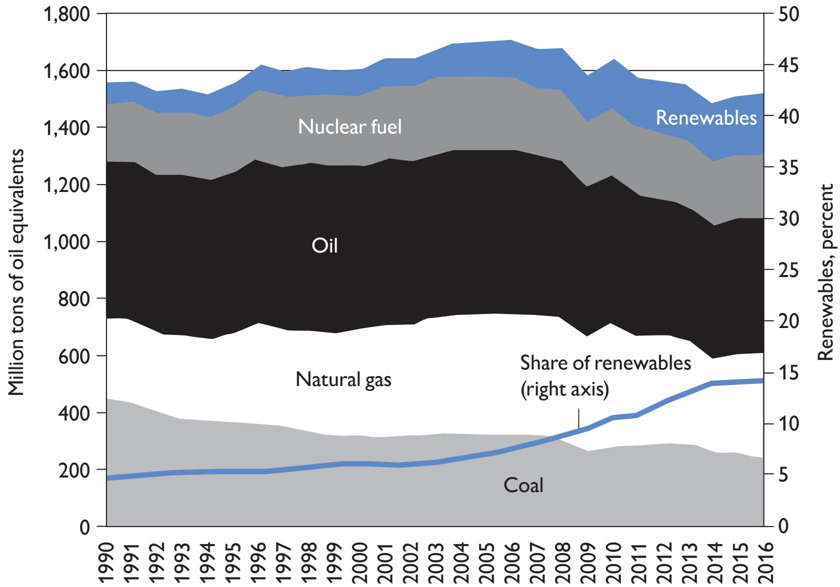

Figure 12 Energy supply in the EU28.

Source: Data from the European Environment Agency.

fairly constant. Figure 12 shows the trends for the contributions of various types of energy to the EU's energy supply.

Unlike the global energy system, which is 80 percent based on fossil fuels, the Swedish system is not as carbon intensive. Figure 13 describes its energy supply. The proportion of renewable energy is much higher, mainly due to considerably more hydropower. The proportion of coal and natural gas is much lower in Sweden than in the world as a whole and in comparison with the EU. Nuclear power expanded rapidly in Sweden in the 1980s, reducing the dependence on oil to produce heat and power (an increased proportion of electrical heating). The expansion of hydropower and nuclear power took place before the climate was on the agenda, and they have long made up the majority of Swedish electricity production. The transition away from oil was simplified thanks to Sweden's use of district heating networks, so that much of the heating sector was based on large-scale production plants, which could be replaced and converted to the combustion of biofuels and waste. District heating has also facilitated the utilization of waste heat from industry and sewage treatment plants.

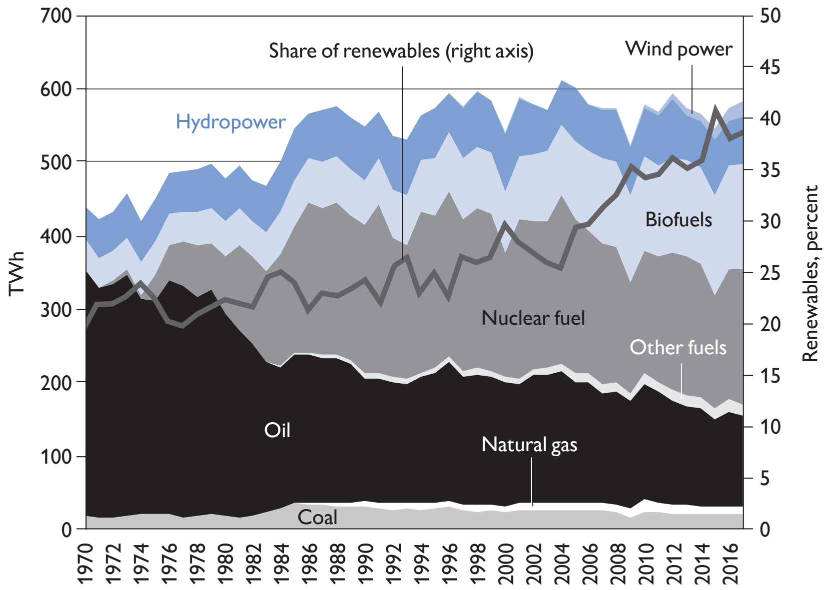

Figure 13 Energy supply in Sweden.

Source: Data from the Swedish Energy Agency (2019d).

4.2.2 Conversion

Flow resources provide electricity straight from solar panels or generators, primarily in wind turbines and hydropower plants. For fossil fuels and biofuels, conversion occurs through combustion, generating heat and/or electricity. Fossil fuels can also be converted through intermediary products, such as gasoline and diesel, and raw materials for the chemical industry, e.g. producing plastics.

Considerable losses are involved in the conversion of fossil fuels; up to two-thirds of the energy is lost as heat when obtaining fuel for electricity production or for transportation. However, in the Swedish energy sector, much of this heat is used for district heating. Most fossil fuels are converted in the transport sector in Sweden, but as mentioned above, some fossil fuels—in the form of natural gas and plastics—are combusted in waste-powered co-generation plants for heat and power, as well as a small amount of coal (currently being phased out). The greatest share of losses occurs in the conversion to heat and electricity, while losses in refinery processes are low (typically less than 5 percent), with losses instead occurring in vehicle combustion engines.

Biomass is used in both the energy and transport sectors. In the transport sector, the biomass must undergo a suitable conversion process to become biofuel. Biofuels such as ethanol, primarily from maize, are also imported.

Sweden has relatively good conditions for the supply of renewable energy, thanks to advantageous locations for wind power, significant biomass resources, and hydropower. Sweden's national rivers have received legislative protection from regulation, so there is little potential for additional hydropower. We will return to this in chapter 6.

It is important to divide costs for the various types of energy into investment costs and variable costs (fuel cost and costs for operation and maintenance), and different types of energy have different cost structures. Nuclear power has very high investment costs but a long life with low variable costs. A similar cost structure applies to large-scale hydropower and to wind power, where the majority of the costs are investment costs. However, compared to nuclear power, each unit is much smaller and has a shorter life. Power plants that utilize combustion have a greater proportion of variable costs in the form of fuel costs. Within the EU, plants that combust fossil fuels must also pay for emission allowances that are equivalent to their carbon dioxide emissions.

Forms of power with high fixed costs but low marginal costs are suitable for maximal use throughout the year. Plannable forms of power, such as nuclear power, are viable for many hours of the year, making them the baseload supply. Non-plannable power, such as wind turbines, are not part of the baseload supply because the wind is not constant. Instead, forms of power with a high proportion of variable costs and with production that can be controlled can be important when demand is particularly high and/or production is particularly low, i.e. peak load supply. Running them is only profitable when the electricity price is high enough; if investment costs are not too high, they could then be profitable even if they are not used for many hours per year. Sweden has reserve power plants in the form of gas turbines and a few oil-fired plants that fulfill this function.

For plants that produce electricity, cost is usually expressed as the price the plant must receive as payment per produced unit of electricity for the investment to be profitable. This is usually called the levelized cost of electricity (LCOE) and is stated as SEK per MWh.

For a form of energy that is a baseload type, i.e. one that is intended to supply an even flow of electricity throughout the year, comparing the LCOE and the average electricity price is a good indication of profitability. This is not as simple for other forms of energy; as we said, peak load plants are only used when the electricity price is higher than normal, so they may therefore be profitable even if their LCOE is higher than the average electricity price. However, the opposite may be true of non-plannable forms of energy, because if they produce the most when the electricity price is the lowest, and vice-versa, they may be unprofitable even if their LCOE is lower than the average electricity price. How much of a problem this is for non-plannable forms of energy depends on how their production covaries with the price, which depends on many factors, of which an important one is the share of non-plannable electricity production in the entire energy system. The greater the share of solar and wind power in the system, the greater the profitability for plannable sources of energy that can generate energy just when it is needed (when the price is highest), i.e. currently primarily the combustion of coal, oil, gas, and biofuels.

Increased price variability also increases the profitability of other measures that benefit from variations in pricing, such as storage, and measures that increase the flexibility of demand. These measures usually go under the name of variation management: when they are introduced, they reduce the variation in prices, which has a positive effect on the profitability of non-plannable energy sources. Overall, this leads to a balance in which electricity production with different LCOEs can coexist. In other words, we should not expect energy forms with a low LCOE to automatically and completely outcompete those with a higher LCOE.

A system cost linked to the delivery of electricity to the final consumer is added to the cost of producing electricity, which is assessed at the level of the power plant. These delivery costs include ones for transmission and distribution networks, and other actions that may be necessary to deliver electricity to the final consumer. These costs are large, and like all other costs, they are carried by the final consumer. The costs for transfer to apartments and other smaller consumers are of the same size as the costs for the electricity itself, though are typically lower for large consumers.

In much of Europe and the world, electricity production is dominated by fuel-based electrical power. The transition to a system that is dominated by renewable electricity, with wind and solar power, means that society must move from a system in which most of the operating costs comprise fuel costs to a system in which the greatest part is instead the investment cost, with the remainder being operating and maintenance costs. At the same time, the system costs will differ for today's and tomorrow's electricity production systems. The latter will require more investment in network capacity but has low or no fuel costs.

The situation in Sweden is slightly different, as the fuel's share of the cost is much lower thanks to the electricity production system being based on hydropower and nuclear power. Co-generation plants for heat and power are, naturally, dependent on fuel. Here, efforts are made to combust fuels of as low value as possible: waste fractions, including forestry waste.

One effect of the fact that the cost of wind- and solar power are dominated by the investment cost is that the learning process involved in the production of power plants substantially drives down costs. Solar panels and wind turbines are characterized by relatively small units and large numbers being installed over time, providing continuity in building experience and know-how.

4.2.3 Distribution

The distribution of energy is done through power lines for electricity and through district heating pipes for the heat that is used in the district heating system. District heating dominates in urban areas in Sweden, although electricity-based heating is used, with heat pumps common in small homes on town outskirts. Rural areas have a mixture of electrical heating and various forms of combustion in individual heaters, such as pellet stoves, where the fuel is delivered to the consumers. The electricity produced is largely distributed from high voltages in the transmission network down through lower voltages—regional and local networks—to the customer.

The Swedish electricity system has links for transferring electricity to neighboring countries, which are, in turn, linked to continental Europe (Denmark–Germany, Sweden–Poland). The Nordic system also has a joint electricity market called Nordpool.

There is a lack of distribution capacity in several Swedish cities, such as Stockholm, Uppsala, and Västerås, due to increased demand from newly established industries, among other things. This lack of capacity is found at various levels of the network, but the regional level that determines the incoming capacity for towns and cities is particularly critical. An increased volume of renewable electricity, primarily in the form of wind power, will increase the volatility of electricity production and lead to additional demands for increased network capacity. In principle, these costs should be priced in a way that reflects the various producers' different costs and contributions, and may need to be priced differently from the way they currently are if the system has a greater proportion of non-plannable power.

To some extent, a lack of capacity can be mitigated by building local electricity production that can be combined with energy storage, such as on-site battery storage at the consumer's location. This electricity production will primarily comprise solar cells, which can thus reduce consumption in the daytime and contribute most during the summer. These electricity consumers can be called prosumers, i.e. customers who both produce and consume electricity; they may be households or businesses. Depending on how many solar cells are installed, these prosumers may be net consumers or net producers over the year.

4.2.4 Final use

Energy use is usually divided into three sectors: industry, residential and service, and transport. Sweden generally has low emissions from the residential and service sector thanks to the small amount of fossil fuel in Swedish heat and electricity production. It is important to note that the service sector also includes office buildings, so not only trade and services. Renovation and new builds are responsible for a considerable amount of the climate emissions from the residential and service sector, although much of these emissions are attributed to the industrial sector.

Even if Sweden's energy-intensive industry is relatively energy efficient compared to many other countries, it represents a significant share of our carbon dioxide emissions. Of a Swedish aggregate of 53 million tons of greenhouse gas emissions, 17 come from industry, primarily as carbon dioxide. A significant part of industrial admissions come from basic industry, primarily petrochemicals and refineries, as well as cement and the iron and steel industries, all of which are part of the trade sector. Sweden also has considerable biogenic emissions, i.e. ones that arise from combusting biofuels, from the paper and pulp industries, and from co-generation plants. There are currently no incentives or motivators to reduce biogenic emissions. As we mention in chapter 12, there are significant opportunities for reducing emissions from basic industry in Sweden through the separation and storage of carbon dioxide.

In the transition of the energy system, it is probable that the need for heat will only grow marginally, while electricity use is expected to grow significantly. Increased construction is expected to increase the need for heating, but this is compensated for by the effects of energy efficiency measures, both in the existing building stock and by making new buildings more energy efficient. Overall, no major changes are expected in the need for heating. Both energy and power needs are increasing significantly due to the predicted electrification of primarily the industry and transport sectors; electricity use in industry is estimated to increase by 60–100 percent from the current 50 TWh to 80–100 TWh (IVA, 2019), while electricity use for transport is estimated to increase from about 3 TWh to 20–25 TWh (IVA, 2019).

The introduction of more intelligent systems, like self-driving vehicles, can be utilized to make transport more efficient, but this technical development may well give rise to higher transport volumes. In summary, it is probable that the demand for transport services will increase, but if instruments provide incentives for more efficient transport, then transport volumes do not have to increase by the equivalent amount. In particular, it should be possible to drastically reduce the climate impact of transport through the introduction of new technologies, such as electrification and biofuel.

Regarding opportunities for the residential and service sector to contribute to reducing climate impact, the potential direct contribution is limited because so much of the energy supply is already free of carbon dioxide. It will therefore be difficult to motivate efficiency measures as cost-effective policy from a purely climate perspective. However, there are important indirect contributions to be made, with fuel that would otherwise have been used for heating being used differently, as raw material for second-generation biofuels, such as in the aviation sector.

4.3 Energy markets

4.3.1 Markets for fossil fuel

Most climate measures aim to reduce demand for fossil fuels, such as through energy efficiency measures, the development of better fossil-free options, or taxes. When thinking about how these measures affect use, it is vital to understand that fuel is traded on global markets. The final use is decided by the interplay between supply and demand on these markets.

Assume that a country implements a measure that reduces the demand for a fossil fuel. Everything else being equal, this tends to reduce the world market price for that fuel, which has a number of effects. One is that the lower price leads to more being consumed somewhere else or at another time. The original reduction in demand is thus counteracted by this price effect, and this counteracting effect is called leakage, because the demand leaks out from the time and place where demand is reduced to another time or place. We usually differentiate between spatial leakage, where use increases somewhere else in the world, and intertemporal leakage, where use increases at another time. Spatial leakage is great if the user can easily move to a country that is outside the measure, such as moving oil-intensive production. However, leakage occurs even if users do not move; the reduction in price is enough for users in other locations to increase their demand.

The other effect of the falling price is that producing the fuel is not as profitable, so some production might no longer be profitable and will thus cease. How much production will be unprofitable is decisive for the effect of the measure to reduce demand. If no part of the production becomes unprofitable, then the supply will remain unchanged and there is complete leakage. The price will fall just enough for the reduction in emissions where demand fell to be balanced by increasing demand somewhere else or at another time. The other extreme is if the fall in price leads to supply decreasing as much as demand where the reduction in demand occurred. Then there is zero leakage.

The term used by economists to describe how a price change affects supply is supply elasticity. In formal terms, it describes the percentage by which supply falls for every percentage point of price increase. Supply elasticity varies between different types of fuel; it is very low for conventional oil because the costs for extracting and transporting this oil are low in relation to the price, so the market for oil is global. The large difference between the extraction cost and world market price means that even if reduced demand—perhaps due to a tax on oil use—leads to the producer having to accept a lower price, extracting and producing oil are still profitable. Supply elasticity is therefore low. The situation is different for coal, as the price of coal is not far from the cost of extraction and transport. Also, a small drop in price for selling coal can stop significant parts of the coal industry from being profitable. Supply elasticity is therefore high. Nonconventional oil and gas also have high extraction costs, so any reduction in price does not have to be large to make extraction unprofitable.

Figure 14 explains the principle of leakage. In both diagrams, the upward sloping curves show supply, i.e. how the amount of fuel it is profitable to extract depends on price: the higher the price, the larger the volume that it is profitable to extract. In the upper diagram, supply elasticity is low, i.e. supply only changes slightly when the price changes. The supply curve is therefore steep. Instead, in the lower diagram, supply elasticity is high, i.e. supply changes a lot when the price changes. The supply curve is flatter.

In both diagrams, the downward sloping curves represent demand, which is lower the higher the price is. Market equilibrium occurs at the point where the demand curve and the supply curve intersect. The solid demand curves represent the situation before the implementation of a measure to reduce demand. Balance occurs at the starting point for the prices P_0 and quantities F_0 in both diagrams.

If a measure leads to falling demand for fossil fuel—such as a tax or the development of an alternative energy source—the demand curve shifts to the dashed line "Demand after measure." If the price had remained at the same level, use would have changed to F_1, which is an equally large drop in both diagrams. But this is not an equilibrium, because at this price, demand is now lower than supply. The price therefore falls, and the new equilibrium between supply and demand occurs where the supply curve intersects the new demand curve.

We can see that this market effect has a different strength in the two cases. The price falls significantly in the upper diagram, while supply falls only slightly. Considerable leakage has thus occurred, because the large fall in price creates a large increase in demand. The fall in price is smaller in the lower diagram, so there is less leakage. In the extreme case, when supply is constant—i.e. the supply curve is vertical—a change in demand will not change use at all: all that happens is that the price falls and the producers thus make less profit, because the difference between extraction cost and price is reduced.

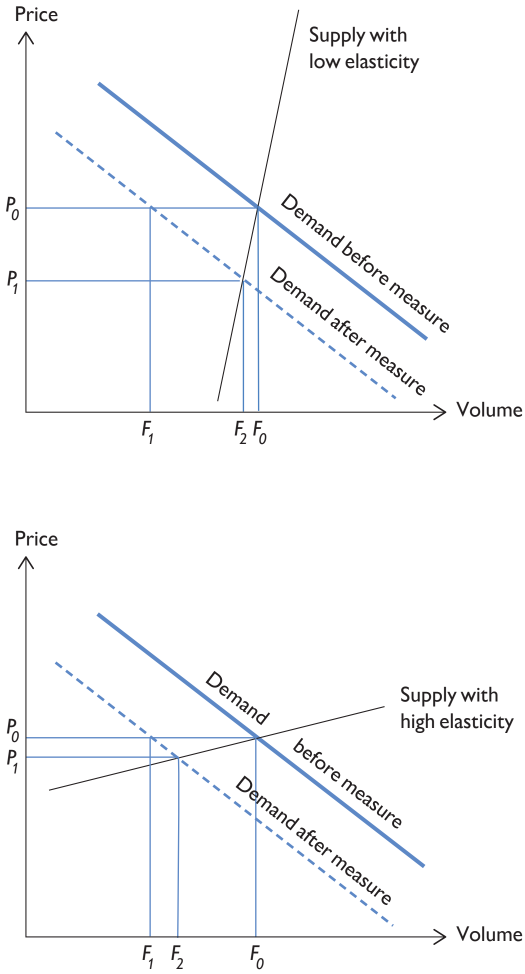

Figure 14 Markets for fossil fuels with different supply elasticities. A reduction in demand is partially compensated by a drop in price.

To take a concrete example: assume that the price of electric vehicles falls so much that, overall, they are cheaper to use than fossil vehicles at the current price of oil. This would still not imply that oil was outcompeted and stopped being produced. Because oil has low supply elasticity, the oil price would fall so that almost as much oil was consumed as previously, but at a lower price. If the reduction in demand is caused by the introduction of another green energy source, or subsidies on it, the result will be that more energy is used overall. In addition to almost the same amount of oil being used as previously, energy from the green energy source is also used. A common mistake when comparing the competitiveness of new sources of energy is to compare them to the current market price for oil. For example, to determine the degree to which cheaper electric vehicles can outcompete oil power at a global level, you must instead compare them with the lowest price that would allow extraction without losses, which is a much lower price than the current market price for the majority of oil resources. Quite simply, an unreasonable amount must change to make it unprofitable to extract Saudi oil.

The situation for coal is the opposite. If the demand for coal falls—for example, due to taxes or better alternative sources of energy—the price reaction will not be particularly significant, and there will thus not be much leakage. Nevertheless, a substantial amount will cease to be produced. The potential for better alternatives to outcompete coal is therefore much greater than for oil.

The different supply elasticity for coal and oil also means that measures to reduce supply—such as closing deposits—have different effects. Because coal has high supply elasticity, there is almost no point in individual owners of coal deposits reducing their supply—such as closing a mine—to reduce carbon dioxide emissions. Such a reduction in supply is quickly replaced by other coal producers, because there is so much coal that can be extracted for about the same cost. Transporting coal is quite expensive, so it is reasonable to assume that if *all* the coal mines in Europe reduce their production, this will not lead to much increased production somewhere else that is then imported to the EU. However, it does make a difference if individual oil resource owners do not extract their deposits. Because supply elasticity is low, the missing supply is not replaced to a great extent; instead, total oil use falls by approximately the amount that has been taken away from the market.

There is an important complication in the analysis due to the time factor. If producers of fossil fuels believe that demand—and thus price—will fall in the future, it is better for them to sell the resources earlier, while the price is still high. However, this only applies if they are planning on selling all their assets sooner or later. This is probably the case for conventional oil, because it is cheap to extract in relation to its price but is found in relatively limited amounts. One sold unit of conventional oil now means one less unit sold in the future, so the owner has reason to consider which is best: selling now or in the future. Measures that mean that future demand will fall quickly can therefore, paradoxically, increase emissions in the near future, because producers react by selling fossil fuels sooner. This is called the *green paradox* (Sinn, 2012).

This reasoning does not apply to fossil fuels that are expensive to extract and where reserves are so large that it is reasonable to assume that they will not run out. For coal, hopefully large amounts of coal will remain in the ground, and as we said in the previous section, anything else would be incompatible with even very modest climate ambitions. One unit sold today thus does not necessarily reduce sales in the future. The market price will be close to extraction costs, and supply will be elastic. This applies to coal and nonconventional oil and gas, such as that extracted by fracking.

In summary, our discussion means that measures that reduce demand for oil have much less effect on emissions than one might think, because reduced use is compensated for by increased use somewhere else or at a later date. The situation is different for measures that reduce the demand for coal. Reductions in demand will make it less profitable to produce coal, and because the profit margin is low, a significant part of production will thus be unprofitable. More coal will thus remain in the ground permanently. In terms of policy that reduces demand for fossil fuels, we can therefore expect that it is effective at reducing the use of coal.

Production of nonconventional oil and gas, such as reserves in the Arctic and deep oceans, tar sands, and reserves extracted by fracking, are somewhere in the middle. Reduced demand can make this production unprofitable, particularly if it slows the technological development that makes it easier to extract nonconventional reserves. However, we have not yet seen much policy that could reduce the use of fossil fuels—quite the opposite: these have increased more than the renewable forms of energy (Johnsson, Kjärstad, and Rootzén, 2019). Growth in the use of fossil fuels is primarily occurring in newly industrialized nations such as China and India.

4.3.2 The electricity market

The market for electricity is very different from that for fossil fuels. As we noted above, electrical power is not a source of energy; instead, it is converted from a source of energy, such as uranium, coal, oil, wind, or flowing water. To understand the electricity market, it is essential to realize that this conversion must occur at the same moment as the electrical power is consumed, which places special demands on conversion and distribution. Oil can be stored cheaply, so anyone who lives in a house with oil heating can have their own reserve, as the storage cost is manageable even if one wants to store enough for a year. Electrical power, on the other hand, is expensive to store using current technology. A battery for a normal day's electricity use in a normal household costs as much as several years of use. Electricity is therefore instead continually transferred from the supplier to the user via the electrical grid. The cost of this grid primarily arises when it is built, after which the cost of using it is low. These technical conditions make it practically impossible to have a competitive market—it is unreasonably expensive to have several competing electrical grids to choose from, so a natural monopoly therefore arises.[2]

Electricity is supplied to markets on which prices must always be set so that supply and demand are equivalent. For this to work, the demand and/or supply must be able to react to price changes. Prior to the Swedish electricity market's deregulation, this meant that the major electricity producers (Vattenfall) had to supply as much as was demanded at any given moment. Naturally, this changes when fluctuations in supply and demand occur as a result of price variations; when demand is high and supply is low, the price is high, and vice-versa. The more sensitive supply and demand are to price changes, the less the price will vary over time.

The conditions for supply and demand to be able to react to price changes vary greatly between different users and producers. For users to be able to react, electricity use must be registered very

2. However, storage is not an example of a natural monopoly. Here, the economic driving force is to buy when it is cheap and sell when it is expensive. This does not have be done on a large scale and allows a competitive market.

frequently; it must be known at what hour a kWh was consumed, not just in which month. Even if this kind of metering has become more common, there are still many users who simply cannot react because they do not have hourly metering.

For producers, the preconditions to be able to react to price variations are extremely different for the various types of energy source. Wind and solar power are at one end of the spectrum and cannot react to price at all. Instead, production is decided by how much wind there is and how much the sun is shining, which varies greatly over time. However, wind power has developed rapidly in recent decades, and there is sometimes talk of a silent wind power revolution, which has not only reduced production costs but also increased the number of full load hours.

The amount of electrical power a nuclear plant can supply can be controlled, but varying production over time is not efficient, partly because the marginal cost of production is low. Hydropower has a greater capacity for varying production over time and thus plays an important role in balancing supply and demand. In periods of peak demand, Sweden still uses power plants that run on fossil fuels, mainly in the form of natural gas; due to high marginal costs this is only profitable when the electricity price is high.

Variations in supply and demand are not perfectly correlated across different geographic areas—when it is unusually cold in Kiruna it could be warmer than normal in Malmö. If it is very windy in the south, it could be calm in the north. The ability to transfer electrical power between different areas is thus an important means of reducing variations in the price of electricity. In Sweden, the electricity market is divided into four price areas and the transfer capacity among them is generally adequate for the price to be the same everywhere. However, this is not always the case and prices can differ across different regions of the country. The transfer of electricity between the Nordic countries, Germany, and Poland is also important for balancing out variations in supply and demand. Overall, this leads to lesser variations in price, but also means that variations in other countries' supply and demand affect the price in Sweden.

It is conceivable that the electricity market will see increasing numbers of prosumers in the future, contributing to reductions in price variations and decreasing pressure on the capacity of electricity distribution grids, such as at the regional grid level. Energy storage allows prosumers to react to price signals, so their own consumption is steered to times of the day when there is a risk of a lack of grid capacity. There may also be differences depending on whether prosumers act individually or become organized and trade electricity between themselves within a "trading community" (Heinisch et al., 2019). It is reasonable for prosumers to want to minimize their energy costs and to avoid buying electricity from the grid during high cost hours, which are typically in the daytime, particularly the morning and late afternoon. Managing their own production among the consumers then becomes a question of pricing, so consumers must have batteries to be able to achieve flexibility of demand. This is, however, hardly profitable at today's electricity prices.

Most electricity markets are "energy only" markets, i.e. the electricity is primarily priced and traded on the basis of energy (SEK per kWh), which works well in traditional systems with a considerable amount of plannable electricity production. However, in a system with a large amount of variable—non-plannable—electricity production, this leads to highly volatile electricity prices and an uncertain climate for investment in new production. This therefore entails risk of power shortage. One way of reducing this risk is to introduce an output power-based market, on which users can pay to access a specific output (wattage) when they wish to, so the payment is not dependent on how many kWh are actually used. In addition to reducing risks for the user, this may also make investments in plannable power less risky and thus more attractive. In principle, the same thing could be achieved by using other types of financial instruments. This is already the case for long-term supply contracts with fixed prices, but creating a direct market for power should be considered.

A considerable amount of Swedish electricity production is exported at present, with net export at about 10 percent of Swedish electricity production since 2010. In physical terms, a significant part of this goes to Germany and Poland, where it can replace electrical power produced by coal. Before the EU trading system of emission allowances was reformed, increased export of carbon dioxide free electricity just meant that emissions could increase somewhere else, but after the reforms in 2018 this no longer applies—because a reduced demand for emission allowances also reduces the number of emission allowances that are distributed (see section 7.3). Additional exports of carbon dioxide free electricity from Sweden can thus replace coal power and reduce the EU's total emissions. The effects of this can be very significant.

In 2017, Sweden produced 159 TWh of electrical power, of which 98 percent was fossil-free. Of this, 12 percent was exported (net). Assume that we are to increase electricity production by 1 percent, i.e. 1.59 TWh, and export it to Poland, which generally produces electrical power using coal. On average, a Polish coal-powered plant emits 0.8 million tons per TWh of electricity. In other words, a 1 percent increase in Sweden's production of electrical power would help Poland reduce its emissions by 1.59 x 0.8, i.e.

around 1.3 million tons of carbon dioxide every year. A new fossil-power car emits around 120 grams of carbon dioxide per kilometer. If it drives 15,000 kilometers each year, that's 1.8 tons of carbon dioxide; 1.3 million tons of carbon dioxide is thus equivalent to the emissions from about 700,000 cars.[3]

It is not possible to say exactly how great the effect of increased or reduced fossil-free exports from Sweden would be on the EU's total emissions; this depends on whether electricity export is changed for a single year or whether we can foresee a permanent change, as well as when in time increased export occurs. The effect will probably be greater the earlier the change happens, for two reasons: Firstly, and hopefully, the coal content of electricity production will decline over time in Poland and Germany. Secondly, according to current rules in the EU ETS, reduced emissions will lead to a reduced allocation of emission allowances during a transition period, creating a window during which Swedish electricity exports can contribute to lower emissions in the EU as a whole.

4.4 Cheap green energy does not automatically outcompete fossil energy

Many people have taken the rapid development of renewable energy—particularly the expansion of solar and wind power, for which prices have significantly fallen since the turn of the millennium—as an indication that the fossil-based systems are on the way to being outcompeted. In actuality an increased use of green energy driven by lower prices has gone hand-in-hand with the increased

3. Naturally, this is a simple back-of-the-envelope calculation that only aims to show orders of magnitude.

use of fossil fuels around the world as a whole. There are several reasons for this.

- There are strong interests in the fossil fuel industry, which too often succeed in blocking policies that would threaten these industries' profitability. Johnsson, Kjärstad and Rootzén (2019) show that countries with large reserves of fossil fuels have expanded their use of these over alternative sources of energy considerably more than other countries have done.
- Fossil fuels are subsidized in many parts of the world, with total direct subsidies of fossil fuels estimated at 340 billion dollars in 2017 (OECD/IEA, 2019).[4] Distributed across all fossil emissions—about 33 billion tons of carbon dioxide—this is equivalent to a subsidy in excess of 10 dollars per ton of carbon dioxide. Subsidies are a particularly important factor in countries with large fossil fuel reserves.
- Emerging market economies like China and India have significant reserves of coal and the expansion of fossil fuel use has been much greater than the growth in renewables. New figures from the IEA (2019) show continued and accelerating growth in the world use of fossil fuels. It is particularly notable that the use of coal increased the most, while the increase in natural gas has slowed but is still increasing. Given that the supply of coal is elastic, as we have described, it is no surprise that production is increasing rapidly as fast growth is driving demand, but it is a clear example of a lack of climate policy.

---

4. Subsidies can also be defined as the difference between what it actually paid for fossil fuels and what should be paid, given the environmental and climate damage and other costs. With this way of counting, subsidies are many times greater. See Coady et al. (2019).

- When the cost of fossil fuel energy is compared to energy from renewables, the comparison is often limited to electricity production—such as comparing a new wind farm to a new coal plant. However, one must look at the entire chain, from inflow to use, as described in section 4.2 above. The transition to fossil-free energy often entails only the transition from using a liquid or solid fuel for electricity, which means that both distribution and use must change, and requires expensive investments in both these areas. The comparison must be of the total cost—electricity production + electrification—with the existing fossil fuel alternative.
- Substitutability between green energy and fossil fuels is not as great as one might hope. As we have described, the majority of renewable energy sources are not plannable in the same way as ones that are fossil-based; the wind blows when it blows, but a fossil-fired power plant can be run when demand exists. The problems this creates increase with the proportion of non-plannable electricity and different areas of use are differently easy to make fossil-free. Even if these problems are far from insurmountable, at the margin they mean that the more that is done, the more difficult it becomes to transition to fossil-free energy—or, to put it another way, fossil-free and fossil energy are not perfectly substitutable.

Economists measure the degree of substitutability between different inputs, such as energy sources, as their substitution elasticity. Simply put, it measures how the ratio between the use of the different inputs changes when their relative price changes. If a 1 percent drop in the relative price of green energy leads to the relative use increasing by 1 percent, the substitution elasticity is 1, while it is 0.5 if the relative use increases by 0.5 percent.

One can show that if the substitution elasticity is greater than 1, a declining trend in the relative price of green electricity will lead to green energy eventually outcompeting fossil energy.

In this case, investments in new green technology could in themselves lead to a fossil-free society and, if the elasticity is considerably greater than 1, this transition can happen rapidly. As soon as green energy is cheaper than fossil energy, a great deal of consumption will transfer from fossil to green. However, the problem is that reality is not like this. Instead, there is much to indicate a lower substitution elasticity, and we cannot be sure that it is greater than 1. If the elasticity is lower than 1, technological development that makes green energy cheaper is not in itself a functional means of creating a transition to a climate-neutral society: fossil energy must become more expensive.

CHAPTER 5

Climate policy—theoretical foundations and practical considerations

5.1 Chapter summary

The climate issue is global and requires a global solution. The best solution would be a common international price for emissions. To achieve as much as possible, the policy of small nations, such as Sweden, should focus on increasing the likelihood of an effective global climate policy. A small nation can have a sizeable effect, not least by setting a good example and by developing technology and policies that are viable in the rest of the world.

The basic cause of the climate problem is that the absence of climate policy means emitting greenhouse gases is free, despite the damage they cause. Since banning all emissions immediately is not feasible, other policies must be used. Centrally deciding plans for individual emitters would, in practice, lead to an extremely expensive transition, one so expensive that it risks being politically impossible. Instead, the cost-effective way of achieving climate neutrality is to set a price on emissions, via taxes or an emissions trading system. In some situations, control via targets, regulations, and subsidies for technology may be beneficial, but this cannot replace a price on emissions. Even a moderate price on emissions, such as one in line with the current price in the EU ETS, which is about SEK 250 (EUR 25) per ton of carbon dioxide, roughly SEK 0.5 (EUR 0.05) per liter of gasoline, would have a large effect on emissions if it was introduced globally and comprehensively.

Climate policy affects the distribution of income and wealth. Even though such effects would probably not be large in countries like Sweden, they must be considered to gain broad policy acceptance. A policy that puts a price on emissions generates significant government revenues, thus generating a revenue base from which to compensate people who are particularly affected. However, this compensation should not entail a reduction in the price of emissions.

There is a great deal of uncertainty about the scale of climate change and how much damage it will cause. Calculations show that an intelligent climate policy, based on the global pricing of greenhouse gas emissions, is a cheap form of insurance against the worst-case scenarios. In reality, there seems to be little reason to worry that a global carbon dioxide price will be too high.

5.2 Starting points

The design of climate policy presupposes an understanding of how various types of policy work, and here there are many questions that need answering. These include the scale of global warming in different policy scenarios and how this warming will affect people in various parts of the world and at different times, the issues are thus the impact of various types of climate damage and the positive effects, in some places, of a warmer climate. This type of analysis is descriptive and can, in principle, be conducted without value judgements.

Even if the focus of this report is describing the ways in which various types of policy work, we also want to evaluate different alternatives. Different policies bring different consequences; these are not only the local effects on carbon dioxide emissions, but they can also have different costs for different agents in society. We need a consistent framework to evaluate these consequences. In this report, our foundation is utilitarian—the consequences are assessed based on their implications for an aggregate in the form of a weighted average of human welfare. Let us now discuss what we mean by this.

"Human" means all humans—those now alive and the generations to come. "Welfare" describes a person's overall living conditions, in that it not only includes the traditional economic measures, but also the value a person places on factors such as health, length of life, and leisure—where the value of leisure should be interpreted widely to include access to nature, etc. Economists express this utilitarian perspective using an objective function that is a weighted average of the welfare of now living and future generations. Various outcomes can then be assessed using this objective function: the higher its value, the more desirable the result.

As regards the "weighted average" of human welfare, this naturally involves issues of distribution, and climate policy affects the welfare of future generations more than economic policy normally does. Carbon dioxide emissions have significant effects for several hundred years, and if they are reduced now—through sacrifices made by people now alive—this is likely to have positive effects for many future generations. When future generations are weighed against present generations in policy evaluations, we need to specify the rate of discounting, i.e. the relative weight assigned to future generations. Climate policy also affects people in different countries in different ways. Climate policy impacts the distribution of resources among people in different countries and at different times, but also between people in a given country and at a given time.

So how should the welfare of different people be weighted? In practice, we generally have to accept that policy changes generate both winners and losers, and how these changes should be balanced is basically a question of values. It is apparent that the weighting used to balance the welfare of different individuals cannot be done without value judgements, quite the opposite. Despite this, market weights are often used in economic models without much explicit motivation. Using market weights implies that the weight put on the welfare of individuals is proportionate to their wealth. This choice appears to rest on quite stark value judgements, but should not be regarded as an expression of economists' support for the world's current unequal income distribution. Instead it builds upon the principle that economic models should have an empirical foundation and be able to describe the world as it is. A policy that maximizes welfare using market weights is only optimal for that weighting.

It is not possible to provide advice about the right climate policy without taking a position on the value of different people's welfare. One perspective here is that, as researchers, our advice should be based upon a perception of how the agents that will be advised—be they politicians or the public—appear to make these valuations. Often, but not necessarily, this leads to market weights being used. For example, we do not see large transfers to poor countries, so the question is whether climate policy should be used for such redistribution. The answer here could be yes, if the reason why such transfers do not currently happen is that there are no effective transfer instruments, but that climate policy can now provide them. Otherwise, if the absence of massive transfers is due to a lack of willingness from the policy makers, the answer is probably no, provided the adviser respects the values implied by other policies chosen by the policymaker. The same argument can be used with respect to concern for future generations.

Naturally, researchers are also entitled to have opinions about value issues. However, when researchers make statements about desirable policies, it is important to clarify whether this advice includes opinions on these or is only based upon what decision-makers explicitly or implicitly appear to prefer.

5.2.1 Ideal climate policy and what can be done in its absence

In the introduction to this report, we stated that well-defined ownership rights for scarce resources are necessary if we are to keep using them sustainably, but that there are no such ownership rights for the atmosphere—its use is free and unlimited. We also established that the absence of ownership rights motivates global instruments that can turn the decisions that govern emissions in the right direction, without this leading to avoidable societal costs. In economic terms, an "ideal climate policy" has been achieved when it is not possible to achieve the same effect on emissions/the climate using another policy at a lower cost to society. Concretely, many people, including the authors of this report, maintain that a global carbon dioxide tax at a jointly agreed level would be an ideal way of managing the climate problem.

It is important to realize that we are currently a long way from an ideal climate policy; at a global level, we are not even achieving the targets we have established. The climate measures that have been implemented so far can be summarized as limited and far from adequate. A carbon dioxide tax currently exists in just a few (small) countries and the widely held opinion is that it is unrealistic to envision a global agreement on a carbon dioxide tax. Additionally, the production of coal power is often subsidized by states, so that the global average price of carbon dioxide emissions is instead actually negative! Even if a global agreement on a minimal price level for emissions of greenhouse gases is not an impossibility, it will not occur in the near future. We should therefore consider other measures, such as aggressive subsidies targeting the production of alternative energy sources.

5.2.2 Climate policy at different regional levels

The climate issue is global and requires a global solution. However, because decisions about various measures are generally not made globally—at least not yet with any success—it is important to distinguish global climate policy from national climate policy. Also, can national climate policy be distinguished from that which can be implemented at a local level, or even at individual or corporate levels? Should different types of climate policy be implemented at different levels? If so, how? What are the analyses at these various levels?

One possible answer is that in Sweden, or even in the EU and larger regions, we cannot do very much. The climate is determined by global emissions and the emissions that occur in Sweden are, globally, negligible; similarly, the EU's total emissions are small on a global scale. However, to draw the conclusion that we should not do anything is not satisfactory. Every country can define its emissions as negligible, but what alternative approaches and principles should be used instead?

There are several potential paths open to us, and one of the primary purposes of this report is to attempt to answer the above question. One answer could be the principle of doing as much as possible at every level—by every individual, in every region, in every nation—to reduce global warming. Of course, this principle is problematic because it leaves the definition of "as much as possible" wide open. This is also problematic because it does not clarify the system boundary, i.e. which emissions we have a responsibility to try to reduce. As discussed in chapter 4, it is not unusual that a measure reduces emissions in one's own country—or area—but increases emissions elsewhere, unless all countries take similar measures. The principle does not tell us the right thing to do.

An entirely different type of answer is to attempt to imitate an ideal global climate policy. Such a policy could, for example, mean that every local level taxes carbon dioxide at the level that would be ideal globally. If Sweden then has a national carbon dioxide tax that is the global ideal, no other measures are necessary, but if the national tax is too low, actors at lower levels—such as that of the individual—act as if the "missing" tax actually were in place.

A third answer is to more explicitly adopt a strategic global perspective. The big question is how we achieve a powerful and effective global policy that is adequate to meeting the climate challenge; according to this answer it would be to implement a policy that increases the likelihood of successful international cooperation on the climate issue. For example, this may entail good, cost-efficient examples of measures and new technology that others are able and eager to imitate, actual reductions in emissions in accordance with stated targets, and working to build appropriate institutions and create climate agreements. Here, we must not have a narrow perspective when defining the effects of our own policy on global emissions. A small nation can have a considerable influence, by setting a good example and by developing technology and policies that are viable in the rest of the world. Nor should we take a short-term view of investment so that only low-hanging fruit are dealt with; long-term projects for societal transition should also be implemented. We believe that this is the correct answer.

5.2.3 Using models

A consistent framework for analysis is needed to answer questions about what type of policy influences development, what happens under different assumptions about climate sensitivity, for example, and how climate change impacts society. Integrated assessment models (IAM) have come to be the standard tools in climate study.

The IAM method was developed at the start of the 1970s by William Nordhaus, recipient of the Prize in Economic Sciences in Memory of Alfred Nobel, and has been used regularly and further developed by several of this report's authors.

There are many different IAMs; they can be more or less detailed and are built up using a range of assumptions, but what they have in common is that they consist of three linked sub-models (see figure 15).

The first sub-model describes the global economy. The level of detail may vary, but it must be global, describe the economy in the short and long run and include the mechanisms that generate greenhouse gas emissions. For it to be used to describe how different types of policy affect the economy and its emissions of greenhouse gases, the model must describe markets and how individuals and firms make decisions. To be able to evaluate the various results, explicit assumptions about objective functions—involving a description of how individuals derive welfare and how individual welfare is aggre-

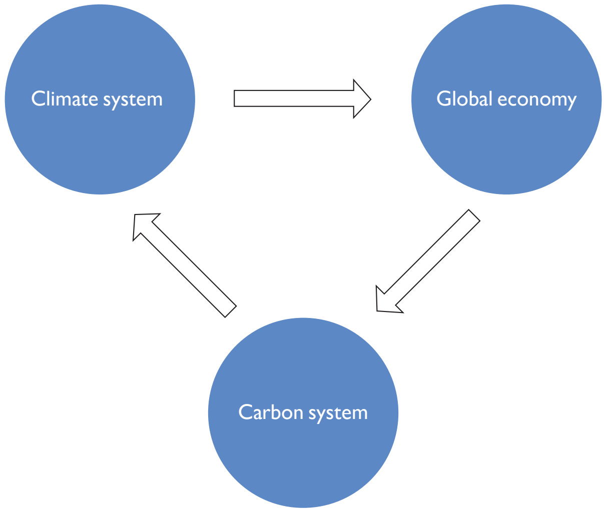

Figure 15 IAMs' three interconnected sub-models.

gated, as described in this chapter—are needed, but not if the model is only to be used for descriptive analysis.

The second sub-model is the carbon system. This describes, again at varying levels of detail, the processes we cover in chapter 2 that determine how a given emission pathway for carbon dioxide leads to a particular pathway for the level of carbon dioxide in the atmosphere.

The third sub-model describes the climate system using the principles of the greenhouse effect, energy transfer and the net uptake of energy that we also covered in chapter 2.

As the name IAM suggests, the three sub-models are interconnected. The economic model produces a time path for carbon dioxide emissions. This becomes an input to the carbon system, which produces a time path for the level of atmospheric carbon dioxide. In turn, this becomes an input to the climate system where the net uptake of energy is affected. The circle is finally completed when climate change impacts the economy through damage functions, as described in chapter 3. IAMs are thus a way of describing the linked system of processes studies in the natural sciences and social sciences that we discussed in the introduction to this report.

5.3 Climate policy instruments

5.3.1 Three types of instrument

As we have mentioned, the basic reason why an unregulated market does not lead to private decisions aligned with what is good for aggregate welfare is that ownership rights to the atmosphere are not well defined. This makes it a resource that can be used for free, despite it existing in limited supply and having a socioeconomic value, leading to overuse and unsustainable development. Markets therefore need to be complemented with policy, which can be done in several ways. We begin with the basic policy instruments that are available and compare them from the perspective of different principles.

To deal with the lack of ownership rights to the atmosphere or, to put it another way, with the externalities arising from greenhouse gas emissions, we can:

– set limits on quantities (at different levels of society), i.e. decide the maximum amount of emissions
– define ownership rights in the form of emission allowances that can be traded on a market
– impose a tax on emissions

All three alternatives are equally well-functioning in a fictional environment with perfect information about how the economy and the natural systems function, down to the tiniest detail. In practice, these conditions are not fulfilled, so these different options will have different results.

Perhaps the most important difference between the approaches is that the first one builds upon the idea that decisions about every agent's emissions are made centrally, while the other two are based upon emissions decisions being made by individuals and businesses acting on a market. This means that the latter two—emission allowances and taxes—are considerably easier to construct. Here, only a decision about how many emission allowances should be distributed or what tax rate should be used is adequate.

The central planning model requires decisions about exactly how much each emitter may emit. However, sometimes this is not a problem—for example, if the conclusion is that the right amount is zero for all emitters. The simplest and most direct regulation is then to prohibit all use.

Another occasion when the central planning model can be simple to implement is if there is an available technology that is known to be effective at reducing or eliminating emissions of hazardous substances and that works for everyone. In such a situation, it may be reasonable for society to decide that everyone must use this technology. In the area of the climate, there is research to support rules and prohibitions playing a major role. Mehling and Tvinnereim (2018), for example, argue that a policy mix of taxation, regulation, and prohibition is necessary. See also section 5.3.2.

However, the market mechanism has a particular advantage when there is great variation between the reduction costs for different actors and the value of using fossil fuels differs between users. If the cost of reducing carbon dioxide emissions is the same in all sectors and activities, there is no need to use the market; you could just order all actors to reduce their emissions by 50 percent, say, over ten years. If instead rapid emission reduction is easier in some sectors or businesses than others, then they should have greater demands to reduce their emissions placed upon them. In practice, it is impossible for a state or other central authority to accurately assess the scope of adaptation costs for different actors. Central planning thus risks leading to very erroneous distribution of the adaptation condition, making the adaptation cost unnecessarily high, perhaps so high that it becomes politically impossible. This is the argument for rejecting the planning model as the primary way of dealing with the climate challenge.

The market solutions of taxation and emission rights do not have these problems. If the markets are constructed well, the markets will automatically result in those who find it easiest to make the transition actually doing so. The question, then, is whether the cost of reducing emissions of climate gases varies greatly between sectors, and there is much to indicate that this is the case. Because there are so many completely different activities in different countries that lead to carbon dioxide emissions—and emissions of other climate gases—it appears very unlikely that the cost of emission reductions will be the same everywhere. In chapter 8, we present calculations that indicate that the actual cost of reducing emissions varies greatly between different sectors and actors in Sweden too. This range can be in the order of 1:10. This means that at the margin you could have 10 times the size of emission reductions for the same cost—or other sacrifice—if you use the market to ensure that emission reductions and adaptations are implemented in the easiest manner.

Official climate plans in Sweden and other countries that aim at climate neutrality by around 2050 entail significant structural change of the social economy in a relatively short time. For the individual entrepreneur or individual household, this requires them to make thousands of decisions: to replace light bulbs with LED lamps, replace boat motors, take the train rather than flying on some routes. In practice, for individuals, it is impossible to determine where their efforts have the greatest benefit in reducing climate change. A price on emissions then provides a clear signal, making goods with a large impact on the climate expensive for the consumer.

We can take steel and cement as examples. Eventually, we can perhaps make these goods almost carbon dioxide free, but in the short term, the use of cement and steel entails extremely large emissions. So, at what rate should we expand wind power, which is obviously necessary but requires so much steel and cement in the short term? This, and literally thousands of similar decisions, should be guided by a price on carbon dioxide, making it possible to calculate which investments are beneficial from a societal perspective. If carbon dioxide emissions have a price, this facilitates decision-making by consumers who want to do the right thing, as the price gives them a clear signal of the damage caused by emissions. Furthermore, it clearly steers people who do not think about these issues in the right direction.

When comparing the two market-based systems of emission allowances and taxes, they each have different strengths in relation to the other. With a tax, we know what the price on emissions will be, but it is impossible to exactly know their volume, as this will depend on how difficult and expensive it is to reduce emissions. On the other hand, with emission allowances, we know the volume of the emissions but not their price. If reductions turn out to be much easier than predicted, the price will be low—perhaps too low, i.e. a more ambitious target should have been set. A clear example of this was the market for emission allowances in the EU, where the number of emission allowances was initially set too high. Even though this has now been partially corrected in the 2018 reform, it led to many years of more emissions and less structural change than was desirable. This difference creates benefits for taxes versus emission allowances that depend on which of the uncertain costs for emission reductions or uncertain reductions in volume is most serious.

Emission allowances are preferable if controlling the quantity of emissions is very important. Such a situation may occur if the damage that is caused by the emissions grows rapidly at a certain level, a tipping point, which is discussed in section 2.5.1. This can apply to the climate, for example, non-linear effects from the melting of the Greenland ice sheet, and damage caused by global warming, such as flooding, which is especially significant when major cities are threatened. It is important that this level is not passed. However, emissions in a single region or a country are unlikely to cause this because the size of the damage is determined by global emissions. If a single country exceeds its emissions targets, it therefore hardly affects the costs at the margin. Another reason for emission allowances could be that individual countries or regions have committed to achieving certain emissions targets. The political cost of not achieving them may then be high.

If there is great uncertainty about the costs of achieving a particular emissions target and if the costs can be expected to increase quickly with greater reductions, this indicates that a tax is better. If an emission volume is set in advance, the price of emission allowances becomes very uncertain under these conditions. This increases the risk of investments with returns that are dependent on the price of emission allowances, such as investments in renewable energy.

Large fluctuations in price have been shown in existing systems for emission trading, such as that of the EU, the EU ETS (shown in figure 23, p. 215), and in similar systems for emission allowances for sulfur dioxide in the USA. A carbon dioxide tax also reduces the fluctuations in the consumer price of fossil fuels. There may also be a risk that emissions targets in an emission trading system are set too low due to a fear that the costs of emission reductions—equaling the price of emission allowances—will be very high.

Recently, another disadvantage of emission trading systems has been highlighted. Allowing the saving of emission allowances for use on a later occasion is reasonable, but Silbye and Sørensen (2019) show that, from a socioeconomic perspective, too few emission allowances will be saved. This means that more emission allowances than are socially and economically optimal are now used—i.e. the reduction in emissions is more back-loaded than is ideal. The reason for this is that emission allowances are a financial instrument, and market actors will require a return given by the price increase in the emission allowance. Given that the financial risk of holding onto emission allowances is relatively high, the market will generate a high expected return—i.e. the price will increase rapidly. The other side of this coin is that too few emission allowances are saved.

For international agreements, Weitzman (2014) has indicated that it is probably easier to achieve agreements for a price on emissions than on the quantity of emissions. This because price is a one-dimensional variable. However, agreements on a global emissions quantity, which is also one dimensional, must be followed by agreements on how much each country may emit. This will cause a multi-dimensional and much more complicated negotiation. For the same reason, it is possible that if negotiations for a price on emissions are combined with negotiations about international transfers, they may become more complicated because there are so many parameters on the table.

In practice, there are also in-betweens, where the advantages of both emission trading and taxation can be combined. This can be done by allowing price to influence the number of emission allowances that are allocated. For example, a price ceiling and a price floor can be decided. If the price ceiling is reached, the number of emission allowances that are allocated is increased, while it is reduced if the price floor is reached. The reforms to the EU ETS that were implemented in 2018 have a similar effect to this (see chapter 6). In the same way, tax can be adapted to the size of the emissions and thus the size of the damage. Therefore, the difference between a tax-based system and one that uses emission allowances should not be exaggerated.

5.3.2 Management by setting targets

In the above section, we have argued that management by quantity may be preferable when a phase-out of particular substances must happen rapidly or when there are identifiable threshold values for emissions that must not be exceeded. There is another class of argument that is also viable in other situations, which builds upon the idea that an explicit formulation of a long-term target can, in several ways, contribute to—or even be a condition for—achieving a particular goal. Sometimes, the economy can be characterized by several possible equilibria. One example of this is when there are network externalities; the reasoning can be illustrated through the following example:

If there is no charging station network, demand for electric vehicles will be low, but few electric vehicles mean that it is not profitable to build a network of charging stations. Charging stations and electric vehicles are complementary, but the market may lack a mechanism for coordinating all the agents' behaviors to utilize this complementarity. Here, a long-term target for emission reductions may help coordinate expectations so that vehicle purchasers assume that a system of charging stations will be built and thus choose an electric vehicle. These expectations therefore also create an incentive for other actors to start building a system of charging stations.

A related argument is that short-term thinking is prevalent in the political decision-making process. Even when everyone knows that an adaptation must be made, delaying it a little can be tempting. Here, formulating a long-term objective so that its fulfilment can be evaluated along the way could be a way of managing this temptation to push costs into the future. When a policy sets clear objectives for the future, actors can respond to softer incentives and start a transition before tougher governing regulations and taxes are utilized. This type of transition is both smoother and cheaper for society than one where the majority of actors mistrust the established targets and wait for as long as possible, making changes only when their behavior is shown to be very expensive or entirely unacceptable and prohibited. For target setting to be effective, the targets must be credible. This, in turn, requires stability: targets that change frequently will not be credible and will thus lose their steering effect.

5.3.3 Management by changing technology

Technological development is important, not least in the area of the climate, although this does not in itself motivate government subsidies: subsidies should not be given to everything of value. Subsidies may sometimes be motivated as a substitute for carbon dioxide taxes, but as we show below, technology subsidies risk being a weak tool for managing climate change. Furthermore, in cases where small nations, such as Sweden, want to influence climate change by developing new technologies, it vital that these are scalable, i.e. they can be used broadly and globally.

Technological development is sometimes promoted as a win-win strategy because it could provide commercial or national gains in addition to the services provided by reducing climate change. However, this reasoning must be accompanied by a warning: commercial profits from developing a new technology require that the developer restricts its availability and charges fees for it. This results in the new technology being used less than would be socially desirable and, for green technologies, this would hurt the climate. If new and valuable technology are discovered, to have the greatest impact on the climate, it should instead be given away for free. In other words, the win-win perspective is often wishful thinking, with an intrinsic conflict between win and win.

More generally, technological development, both its level and focus, cannot be expected to be optimal on an unregulated market. The problem is that the market solution requires the private ownership of new ideas for there to be incentives to develop them. If those who develop new technology do not own it and the technology cannot be copied by others, the driving forces for developing technology are too weak. On the other hand, ownership rights to new technology through patents or similar give the owner a monopoly situation that leads to too little use of already-existing technology. Total and eternal patent protection is thus hardly optimal, and because new technology almost always builds upon old and general knowledge, we cannot expect developers to reap all the social value of a discovery or invention. These are arguments for providing support for new research into alternative energy, for example.

Motivations for supporting the development of technology could be greater for some green alternatives, as for other young technologies; expanding and using a particular technology generates useful knowledge and experience that benefit society as a whole. The learning curve is often steepest at the start. If the new knowledge is useful for society, there is thus a special reason for supporting young technologies, which could be done by the supplier receiving a guaranteed price for the energy that is delivered, feed-in tariffs, or investment support for new technology. If—and if so, how much—support should be given is a quantitative issue. Just because a form of energy is young and green, it does not go without saying that it should be subsidized. On this point, green energy is no different from other technologies, such as IT and AI.

Funding for technology can sometimes also be motivated by network externalities creating a situation with multiple equilibria. If, as in the example above, there is no charging station network, the demand for electric vehicles will be low, so it will not profitable to build a network of charging stations. Support for infrastructure can play a role in getting the market to tip over into the desired equilibrium.

The conclusion of this reasoning is that there are good arguments for climate policy not only using taxes or emission allowances, as support for research and development may also be necessary. However, we would once again like to bring up the reasoning in section 4.4. Unless fossil-free technology is a sufficiently good substitute for fossil-based technology, support for developing technology that reduces the price of fossil-free technology is a very ineffective policy instrument. Lower prices for fossil-free alternatives then increase their use without them outcompeting those that are fossil-based. A key element of any effective climate policy must thus be that technologies based on fossil fuel are burdened with increased costs.

This is illustrated by a global climate-economic model described in Hassler et al. (2019). It investigates whether technology subsidies that make green energy cheaper could be a substitute for a global carbon dioxide tax. The results are shown in figure 16. The blue dashed curve shows what would happen to the average global temperature if a moderate global carbon dioxide tax of 21 dollars per ton of carbon dioxide is introduced. This tax is just below the current price of emission allowances in the EU ETS and is equivalent to about 50 öre per liter of gasoline. After the tax is introduced, it increases at the same rate as global GDP.

The blue curve shows what happens if, instead, subsidies succeed in speeding up the development of technology for producing green energy, so that its price falls by 2 percent per year, while also succeeding in slowing technology development in fossil-based production so that prices there increase by 2 percent per year. In this case, no carbon dioxide tax is introduced. We can see that such a policy is an excellent substitute for this tax. The average global temperature shows an almost identical trend in both cases.

However, the positive climate effect does not depend on the more rapid development of technology in the green sector. We can see this if we study what happens if we only subsidize green energy technology so that its price falls over time but the prices of fossil fuels do not increase. The effects are shown by the black curve. As we see, it leads to a completely unacceptable development of the global average temperature. The use of green energy does increase quickly, but it does not outcompete fossil-based energy, which also increases. This is entirely compatible with the trends that have so far been observed (Johnsson, Kjärstad, and Rootzén, 2019). Green technology has

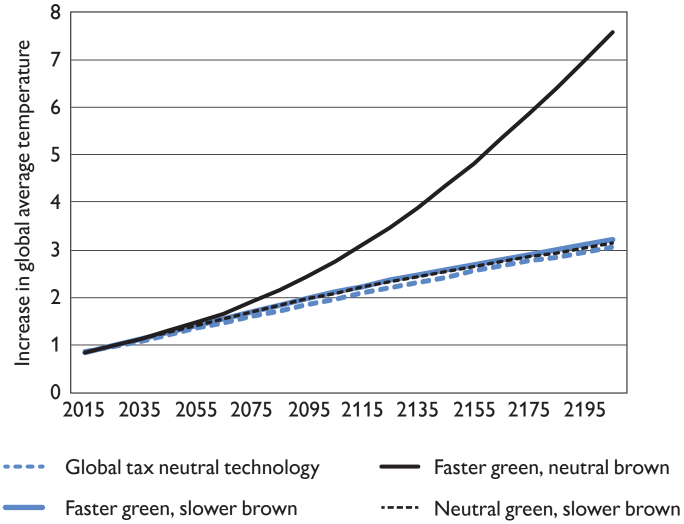

Figure 16 Global warming in different scenarios with taxes or technology subsidies.

Source: Hassler et al. (2019).

generally been developed using subsidies, which has led to its significant growth in some regions, but the use of fossil fuels has continued to grow overall. Green technologies have not replaced fossil fuels; instead, we now have both.

The model in Hassler et al. (2019) uses an empirical basis to assume that the substitution elasticity is just below 1, i.e. the fossil-free alternative is not a particularly good substitute for the fossil one. If the substitutability were much higher, the results could have been different. In a well-known article, Acemoglu et al. (2012) have instead assumed that the elasticity is much higher than 1. In this case, the fossil-free alternatives will outcompete the fossils ones as soon as they are cheaper, so support for new technology can then be a good substitute for climate taxes.

There is also an assumption in the article that the focus of technological development is driven by where research and development is most profitable. This, in turn, is strongly influenced by the size of the market. If technology subsidies succeed in making fossil-free options cheaper than the fossil ones, they will take over the market. Because the market for fossil-free alternatives will thus be much larger, research and development will change focus to further improving and reducing the price of fossil-free technology. Support for fossil-free alternatives is thus not needed in the long term but only for a transitional period while fossil-free technology cannot stand alone.

However, so far, it appears that development is not corresponding to this reasoning, and an elasticity far above 1 is not in line with empirical overview studies. What we so far observed—i.e. that lower energy prices for green energy have increased its consumption but not led to less use of fossil fuels—is also more compatible with a relatively low degree of substitutability. Even if the opposite cannot be excluded, a strategy that only builds upon technological subsidies appears to be highly risky.

A low degree of substitutability also means that subsidies for alternative sources of energy are not an effective way to reduce fossil fuel use. The purpose of such subsidies is to reduce the demand for fossil energy so that producing fossil fuels is less profitable. How much the demand for the latter reduces when the price of alternative fuels falls depends on how high the substitution elasticity is. If it is high, a low price for the alternatives will shift demand from fossil fuels to alternatives. With an elasticity of around 1, this effect disappears and subsidies lead to more alternative energy being used without reduction in the consumption of fossil energy. Subsidies of renewable energy then increase total energy use; even with higher elasticity, subsidies lead to an increase in total energy use. This is because subsidies generally reduce the price of energy. This effect does not occur if, instead, pricing emissions is used as a control instrument. Instead, the general energy price increases, which leads to reduced energy use.

5.3.4 Effects of emission pricing

As described in section 5.2.3, integrated assessment models (IAMS) are used to study the effects of different policies.

One interesting example is the effects of the introduction of carbon dioxide taxes of different levels and scopes. This is studied in Hassler et al. (2019). Four different levels are analyzed: (1) no tax; (2) a tax of 5 US dollars per ton of carbon dioxide; (3) a tax of 21 dollars, i.e. just below the present price of emission allowances in the EU ETS; and (4) a tax of 140 dollars, i.e. around the current Swedish carbon dioxide tax. Tax is assumed to grow at the same rate of global GDP.

A few different tax systems are also analyzed:

— a tax on just coal, not on conventional oil
— a tax of 21 dollars, only in the EU
— a tax of 21 dollars in the EU and 5 dollars in the rest of the world
— a tax of 140 dollars in the entire world

The results are shown in figure 17. The upper blue curve shows what happens if no taxes or other policies are introduced. Just below the upper curve, there are two curves on top of each other. They show what happens if a tax of 21 dollars is introduced on coal, and on coal and oil. The figure also shows what happens if these taxes are introduced globally. As we discussed previously, the effect of a tax depends on how price-sensitive the supply is. The model has assumed that the supply of conventional oil is not price sensitive, because selling oil is profitable even if the price is driven down—for example, by taxation. The same does not apply to coal, the supply of which is price sensitive, because the costs of extracting and transporting coal are already close to the sales price, even without tax. It is the tax on the price-sensitive supply—coal in this case—which is important for emissions.

We can also see that a tax as low as 21 dollars per ton of carbon dioxide, approximately equivalent to 5 cents per liter of gasoline, has significant effects. Warming cannot be kept below 2 degrees in the long term but can stay below this level for the rest of this century. A tax of the same level at the Swedish carbon dioxide tax (the lowest line) keeps warming below 2 degrees in the long term and around 1.5 degrees for the rest of this century. The pale blue line is the case where the tax in the EU is 21 dollars and 5 dollars in the rest of the world. As we can see, this policy also has considerable effects and leads to much less warming than if only the EU introduces a tax.

So, different taxes generate different results, and in general, global warming is smaller the higher the tax that is introduced. So, what level of tax should be chosen? Unlike the descriptive analysis, there is no correct answer that is independent of a value judgment. The answer to the question of the right tax level depends in principle not only on observable quantities such as climate sensitivity, how long carbon dioxide stays in the atmosphere, and the size of the effects they have on the economy, as we have described; the answer also depends on how we value future generations' welfare in relation to our own.

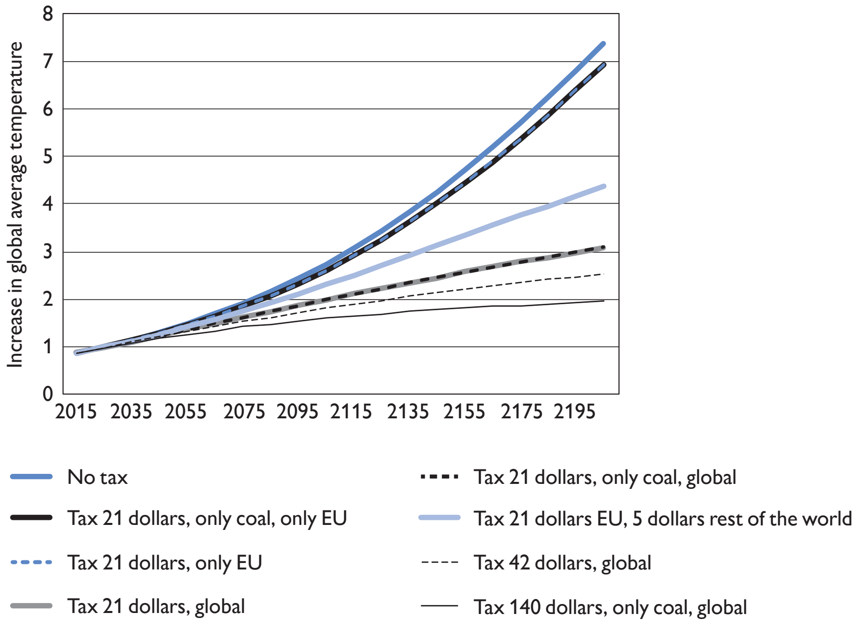

Figure 17 Global warming for different levels and scopes of carbon dioxide taxes.

Source: Hassler et al. (2019).

If we specify an objective function in the manner we discussed above, we can use IAMs to tell us the correct tax level, which will also depend on how we value future generations' welfare in relation to our own. An article by Golosov et al. (2014) shows that under somewhat reasonable assumptions, the right carbon dioxide tax can be described as a simple function of this valuation. Economists often express this relative valuation as an interest rate stating how many percent per year the valuation of future welfare falls (is discounted). The right tax then depends on this discount rate.

Because a significant part of an emitted ton of carbon dioxide stays in the atmosphere for a very long time (see section 2.4) and can thus be assumed to lead to long-term damage, the accumulated value of the damage that is caused depends positively on how much we value the welfare of future generations. In other words, the lower our discount rate, the higher the tax. Figure 18 shows this relationship under a set of assumptions about climate sensitivity, economic damage due to climate change, and the persistence of carbon dioxide in the atmosphere.

The horizontal axis shows the discount and the vertical one the correct tax. Figure 18 shows the discount rates from 0.1 percent to 3.4 percent per annum. When it comes to long periods of time, it can be difficult to envision the effects of these rates. Another way of expressing discounting is to calculate how far we need to go into the future for us to care half as much about the people who will be alive then as we do about ourselves.[1] If we assume that the distance between generations is 35 years, there is a simple mathematical rule for translating the discount rate to how many generations it will take before our valuation of their welfare is halved. The mathematical rule says that the number of generations it takes is two divided by the discount rate in percent. With a 2-percent rate, it will take a generation (35 years); with 1 percent, two generations; and with a rate of 0.1 percent per annum, it will take 20 generations (700 years).

We can note that, if the discount rate is 0.1 percent per annum, the figure supports a global carbon dioxide tax at the same level as

---

1. In this reasoning, everything is equal, in that we have removed the effect of future generations perhaps not having the same consumption level as ourselves. Such differences create other arguments for the relative valuation. For example, we usually assume that, at the margin, individuals who have a lower consumption benefit more from increasing their consumption.

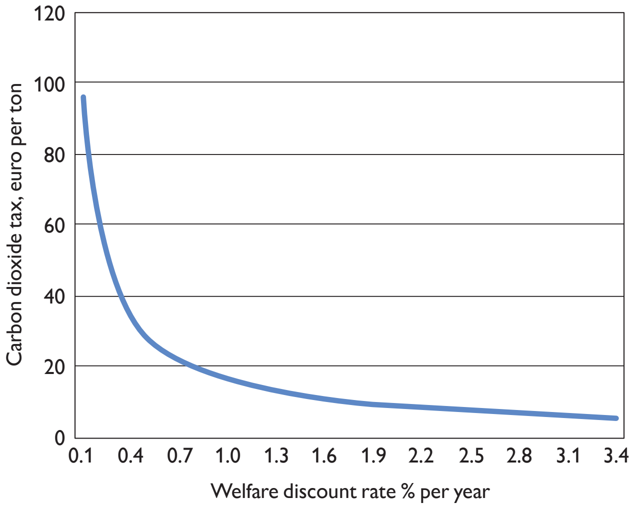

Figure 18 The value of future generations' welfare relative to our own: the right carbon dioxide tax as a function of welfare discount rates.

Source: Our calculations using Golosov et al. (2014).

the Swedish carbon dioxide tax of just over 100 euros per ton of carbon dioxide. A tax equivalent to the current price of emission allowances in the EU ETS is right if the discount rate is 0.6 percent per annum. The half-life of altruism is then 2/0.6 = 3.3 generations, or about 120 years.

Naturally, the results shown by this model are dependent on many other assumptions. If climate sensitivity is higher or if the damage caused by climate change is greater, then the curve shifts upward. Similarly, it also shifts upward if carbon dioxide persists for longer in the atmosphere than has been assumed. As we described in chapters 2 and 3, there is great uncertainty about these parameters. The figure should therefore not be seen as an attempt to exactly describe the truth but rather as an illustration of the sensitivity of the answer to the question of the right carbon dioxide tax for how we value future generations.

So, what is the correct discount rate? As we discussed above, this is a moral issue. As researchers, we can either try to find out how voters and politicians appear to see this or we can argue ourselves for how the future should be discounted. In the first case, we can ask voters and politicians, as well as study other types of decisions and thus draw conclusions about their values. In the second case, we enter a moral discussion about the correct valuation of future generations' welfare.

The lively discussion between William Nordhaus and Nicholas Stern, who had primary responsibility for the very influential Stern Report (Stern, 2006), can be interpreted in these terms; see Nordhaus, for example (2007, 2015a). A reasonable interpretation of Nordhaus' position is that researchers should try to use the first approach, which, according to him, leads to discount rates of up to a few percent. Our interpretation of Stern's argument is that researchers also have a responsibility to take a stand in the moral discussion, particularly regarding the climate, which obviously has a long-term intergenerational perspective.

In this report, we do not express an opinion on the morally correct discount rate, but the Economic Policy Council is unanimously inclined toward the opinion that the rate often used to discount future welfare in social economic calculations for other policy areas—of the size of a few percent—is far too high in these very long-term contexts. If we want a considerably lower discount rate than that which is normally used in policy contexts, we should prefer a higher carbon dioxide tax and a more forceful climate policy in general than that generated by a higher discount rate. The reason is that such a policy is a way of transferring resources to the future, which is good even if it entails costs for the current generation.

One important objection is that it would be reasonable for this to also have consequences for other policies, because climate policy is not all that can be used to improve the welfare of future generations. To be consistent, we should recommend more resources for research and education, perhaps greater public investment and increased resources for acquiring knowledge about and reducing the risk of threats to humanity, such as antibiotics resistance and the collapse of biodiversity.

5.3.5 Distributional issues

In the same way that the consequences of climate change vary greatly for different people, climate policy does not affect all individuals in the same way. There are several reasons for obvious differences between countries; increased climate taxes on oil reduce export income for Norway and oil nations but do not have any effect on Sweden. The costs of transition depend on natural conditions and the opportunities to bear those costs at a country's level of economic development.

If a well-developed transfer system existed between countries, these differences could be evened out. Apart from increasing global justice, this could reduce the risk of some countries blocking global agreements on climate policy. In principle, a well-designed global climate policy can create space for increasing everybody's welfare, but for this to happen, it is highly probable that it must be supplemented by direct distribution. Redistributive policy is thus probably required to gain adequate acceptance for climate policy. One important element of global climate policy should therefore be to develop mechanisms for sharing the burdens brought by the transition to climate neutrality.

However, at least in the Western world, there are national transfer systems. Above, we have argued for not using climate policy as a distributive policy instrument other than if there is a lack of other effective ways of achieving the desired distributive policy objectives. However, this does not mean that the distributive policy consequences of different climate policy instruments are uninteresting. Quite the opposite, highlighting them is of great importance.

One great advantage of taxes and auctioning emission allowances is that they generate significant income that can be used for redistribution. The Swedish carbon dioxide tax generates 23 billion kronor (2.3 billion euro) in income every year, and other energy taxes generate more than twice as much. There are no direct climate policy arguments for what this money should be used for. There are arguments of fairness for helping those affected by this damage or perhaps those who particularly bear the costs of adaptation. Policy arguments can be utilized so that the money is used in a manner that makes them more politically acceptable. In the EU, considerable numbers of the emission allowances that have been allocated have been given for free to companies that have sizable emissions. Because emission allocations can be sold, this creates an incentive for the companies that get them for free to reduce their emissions. For emissions outside the emissions trading system, the EU has allocated the joint obligations in a way that tries to correspond to the different member states' ability to adapt. By 2030, the richer west European countries must reduce their emissions by 35–40 percent in relation to 2005. In Hungary and Poland, the obligation is instead 7 percent, and in Romania and Bulgaria, it is 2 and 0 percent respectively.

One common opinion is that climate policy is good for the rich but bad for the poor. Because the more visible effects of climate policy often include increased gasoline and diesel prices, it is important to analyze the issue of whether energy taxes would be particularly hard on low-income households. Despite the pressing nature of the issue, there are not many studies about the distributional consequences of climate taxes. However, some do exist.

Sterner (2012) analyzes how much households with different income levels pay in fuel taxes. The study includes six European countries, including Sweden, and shows that the relationship between income and the share of income spent on fuel taxes differs between countries. In Germany, the relationship is hump-shaped, i.e. households with medium incomes pay the greatest share. In France, the relationship is weakly negative, with a comparatively small difference between different income groups. Sweden is the country with the clearest negative relationship. Households with lower incomes pay a larger share of their income in fuel taxes than households with high incomes. The decile with the lowest incomes paid 2.2 percent of their incomes in fuel taxes, while the decile with the highest incomes paid 0.7 percent. Similar results have been presented by Kriström et al. (2003). Their study found that expenditure for energy-intensive goods—fuel, travel, and heating—as a share of disposable income reduces with increasing income. Among the households with the 20 percent lowest incomes, 15 percent of their income was used on these goods. The richest 20 percent used just half that proportion on these energy-intensive goods.

The implication of these studies is that, at least in Sweden, an increase in energy taxes would reduce the purchasing power of low-income households to a greater extent. However, this conclusion needs some qualification. Poterba (1991) showed that the distributive policy profile of taxes depends on whether you relate tax expenditure to disposable income or to consumption expenditure. The usual way is to relate it to disposable income, but it is not apparent that this is the correct method. A household's expenditure on consumption is not identical to its income because households can save and borrow. If income is temporarily high, we expect the household to save for its consumption, and the same applies in reverse: with a temporarily low income, it borrows for its consumption. Similarly, a household that consists of young people who expect an increased income in the future can be expected to borrow, while a household with older people are more likely to save or pay off the capital on their loans. Based on this, it is possible to argue that the household's long-term purchasing power is better reflected by its consumption than its current income.

Sterner (2012) calculates the distributive policy profile for expenditure on fuel taxes as a share of annual consumption expenditure in six European countries. The result is shown in figure 19, and except for Italy, the profiles generally slope upward. This also applies to Sweden. One interpretation of the difference in the results—that the slope of the curve is negative when fuel taxes are related to income but positive when they are related to consumption—is that many of the households with low incomes, which pay a large part of their income in fuel taxes, only have temporarily low incomes.

As we mentioned above, income from climate taxes can be used to compensate people with low incomes. Sterner (2012) shows that if an increase in fuel taxes in Sweden was used to reduce VAT on food, the tax burden is reduced for the three deciles who have the lowest incomes, particularly for the lowest decile. For other households, the effect—measured as a share of disposable income—is

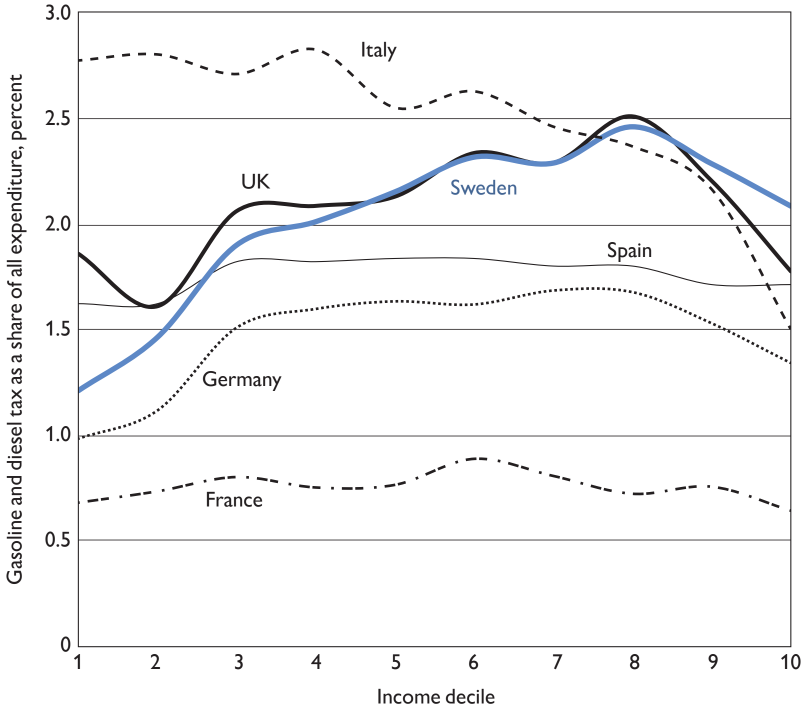

Figure 19 The distributive policy profile for tax expenditure on fuel as share of annual consumption expenditure in six European countries.

Source: Sterner (2012).

negligible. Here, it should be noted that reduced VAT on food is not a particularly accurate instrument for distributive policy (Swedish National Audit Office, 2018). Despite this, it can erase the regressive nature of fuel taxes when it is measured in relation to disposable income.

Another significant aspect of distributive policy is that between urban and rural. In rural areas, cars are naturally used to a greater extent than in built-up areas with functional public transport. The average distance of a journey is shorter in urban areas. In the three municipalities that had the lowest car use per person (Sundbyberg, Tyresö, Lidingö) in 2018, the average distance driven was 4,480 km per person. These municipalities are all densely populated urban areas. The three municipalities with the highest car use (Hedemora, Nordanstig, Ragunda) are all rural municipalities where the average distance driven was 9,890 km per person. Figure 20 shows the relationship between—the logarithm of—population density and the number of kilometers driven per person in 2018. A linear regres-

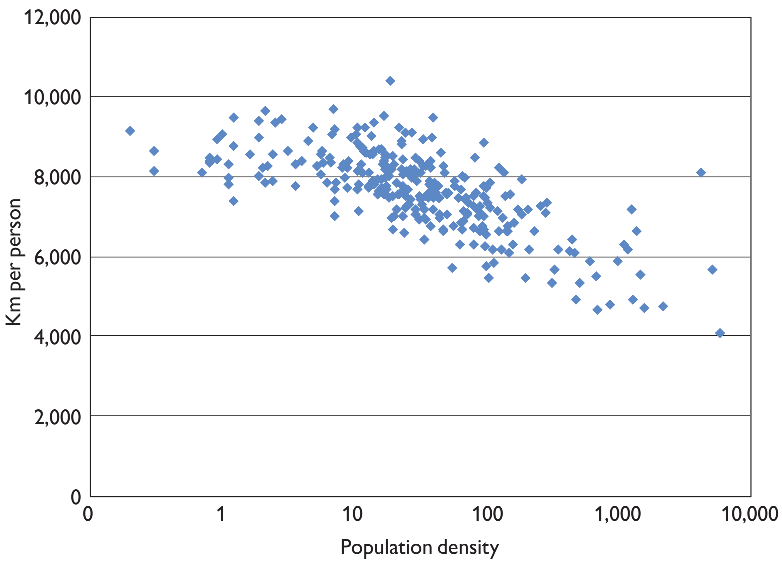

Figure 20 The relationship between population density (inhabitants per square kilometer, logarithmic scale) and average distance driven in km per person 2018.

Source: Statistics Sweden and our calculations.

sion of this data shows a highly significant negative relationship. In a municipality with twice the population density, the average distance driven per person per year is 300 km shorter.

The fact that rural inhabitants drive further also means that they are more affected by fuel taxes. However, a simple estimate leads to the conclusion that the differences in tax burden are not so great that they could not be neutralized. In the municipality with the highest car use (Hedemora), the average distance driven was 10,040 km per person. With a consumption of 0.7 liters of gasoline per 10 km and a carbon dioxide tax of 2.62 kronor per liter, the cost of this tax is 1,840 kronor. Including VAT, this cost increases by 25 percent to 2,300 kronor. In Sundbyberg, the distance driven was 4,070 km, which generated a carbon dioxide tax of 933 kronor including VAT, just over 100 kronor less per month than Hedemora. The economic differences between urban and rural areas are probably dominated by other factors.

Regarding the taxation of gasoline and diesel, the energy tax is considerably higher than the carbon dioxide tax. The social economic costs that the energy tax aims to correspond to, such as local environmental effects, differ between urban and rural areas and could motivate different levels of taxation.

The regional redistribution that occurs through the carbon dioxide tax can be compensated for through other transfers. This should be done in a manner that does not detract from the motivation to reduce the use of fossil fuel. In general, it is a bad idea to exclude some groups from tax for reasons of distributive policy or regional policy. Instead, compensation should be made through a general transfer—or a general tax reduction—in rural areas. It is possible to argue that the motivation for some of the adaptation to climate neutrality—namely, moving to more densely populated areas of the country— is weakened if the rural population receives tax relief as compensation for increased carbon dioxide taxes. However, this could be seen as a low price to pay for a broad acceptance of the carbon dioxide tax. As we have seen, the relationship between the distance driven and population density is nor particularly strong. Additionally, there are probably other factors that are considerably more important for the motivators for and barriers to moving to densely populated areas.

Our conclusion is thus that the consequences for distributive policy, regardless of whether it aims at different income groups or town and country, can be managed with the distributive policy instruments that exist in the Western world. Nor does the structural transformation that follows the transformation to a climate-neutral society appear to be more complicated from this perspective than the structural transformation that our countries have gone through. Nonetheless, there is significant reason to take distribution issues seriously.

In many countries, there is strong opposition to higher taxes and raised prices among the general public, not least regarding fuel. This has been manifested through several recent demonstrations, for example, in Bulgaria, India, and not least in France in 2018, when the "yellow vests" protested against higher gasoline prices. There have also been protests about fuel taxes in Sweden. A report from the Swedish Environmental Protection Agency shows that the Swedish public does not generally support further taxes and charges that are implemented to reduce greenhouse gas emissions (Swedish Environmental Protection Agency, 2018).

What can be done in practice to increase public support for effective climate policy? It is important that the consequences of distributive policy are presented in a credible manner. Research—primarily from psychology and behavioral economics—shows that the design of climate policy matters regarding the perception and support of the general public. For example, policy instruments that are perceived as fair have a greater likelihood of being accepted. The gasoline tax that was discussed in France was regarded as unfair because it would hit people in rural areas and those with low incomes the hardest. The proposed increases were about 50 öre per liter of fuel. Even if the proposal also entailed successive and relatively rapid increases to taxation, the distributive policy consequences should not be difficult to manage. However, such a redistribution may need to be made, and in a situation with a lack of trust for the "political elite," promising that it will happen may not be enough.

One interesting comparison is the carbon dioxide tax that was recently introduced in Canada and received broad acceptance. Much of the tax income is paid back to the citizens under the name of the "people's payout" (Carattini, Kallbecken, and Orlov, 2019). Research also shows that public attitudes to taxes generally follow certain patterns, where most people underestimate the benefit of the tax—here, in terms of lower emissions—and overestimate the negative sides, such as increased costs and lost jobs. However, acceptance usually increases once the tax is implemented and the actual pros and cons are realized. It can therefore be a good idea to introduce a tax so that its level gradually increases (Weber, 2015).

Another way of increasing the acceptance for taxes and a stricter climate policy is to think about how to communicate the facts, such as how the tax should be motivated. We humans have problems interpreting and relating to probabilities and abstract descriptions and therefore feel some distance to climate change and its effects. For us to be able to overcome this distance and comprehend the scientific motivation, it therefore needs to be more personal and concrete (Stoknes, 2015). Additionally, the communication may be used to correct the typical misunderstandings found among the public, such as being able to compensate for a year of commuting by car by eating vegetarian food. In turn, these misunderstandings can influence tendencies to support climate policy measures (van der Linden et al., 2015).

Finally, we note the similarity between the reasoning in this section and that on discounting the welfare of future generations; a fair distribution between different groups of individuals is an issue about values in the same way as the distribution between different generations. As a researcher and adviser, one can thus choose between two approaches. One can either found the approach on the values that are explicitly or implicitly expressed in the choice of a different policy, such as the social insurance system or development aid and other transfers to poorer countries, or one can argue on more subjective grounds for other values.

Just as with intergenerational issues, one should be consistent. If one argues that we should have a forceful climate policy to help the population of poor countries, one should also be positive about other ways of helping these people. In the same way, concern for rural areas regarding the effects of climate policy should motivate other regional policy measures, which may well be more effective than abstaining from an ambitious climate policy.

5.4 Uncertainty

In chapter 2, we described that the level of uncertainty regarding the scale of climate change for a given emissions pathway is very high. Chapter 3 showed that there is also great uncertainty about the welfare consequences of a given level of climate change.

Decision-making under uncertainty is a standard economic field, but the accepted methods are based upon being able to provide statistical probabilities for different outcomes. Assessing such probabilities is difficult or impossible; different models lead to different results, and researchers do not agree on which model is correct.

We believe that models of climate economics, of the type we have discussed here, can nonetheless make valuable contributions to the discussion about which climate policy should be pursued. Given the great uncertainty that exists and that policy decisions need to be made in near time, there is an understanding that the chosen policy may subsequently turn out to be misplaced. For example, we can hope for the best and implement a moderate climate policy that later turns out to have been inadequate, or we can implement a very stringent policy that later turns out to have been excessive.

Hassler, Krusell, and Olovsson (2018) use an IAM to analyze what such policy mistakes cost from a socioeconomic perspective. The first mistake they analyzed is when policy is based on the lowest climate sensitivity in the IPCC's uncertainty interval, i.e. 1.5 degrees per doubling of the carbon dioxide level, and on low economic sensitivity (the lowest sensitivities in a study similar to that presented in section 3.3). In this case, the optimal tax in the model is only about SEK 20 (USD 1.9) per ton of carbon dioxide.

Assume that this turns out to be wrong and that climate sensitivity is actually the highest in the IPCC's interval (4.5 degrees) and that economic sensitivity is among the highest in the available studies. In this case, the global tax should have been set at about SEK 700 (USD 72) per ton of carbon dioxide.[2] The opposite mistake is to levy tax at SEK 700 per ton of carbon dioxide when it turns out that climate

2. This is assuming a discount rate of 1.5 percent per annum. With a lower rate, the correct tax is considerably higher.

sensitivity and the economic sensitivity are low, so the tax should have been SEK 20.

The costs of the two policy mistakes are calculated in the model and shown in figure 21 as loss as a percentage of GDP. The black curve shows the loss caused by inadequate climate policy, when the stringent one would have been correct. The blue curve shows the costs of the opposite mistake, a stringent climate policy that is then discovered to have been excessive. The figure shows great asymmetry: doing too much has small costs, but doing too little is very expensive.

Results like this are also relevant when it is difficult or impossible to assign probabilities to different outcomes. The insurance premium against the policy mistake of choosing a too lenient climate policy is low, given that the policy is based on a global carbon dioxide tax. Of course, other ways of limiting climate change may be much more expensive.

Naturally, the type of result that we just presented only provides an indication of the right policy. In several articles, Martin Weitzman has presented a more pessimistic view of the value of calculations aiming to quantify the costs and benefits of different policies. His argument is that tail risk is the most important component in deciding the right climate policy and level of carbon dioxide tax (see Weitzman, 2014, for example). According to this argument, extremely unlikely but catastrophic possibilities are the most important factor in deciding what policy should be implemented. One way of saying this is that when studying increasingly improbable but all the more calamitous scenarios, probability decreases more slowly than the seriousness of the consequences increases; this is why the extremely unlikely but very serious scenarios should determine policy. However, these extremely unlikely scenarios are

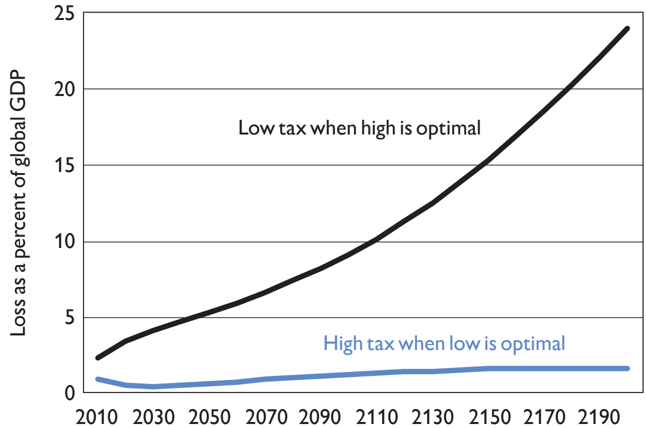

Figure 21 Loss of GDP from different policy mistakes.

Source: Hassler, Krusell, and Olovsson (2018).

the ones for which it is difficult to calculate the probability of both their occurrence and their consequences. The result of this reasoning is the recommendation of an extreme precautionary principle. At the same time, removing all risk is impossible, so this reasoning risks being meaningless when giving advice.

Our view of this is less pessimistic. Calculations like those we have presented are important when it comes to advising politicians, and indicate that the insurance premium for dramatically reducing the risk of serious consequences caused by the emission of greenhouse gases is relatively small. Even if the proposed policy cannot exclude extremely unlikely and potentially catastrophic results, it is arguably worth implementing.

CHAPTER 6

The energy transition

6.1 Chapter summary

Given a remaining carbon budget, i.e. how much more carbon dioxide can be released, the question of how quickly various fossil fuels should be phased out arises. One unambiguous research result is that the socioeconomic value of using conventional oil and gas is much greater than that of coal. There are very large coal reserves, so it is vital that most of these remain in the ground. Conventional oil and gas could probably be used until they run out without posing a threat to the climate.

In Sweden, and in other countries, a transition to climate neutrality is very likely to mean that the electrical system will include many more non-plannable energy sources, such as solar and wind. Everything else being equal, this leads to more variable prices, with the availability of power sometimes exceeding demand even when the price is zero, while at other times there is not enough supply. This does, however, increase the value of measures such as storage, variable production, and increased flexibility of demand, and the introduction of these measures limits price variation.

The potential for continuing to make the economy more energy efficient is good, but in themselves, such measures are ineffective for achieving climate neutrality. Instead, there is a need for technology and fuel exchange, like the capture and storage of carbon dioxide. Sweden has good conditions for wind power, while solar power currently has only a modest share of the energy supply- a small fraction of that from wind power. Solar power will probably be a niche product in decentralized electricity systems, such as in individual households.

Biofuel is an important element in the Swedish energy supply, contributing around 25 percent of the total. However, the combustion of biofuel produces carbon dioxide emissions with the same climate effects as carbon dioxide from fossil sources. The difference between biofuel and fossil fuel is that growing forests to produce biofuel absorbs carbon dioxide from the atmosphere, giving Swedish silviculture the chance to increase the amount of carbon sequestered in forests and in soil, potentially allowing increased biomass extraction over time. However, the climate benefit of imported biofuel is questionable. The system of emission reduction obligations, i.e. the compulsory blending of biofuel in all gasoline and diesel, therefore has considerable risks.

In Sweden, nuclear fuel is about 30 percent of the energy supply, and nuclear power is about 40 percent of electricity production. A decision has been made to decommission the Ringhals 1 and 2 reactors, based on a commercial evaluation by the owners. Whether or not this is compatible with socioeconomic and climate policy considerations is quite unclear.

Capturing and storing carbon dioxide will be vital to achieving ambitious global climate targets, and conditions for carbon sequestration in forests and soils are good in Sweden. Sweden also has great potential for the use of CCS technology to capture and store carbon dioxide from major emissions sources, such as co-generation plants for heat and electricity, cement, and steel manufacturing. The cost per captured ton of carbon dioxide, using current technology, is of the same order as the Swedish carbon dioxide tax. However, the current price of emission allowances is too low to make this technology commercially viable.

6.2 Which emissions should reduce the most and fastest?

In section 2.5, we showed that a good approximation of the results from major interlinked climate models is that the global average temperature is proportional to historical accumulated emissions. We can draw two direct conclusions from this: first, whatever global average temperature we believe to be the highest permissible one, the use of fossil fuel must eventually cease or be compensated for through carbon capture and storage (CCS); second, given a target maximum global average temperature, we can calculate a remaining carbon budget, i.e. how much additional carbon dioxide can be emitted. As we have said, there is huge uncertainty about the scope of the proportionality factor between accumulated emissions and temperature, but regardless of this uncertainty, the accumulated volume of emissions is the most important factor we can control as regards the scale of climate change.

Given a remaining carbon budget, how should it be distributed between various types of fossil fuel: which type of fuel should be phased out first and which last? One robust conclusion from analyses of the best socioeconomic use of the remaining carbon dioxide budget is that conventional oil has a much greater socioeconomic value than coal. This means that, wherever possible, we should fill the global carbon budget with oil, not coal.

This is not difficult to understand; the cost of extracting and transporting coal is close its market price. This means that if the climate damage caused by carbon dioxide emissions is included in the calculations, using coal is not socioeconomically beneficial. Coal use should thus be rapidly reduced. As described in chapter 5, the market can achieve this if a tax that is equivalent to climate damage is imposed on carbon dioxide emissions. Because coal production has such small economic margins, even a very moderate tax will make coal production unprofitable. Another way of expressing this with the concepts we used in section 4.3 is that coal has a high level of supply elasticity, so a carbon dioxide tax will have a significant effect on coal use. Naturally, this does not mean that the phasing out of coal in countries such as China and India is a small problem, nor is it something that can happen rapidly.

However, conventional oil and natural gas are cheap—both to extract and transport—in relation to their market prices. They will thus be used on the market, even if they are subject to a tax that is equivalent to their climate damage. Their use is thus socioeconomically beneficial, even when their climate damage is taken into account. This is the precise aim of the carbon dioxide tax: to ensure that socioeconomically non-beneficial fuels are phased out, while those that are socioeconomically beneficial are still used.

It is also important to note that the reserves of conventional oil and natural gas are likely not large enough to produce unacceptably large emissions if used. It should be noted, though, that estimating the amount of conventional oil and natural gas is difficult, and definitions vary between different sources. Owen, Inderwildi, and King

(2010) estimate the volume of conventional oil at 850–900 billion barrels, equivalent to about 120 GtC. If we use the approximation from section 2.5, which says that the global average temperature is proportional to accumulated emissions with a factor of 0.8–2.5 degrees per 1,000 GtC, then the combustion of this oil would lead to an increase of 0.1–0.3 degrees in the global average temperature.

Figure 22 comes from one of the best-known contributions to research on this question, namely McGlade and Ekins (2015); it is based upon a carbon dioxide budget that, with a high probability, will not increase the global average temperature by more than 2 degrees. Using data on extraction costs, user value, and climate damage, the researchers calculated the optimal socioeconomic mix

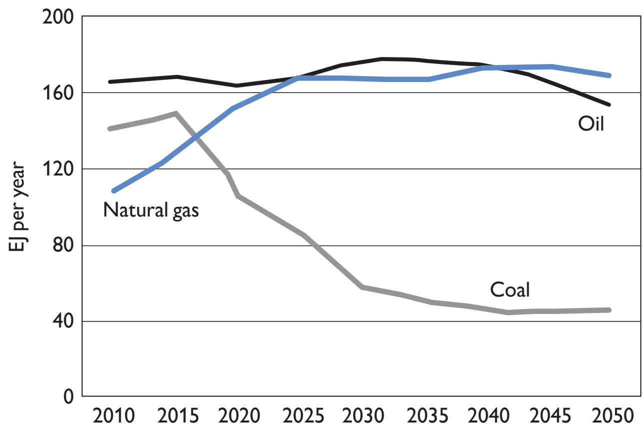

Figure 22 The most socioeconomically optimal global mix of fossil fuels if the 2-degree target is to be achieved. EJ means exajoule, which is 10^{18} joules. 100 EJ is approximately equivalent to 2.5 billion tons (Gt) of oil.

Source: McGlade and Ekins (2015).

Table 3 Changes in energy use to keep global warming below the 1.5-degree target.

Fuel	*2030*	*2050*
Coal	−75	−73
Oil	−3	−81
Gas	+33	+21

Source: IPCC (2018).

of coal, natural gas, and oil. The figure shows that coal use falls rapidly. Coal is partially replaced by natural gas, the consumption of which increases. Oil is used to about the same extent as at present, because there are relatively large reserves that are cheap to extract.

There is a similar calculation in the IPPC report on the 1.5-degree target (see table 3), which presents four possible scenarios for achieving the target of keeping global warming below 1.5 degrees. One scenario, the "middle-of-the-road", is believed by many to be the most realistic of the four and includes rapidly falling coal use, while oil will start to be phased out around 2030 and natural gas after 2050.[1] The calculation also requires extensive use of CCS. Because this target is more ambitious than that of McGlade and Ekins (2015), oil will be phased out earlier in the IPCC's scenario, but the result that coal will be phased out first is the same. However, it should be noted that this is a global perspective and the phasing out may be faster or slower in different regions.

1. Coal use also decreases rapidly in the other three scenarios, while the pathways for oil and gas use, and CCS, vary.

6.3 Transition and the electricity market

As described above, a transition to a climate neutral society means that, in the future, our electricity system will contain significantly greater amounts of non-plannable electricity production, such as wind power, which can only be produced when there is wind. This is of great significance for the electricity market as a whole, both for other electricity producers and for consumers.

Variations in electricity production have already noticeably increased, despite Sweden having nuclear power and hydropower, with major reservoirs allowing most electricity production to be plannable. One reason for the variations is that two nuclear reactors have recently been phased out, while another is that the Swedish electricity market is linked to the Nordic market and to Germany and Poland. As these countries have more non-plannable electricity production—primarily wind power—variations in production will increasingly affect the availability and thus the price of electrical power in Sweden.

Connections between countries enable the management of differences between supply and demand in a country with exports or imports. However, when compensating for variations in wind power, variations are often positively correlated across borders: when it is windy in Sweden, it is normally windy in Denmark too. Even with today's share of non-plannable electrical power, it is not unusual to have negative prices for electrical power. In 2018, Germany had negative electricity prices for 134 hours.[2]

Variations in the electricity price lead to many kinds of problems. For consumers, it creates uncertainty about costs and the need

2. https://www.cleanenergywire.org/news/german-wholesale-power-prices-turn-negative-less-often-2018.

to plan electricity use. For producers of electrical power, it creates uncertain income, as well as costs for regulating production for those who are able to do so. More non-plannable electrical power means that a larger share of a producer's income will be generated on days with high prices or hours with extremely high prices. The number of such days and how high the price will be are much more difficult to forecast than the average price, so investment in power production where the output is not easy to vary becomes riskier. This applies to wind power, but also to nuclear power. All other things being equal, the required rate of return will be higher the more non-plannable power there is in the electricity system.

Another challenge is that wind power does not contribute to what is called grid inertia mass. Many electricity consumers—primarily in industry—are dependent on the frequency of alternating current in the network (50 Hz) being kept very stable. The enormous weight of the turbines in nuclear and hydropower plants helps to maintain an even frequency—more or less like a flywheel in a motor. A smaller proportion of these types of power in the energy system risks fluctuations becoming unacceptably large. Technical solutions are available but are, naturally, not without cost.

Overall, the challenges of a system with a large proportion of non-plannable electricity production in the form of wind and solar power are the following:

1. the availability of power on cold winter days when the sun is not shining and when winds are weak
2. excess power at times of low consumption
3. significant variations in price
4. difficulties maintaining frequency.

These challenges must be addressed, using both policy and the market. We can see a growth in long-term agreements between producers of wind power and major users, in which producers are guaranteed a given price for a long period of time, in some cases, up to a couple of decades. Naturally, these contracts do not mean that the risk disappears, but that it lands on more risk-tolerant investors, thus reducing the negative effect of price uncertainty on the desire to invest.

The variations in price create an incentive to sell electricity when the price is high and to buy when it is low, thus increasing the profitability of investing in storage capacity. Given well-constructed markets, we can expect that these private profit motives coincide with societal ones by contributing to reduced variability in electricity prices. More generally, price variation creates incentives for using technologies that allow electricity use to be planned. Such measures can be called variation management (see Göransson and Johnsson, 2018).

Among other things, variation management means using electricity from variable power that would otherwise risk being wasted, e.g., in periods with good wind availability and low demand. In order for price variations to affect the incentive for variation management, the relevant actors must see the price signal and react to it. There are numerous ways of automating this, but they require new forms of cross-sector cooperation, such as between the electricity production sector and the transmission sector, where the link requires the use of intelligent control systems with IT.

Examples of technologies that allow the utilization of electrical power that would otherwise risk being wasted—i.e. in periods with good availability of wind and sun and low demand—include the production of hydrogen gas and the associated hydrogen storage for industry and transportation, the transfer of heat load in the form of heat load control and heat pumps, intelligent charging for electric vehicles, vehicle to grid, and flexible biofuel-fired thermal power plants. One example of a development project in Sweden is the Hybrit project, in which Vattenfall, LKAB, and SSAB are developing hydrogen-based steel production. Hydrogen is produced using electrical power, and because the gas can be stored, production can be adapted so that periods with particularly high electricity prices are avoided. Steel production thus not only becomes fossil-free but can also be done in a way that brings greater flexibility in electricity use over time.

A great deal of research and development is underway in technologies that increase the flexibility of electricity use. There is reason to be optimistic, not least because many other countries will face greater challenges than Sweden in this area, and thus have strong incentives to drive development. The technological development of solar and wind energy may not solve the problems of how we will have enough electricity on the coldest days of the year, but it is not unthinkable that it can create a situation in which electrical energy is very cheap for most of the year. Swedish industry is not yet adapted for such a situation, but long-term flexibility should not be underestimated.

When it comes to grid inertia, wind power can also contribute to solving the problem of maintained frequency using new technology. However, this costs money. The market thus needs to change so that suppliers of grid inertia are paid for it.

6.4 What technologies can feasibly stop climate change?

At an overarching level, we have argued that the most important tool for managing climate change is to ensure that there is a price on all carbon emissions. Pricing at the level of the damage caused by the emissions will eventually lead to the cessation of fossil fuel use, both through direct market mechanisms and through technological development being pushed in a sustainable direction. Still, discussing how this transition will actually occur is vital. The transition cannot be completely left to the market: policy must play a role. Therefore, in this section we discuss which technologies we believe will be significant in achieving climate neutrality.

At a general level, we can divide the ways to achieve climate objectives into three groups:

- using less energy
- switching technology and fuel
- capturing and storing carbon dioxide.

6.4.1 Using less energy

The most effective way to reduce energy use is to increase its price. The alternative, subsidizing efficiency measures without taxing use, risks being ineffective because efficiency measures lead to lower prices for the service supplied by the energy. This reduction in price increases the demand for these services and thus energy use; there is a rebound effect. This effect is sometimes called Jevons paradox, after the British economist who, in the 19th century, noted that when coal use became more efficient, it increased. The word "paradox" may not be so well motivated after all, as it is natural that use increases when something becomes cheaper. How much it increases depends on the price sensitivity of demand, but there is plenty to indicate that energy efficiency measures are, in themselves, toothless instruments for achieving climate neutrality.

On the other hand, increased energy prices lead to efficiency measures, which is an important adaptation mechanism. The negative consequences of higher prices are mitigated as the amount of energy services—such as heating or transport kilometers—increases per unit of energy. Hassler, Krusell, and Olovsson (2019) demonstrate that this adaptation mechanism was strong in the USA during the post-war years. Their results indicate that an increase in energy prices leads to the refocusing of research and development, so that expenditure for energy is a constant share of income in the economy as a whole. In other words, for every percentage point of price increase, energy efficiency over time increased by 1 percent.

Because of the rebound effect, it is not apparent that subsidies for developing energy-efficient technology in the area of the climate are particularly important. Instead, the correct pricing of energy, including a price for climate damage and other negative externalities, should provide adequate incentives for energy efficiency. Naturally, this does not preclude that knowledge gaps and other reasons sometimes prevent the adoption of profitable measures for energy efficiency. Policy, such as such as information campaigns, can then be warranted.

6.4.2 Switching technology

Switching technology in an energy system is an almost self-evident necessity if the world is to achieve climate neutrality. One central element of this is replacing fossil fuels with renewable ones, such as wind and solar power. There has been a significant expansion of renewable energy in Europe and in other places in the world; in some countries, such as Germany, Spain and Denmark, renewable energy is a decisive element in the country's electricity production. For example, in 2018 around 40 percent of Germany's electrical power came from renewable sources. As we discussed in section 4.4, the greater the proportion of non-plannable energy, the harder it is to replace fossil-based electrical power. Balancing this is rapid technological development, in regard to both renewable power in itself and technologies for managing increasing variability, including storage, offset trading, and greater flexibility of demand.

In Europe, which does not overall have large reserves of fossil fuels, there is reason to say that technologies for renewable electricity production have already been important in replacing fossil fuels (Johnsson, Kjärstad, and Rootzén, 2019). However, as described in section 4.4, developing countries and emerging market economies such as China and India, which have large domestic reserves of fossil fuels, have experienced both strong growth–from low levels–in renewable energy and even stronger growth–from high levels–in the use of fossil fuels.

Nuclear power can replace fossil fuel-based electricity production with approximately the same characteristics, i.e. offering plannable electrical power with a high utilization time. However, nuclear power has several challenges: there is opposition to it in many regions, building nuclear power plants takes a long time, and the investment costs are very high. Varying and difficult-to-forecast electricity prices make investment in nuclear power highly risky financially.

A not insignificant expansion of nuclear power is currently occurring in countries such as China, India, and South Korea, although the market situations are different in these countries; the state there has a considerably greater role than in Europe's deregulated market. For nuclear power to be able to make a considerable contribution to reducing climate impact from the global energy system, it is probable that nuclear power plants must be built as smaller and more standardized units to reduce investment costs, lead times, and financial risk. This is one of the main points in the MIT study *The Future of Nuclear Energy* (MIT, 2018), which is MIT's third study on the subject. Sweden conducted extensive research on nuclear power until it was discontinued in the 1980s, a consequence of the prohibition on preparing the construction of nuclear power plants in Sweden. This law was rescinded in 2006.

An important aspect of new technology is whether it will occupy new locations or whether it can be built on land that had been freed from the replaced technology. The availability of land-based wind power is limited by access to locations with good wind and where wind power is accepted. This may bring the major expansion of wind power to a halt, instead giving an S-shaped curve, where expansion levels off as good locations start to run out. It is primarily not a question of a physical lack of locations, but resistance due to various negative local side-effects of power generation, such as noise and the obstruction of scenic views. This development has resulted in wind turbines having to be placed in less beneficial places, such as forested areas.

Coal-based production has been replaced by natural gas as a fuel, not least in Europe. There are two benefits: one is that natural gas contains less carbon than coal does—it has a higher hydrogen content and thus produces less carbon dioxide per energy unit—and the other is that natural gas is usually combusted in power plants that are considerably more efficient than coal-fired power plants. Natural gas is combusted in combined-cycle power plants (which have a gas turbine and a steam turbine), while coal is normally combusted in condensation power plants (only steam turbines). The transition from coal to gas has primarily occurred in the US, the UK and southern Europe in recent decades.

Sweden also uses some natural gas, but this is limited to the west coast where it is transported via a pipeline to users (the natural gas is imported from Denmark). There are combined-cycle power plants in Gothenburg, and they have been used in Helsingborg. Natural gas is also used in industry. Around the world, terminals for liquified natural gas (LNG) are becoming increasingly common and can receive LNG from transport vessels. One criticism of natural gas imported via pipelines is that it risks leading to increased fuel dependence. One current example is Nordstream, where Nordstream II will make Germany and Europe more dependent on Russian natural gas.

6.4.3 Technologies for new fossil-free energy supply in Sweden

WIND POWER

In Sweden, wind power is expected to more than double by 2022, from 16.4 TWh (2018) to 40 TWh (Svensk Vindenergi, 2019). This can be compared to the 10 TWh, which was the approximate electricity production of the two reactors in Ringhals that will be closed by the end of 2020.[3]

The costs of wind power have primarily fallen due to the increased size of wind turbines—both higher towers and increased rotor diameters—as well as technological development that has

3. Ringhals 2 was decommissioned in 2019 and a decision to decommission Ringhals 1 by the end of 2020 has been made.

allowed the number of full load hours to increase from around 2,500 to almost 4,000 hours for new land-based wind power in good locations. Regarding the investment cost, there are tendencies toward it stopping falling, but because of the abovementioned technological development and the increased size of wind turbines, the number of full load hours has significantly increased and the cost of electricity production has thus continued to fall; it is now below 30 öre per kWh for land-based wind power.[4] One effect of the increased number of full load hours is that fluctuations in the production volume of wind power have become much steeper. A modern wind turbine supplies full power at lower wind speeds than previously, so the increase from zero to full power is more rapid, placing greater demands on the flexibility of the surrounding energy system.

SOLAR ENERGY

In 2018, there were more than 410 MW of solar electricity installed in Sweden, across more than 25,000 solar cell systems. Almost half of these (180 MW) were installed in 2018 as a direct result of solar cell subsidies and falling prices for solar panels. In Sweden, the number of full load hours for solar panels is estimated at about 800. Full load hours are defined as the number of kWh produced per year divided by the maximum power (in kW). With an average production of 800 kWh per kW of installed power, the installed systems can generate about 0.3 TWh.

The costs of solar panels have fallen very rapidly. However, it is important to remember that the solar panel only comprises around half the cost of a solar cell system, with the other half being transformers and technical components for the installation. Accord-

4. LCOE, levelized cost of energy, i.e. the necessary price per produced kWh for profitability.

ing to the international organization for renewable energy, IRENA (2018), installation costs are expected to comprise the largest future reductions in cost. By 2025, IRENA's assessment is that the investment cost for solar panel systems will have fallen by almost 60 percent compared to 2015.

For obvious reasons, the profitability of solar electricity is strongly dependent on the region in which the solar panels are installed. Unfortunately, in Sweden, little solar energy is produced when electricity is most expensive, i.e. in the winter. In countries with a great deal of air conditioning, the covariation between production and the price of electricity is more beneficial. It is difficult to assess what the willingness to pay for decentralized solar electricity production will be, including opportunities for local energy storage in batteries. However, there are examples of buildings where solar panels have replaced the façade material when renovating apartment buildings and where the solar panels were no more expensive than conventional façade materials.

Even if the conditions for solar energy are less advantageous in Sweden, particularly in the winter, the installation of solar panels is increasing, and they may become a niche product for decentralized electricity systems. In a future electrical system, in which battery storage is at the consumer's location, more solar electricity can be utilized. Solar electricity is characterized by large night–day variations, unlike wind, where the timescale for variability can be several days. Battery storage is therefore suitable for utilizing the excess that would otherwise have to be fed back into the network. Batteries are currently too expensive for this to be worthwhile. It is possible to foresee a future where solar electricity is stored in vehicles, both to charge the battery and so that the battery can be used and contribute to the household's electricity consumption.

BIOFUEL

In Sweden, biofuel has a large and increasing share of the energy supply. In 2017, biofuel produced 143 TWh, which was equivalent to 25 percent of the total supply, an increase from 15 percent in 2000.

Just like other organic fuels—such as fossil fuels—the biomass used for energy purposes causes emissions of carbon dioxide as well as other greenhouse gases. The greenhouse effect is caused by the level of carbon dioxide in the atmosphere, regardless of where it comes from. The carbon atoms in the biomass return to the atmosphere, from where they were previously absorbed via photosynthesis. Using biomass for energy purposes with a time lag becomes part of the natural cycle of carbon atoms between the atmosphere and biosphere, provided the released carbon atoms are later absorbed by growing plants. For biofuel to be considered a sustainable source of energy, this cycle must be closed; noting that biofuel originates from biomass is not sufficient for it to be called sustainable.

Land use and the conditions for silviculture and other energy crops differ hugely between the various regions of the world, including EU member states. In this regard, Sweden and Finland are notable for well-established silviculture with high production, at the same time as the amount of carbon that is sequestered in forests and soils is increasing. The differences across countries are probably part of the explanation for the debate about whether bioenergy from forests is a good climate measure and that, for example at the EU level, some countries lack an understanding of the potential to run silviculture with large biomass extraction while also maintaining—or increasing—the amount of carbon sequestered in forests and soils. For an overview of the knowledge situation about the role of forests in the climate and different perspectives on how climate benefit should be assessed, see Berndes et al. (2018).

With a long-term strategy for sustainable silviculture, in which biodiversity is ensured, it may also be possible to accept that the amount of carbon sequestered in the forest—the carbon stock—temporarily falls but that this is followed by the establishment of a production forest with a maintained or increased carbon stock. At the same time, it is essential to note that it takes a long time for forests to grow, which, among other things, makes it difficult to ensure that carbon uptake will be as great as promised.

In Sweden, active silviculture, focused on maintaining high growth, can provide the potential for expanding timber stocks and biomass extraction over a long period of time. Increased growth gives increased sequestration of carbon dioxide and allows increased harvests, providing climate benefit, through both the substitution of materials with significant climate impact and the substitution of fossil fuels (see Börjesson, 2016, and Black-Samuelsson et al., 2017). However, a considerable amount of the biofuel used in Sweden is imported; there is great reason for concern about whether their production is followed by uptake by plants. If not, these biofuels may contribute to officially achieving Sweden's climate objectives, but not to counteracting climate change. However, there is ongoing international work on biomass certification with the aim of ensuring that global climate benefit is achieved. From an international perspective, it is not probable that biofuel produced via silviculture or agriculture could be a significant element in the transition to a fossil-free transport sector.

It is important to consider how the value of biomass may change over time. In a world that moves in accordance with the Paris Agreement—or in a Sweden that develops in line with net zero emissions by 2045—the value of biofuels will probably increase, because there will be a scarcity of biomass for different purposes, including energy purposes—and thus, eventually, scarcity for all biomass use. Given this, it is important that biomass-based fuels are used in the sectors in which substitution away from fossil fuels using other technologies, such as electrification, is expensive and technically difficult. This means that, in the long term, using biofuel in road vehicles is not reasonable—since their electrification is possible. Biofuel should instead be allocated to "difficult sectors" such as aviation, shipping, and some industrial processes.

A system of "reduction obligations" has recently been introduced in Sweden, which is the compulsory blending of biofuel into the gasoline and diesel on sale. The amount of biofuel that must be added is gradually being increased. This has some benefits when it comes to predictability and not contravening regulations on state support; Sweden previously had an exception in its tax legislation that permitted lower tax on biofuels. However, this system is in many ways problematic. First, it stimulates the import of biofuel that may be unsustainably produced. Second, it means that large volumes of biomass may be used for road transport with no consideration of how the biomass, in total, could be of most benefit to all sectors that are dependent on carbon-based fuel or constituent raw materials.

NUCLEAR POWER

In Sweden, nuclear fuel provides about 30 percent of the total energy supply and nuclear power represents about 40 percent of electricity production. This is a larger proportion than in the world as a whole. The future of nuclear power has long been discussed in Sweden, and recently, the question has arisen of whether to expand nuclear power in Sweden. There was an exceptional expansion of nuclear power from the mid-1970s to the mid-1980s. Over about a decade, the production of electricity from nuclear power went from about zero to a level that corresponds to the present day. Given the climate challenge, there is a belief that we should do something similar now. However, we should remember that the previous expansion of nuclear power generally took place on non-deregulated markets, where the state assumed the financial risk. The current situation is different because individual businesses must take that risk on in generally deregulated markets.

A new push for Swedish nuclear power would require huge government financial involvement, either directly or via some form of state guarantees, which is happening in the places in Europe where new nuclear power is being built. In the UK, a specific electricity price is guaranteed where a new nuclear power plant is built, but there are currently no calculations to show this would be an economically viable way to satisfy Sweden's climate ambitions. As mentioned above, research into new nuclear power technologies is underway, for both small modules and those that use other fuels. In both cases, the hope is that safety can be increased while costs are suppressed. Still, these technologies will not be part of the Swedish energy supply in the near future, but there is reason to follow development and possibly also contribute to it.

Sweden now has eight operating nuclear reactors, of which decommissioning decisions have been made for two. These decisions have been made on commercial grounds and have not changed despite the specific tax on electricity from nuclear power—the nuclear power tax—being removed. However, it is not apparent that the profit motive of nuclear power companies is entirely consistent with socioeconomic interests. There are multiple reasons for a discrepancy. First, the electricity market is not a perfect market on which the producers take the price as a given. Quite the opposite, it is undoubtedly the case that major producers, such as the owners of the Swedish nuclear power plants, can increase the price of electricity by reducing production. Even if this effect lessens in the long term, when other suppliers are able to increase their production, it is not possible to preclude that decisions to close nuclear power plants are influenced by the motive of driving up the electricity price. Second, it could be argued that nuclear power producers do not receive full payment for the services they deliver. As mentioned above, nuclear power contributes to maintaining stability in the frequency of alternating current (50 Hz) by providing grid inertia. This increases the value of electricity from nuclear power in relation to electricity from wind and solar panels. Despite this, the electricity is paid for with the same price.

The increased costs of transmission, because wind power is produced where the wind blows, also reduce the value of wind power in relation to nuclear power. Additionally, nuclear power contributes to Sweden's generally fossil-free export, which lowers carbon dioxide emissions in the EU. To the extent that Sweden values reduced emissions more highly than the price of emission allowances in the EU ETS, this creates another unpriced socioeconomic value. It is currently unclear whether setting a price for these values would have any significant effect on the profitability of nuclear power. Whether these aspects are enough to motivate the private economic costs that would be associated with extending the life of existing reactors and restarting the ones that were recently closed should therefore be investigated.

6.4.4 Capturing and sequestering carbon dioxide

Capturing and sequestering carbon dioxide can be done using increased carbon sequestration in soil through forestation or cultivating various types of crops, or by capturing carbon dioxide from point source emissions such as power plants, steelworks, and cement factories, or straight from the atmosphere, with the subsequent storage of carbon dioxide in deep geological formations under the seabed or in bedrock, known as CCS technology. CCS stands for carbon capture and storage. One motivation for CCS technology is the improbability of the world rapidly becoming fossil fuel-free, so the technology allows regions that are dependent on fossil fuels to continue using them for the necessary transition period while still reducing their emissions.

Carbon sequestration plays a very large role in the IPCC report on how the world can stay below 1.5 degrees of warming. In their middle-of-the-road scenario, this century, we must capture and store almost 700 billion tons of carbon dioxide, a volume equivalent to almost two decades of current global emissions.

CCS technology should be able to make a considerable contribution to reducing emissions, because everything indicates that the following conditions are probably satisfied:

1. the potential for storing carbon dioxide—the storage space—is large enough for CCS to provide significant reductions in emissions over many years
2. the stored carbon dioxide is unlikely to leak
3. the cost of CCS is on par with other important measures for reducing climate change and its impacts.

For the sequestration of carbon in soils through forestation to be an effective climate measure, it must be guaranteed over a long period. It is important to ensure that sustainable silviculture, where the carbon stock is higher than without these measures, will be conducted over a very long time. As we discussed in chapter 2, it takes hundreds of years for most emissions in the atmosphere to be absorbed by oceans and other carbon reserves, and thousands of years before three-quarters have left the atmosphere. Therefore, for CCS to be equivalent to limitations in emissions, storage must take place over an equally long horizon.

CCS can be applied to fossil sources of emissions and to those that come from biomass, cement manufacturing, waste, or paper and pulp manufacturing. The effect of CCS on the level of carbon dioxide in the atmosphere, and thus on the climate, is independent of where the carbon dioxide comes from. When CCS is applied to biogenic emissions—such as those in the paper and pulp industries—it is called BECCS (bioenergy CCS). If the biomass comes from forests or from energy crops, where the regrowth of the biomass gives at least a net zero carbon uptake, we can talk about "negative" emissions when CCS is applied to this "zero influence" carbon dioxide.

The cost of CCS using current technology is in the order of SEK 1,000 (EUR 100) per ton of carbon dioxide. This price is still high in relation to what developing countries can be expected to be willing to pay. However, in relation to some Swedish measures, it is not particularly expensive; it costs about as much as the Swedish carbon dioxide tax.

CCS is capital-intensive and requires the establishment of infrastructure for the transport and storage of the separated carbon dioxide. To create the right conditions for market-appropriate financing, the financier must assess that the investment will generate income over a long period of time. In one way or another, this income must come from a publicly constructed system. One way is by giving emission allowances for the capture and storage of carbon dioxide. Such financing has the great advantage of treating emissions and capture symmetrically. As we described in chapter 5, this would be the right pricing. However, there are also considerable disadvantages in such a model: first, decisions have to go via the EU; second, the price on emission allowances is currently too low; third, there is substantial uncertainty about the emission price in the future. Financing CCS in this way is therefore not currently possible, but Sweden could undertake to finance CCS for the same compensation as the Swedish carbon dioxide tax and thus achieve symmetry in Sweden. Because Sweden has limited resources, a cap on expenditure is probably necessary. Such a policy can be motivated even without the assumption that the emissions price outside Sweden will reach Swedish levels, if Swedish CCS-financing can drive technological development and make it cheaper.

Another option that is being discussed is to separate carbon dioxide directly from the atmosphere, called direct air capture (DAC). This technology is in its infancy, though there are a couple of demonstration facilities. The technology is considerably more expensive—perhaps a tenfold higher specific cost than “normal” CCS—mainly because the amount of carbon dioxide in the atmosphere is about one-thousandth of that in flue gases.

Even if the technology is currently expensive, it is at least interesting in the long term because it is not physically linked to any emissions. This has several advantages: first, it allows negative emissions with no limitations other than storage space; second, the separation facilities can be located anywhere, e.g. close to suitable storage space; third, like BECCS, it can be used to compensate for emissions in sectors where the cost of removing emissions is very high—even higher than for DAC. In addition to the aviation sector, this could include other distributed emissions from the transport sector, emissions from agriculture, or potential future emissions from melting permafrost, for example.

DAC could comprise some form of backstop technology in a world where large volumes of carbon dioxide must be removed from the atmosphere. There has been discussion about establishing DAC in Iceland, which has ample storage space in basalt formations and where the stored carbon dioxide has proven to transform into solid material within a few years of its injection. Iceland also has good access to geothermal heat that can be used to power the separation process.

Another suggested technology is carbon capture and utilization, CCU, where the carbon dioxide is captured and then utilized as an input in the production of hydrocarbon-based fuel. However, this idea appears less promising, because carbon dioxide is a very stable molecule; it takes a great deal of energy to separate carbon from oxygen and then produce a fuel by combining it with hydrogen. Considerable losses also occur in the production of both hydrogen and the synthetic fuel, with the carbon dioxide then ending up in the atmosphere when the fuel is combusted. Sometimes, enhanced oil recovery (EOR) is included as a form of CCU, when carbon dioxide is used to press more oil out of an oil field at the end of its productive life. Naturally, this has no positive climate effect if it only provides the opportunity to produce more oil.

CHAPTER 7

International measures to combat climate change

7.1 Chapter summary

Successful climate policy requires global coordination. The fundamental reason for this is that reduced emissions entail costs for the emitter, while the benefits—in the form of reduced climate change—are distributed around the world, creating a "free-rider problem" and necessitating international agreements. The research community has long been aware of this. The Kyoto Protocol was negotiated in 1997, and the idea was to use a top-down process for international agreements about how much participating countries would reduce their carbon dioxide emissions. This principle was abandoned with the Paris Agreement, which came into force in 2016. It stipulated that each party unilaterally decide its own emissions reductions, from which they cannot later renege. The idea is that the parties are expected to gradually increase their commitments instead. Agreement on a global price for emissions has not been an important factor in international negotiations.

The EU's long-term target is to reduce the emission of greenhouse gases to 80–95 percent of 1990's levels by 2050. In December 2019, the leaders of all EU member states, excluding Poland, agreed on the more ambitious target of making the EU climate-neutral by 2050.[1] The EU coordinated measures and served as signatory to the Paris Agreement on behalf of its member states. This commitment entails a 40 percent reduction in emissions by 2030 for the EU as a whole. The EU's reduction in emissions will be achieved partly through its emissions trading system (EU ETS), which covers around 45 percent of emissions, and partly through the Effort Sharing Regulation (ESR) that covers the remainder.

The EU ETS was reformed in 2018, when it was decided to reduce the number of emission allowances issued every year at a faster rate. Also, a system is being introduced to automatically cancel emission allowances if too many are saved, completely changing the conditions for how climate policy influences emissions in the EU ETS. Previously, emissions in the EU ETS were set so that measures to reduce emissions in one place simply led to them increasing somewhere else. After the reforms, measures to reduce emissions will mean that more emission allowances are cancelled, while, on the other hand, measures that increase demand for emission allowances will reduce cancellations and increase emissions.

As part of the EU's Effort Sharing Regulation, member states have agreed on the allocation of responsibility for reducing emissions outside the ETS. Richer countries, such as Sweden, are obligated to do more than poorer ones. To prevent significant differences in marginal abatement costs within the EU, member states can trade emission quotas with each other, allowing reductions in emis-

1. At the time of this report's translation, Poland had also agreed to the target.

sions to be distributed across the union in a cost-effective manner, while some member states, such as Sweden, have a greater reductions obligation than poorer member states.

Climate clubs are a more powerful means of creating the international coordination that is necessary for effective climate policy. Climate clubs offer a way to deal with climate policy's free-rider problem. When a number of countries form a climate club, they implement a common emission price and imports from countries outside the club are subject to a tariff. This tariff can either be charged in relation to how much carbon dioxide is emitted in the production of an imported good, or as a general tariff. There are legal and practical problems that must be solved before climate clubs can become reality, but solutions to these problems should be sought, because they have great potential for creating effective climate policy.

7.2 Global coordination

As we described in previous chapters, effective climate policy requires coordination. The fundamental reason for this is that the costs for a single measure in a country must be taken by that country, while the benefits—in the form of reduced climate damage—are distributed across the entire world. If each country acted on the basis of its own interests, without agreements, measures to combat climate change will be too weak. It is important to realize that this problem would arise even if all countries agreed that the total costs for achieving a specific climate objective, such as a maximum of 1.5 degrees of warming, were worth taking on. This is because a single country's climate policy has a small effect on the global climate, but a great effect on the costs that country is burdened with, so there are motivations to leave an agreement because reducing emissions has a cost—either financially or through other types of sacrifice. If an effective agreement has been implemented, a country can reason in the following manner: 'Now an agreement is in place and climate objectives are being achieved. There won't be much effect on the climate if we leave the agreement, but we won't have to carry the considerable costs or sacrifices that specifically affect *us*.'

In one way or another, there must be a counterweight to these drivers for leaving international agreements or failing to sign them in the first place. This can happen in different ways, one of which that other countries are willing and able to punish the country that leaves. Within a country, institutions exist to punish people who do not follow agreements they enter or do not comply with legislation, but these options are more limited between sovereign states, particularly when we are talking about every country in the world. The punishment can therefore be expressed differently and does not need to be of a directly pecuniary nature. Most countries feel that their reputation would be damaged if they contravene the agreements they entered, so a central principle of the Paris Agreement is to hold the agreement together by appealing to moral values on shared responsibility and, by naming and shaming, punishing countries that do not do what they should or have promised to.

The scientific community highlighted the climate issue as a problem early on, one where humanity's combustion of fossil fuels leads to increased imbalances in the Earth's atmosphere, with increased global warming as a result. Politically, the climate issue has subsequently come to be managed internationally for coordinating global environmental protection. International regulations were negotiated at the 1992 UN Conference on Environment and Development in Rio de Janeiro, and the UN Framework Convention on Climate Change entered into force in 1994, when it was ratified by almost every country, including the USA. The Climate Convention provides a framework for environmental law, in which countries have the objective of preventing dangerous interference in the global climate system. To further define this, and state the requirements for action, the Kyoto Protocol was designed as a supplement to the convention.[2] As a party to it, each industrialized country is responsible for reducing its territorial emissions in the first commitment period, to 2012, by an average of 5 percent compared to 1990's levels. However, some important industrialized nations did not ratify the protocol; the USA refused to sign, while Canada and Australia subsequently withdrew. Here, experience shows that international agreements must find a balance between being so demanding that too few nations participate, but not so weak that they have no effect.

The Kyoto Protocol identified a number of flexible mechanisms that allowed individual countries to cooperate on their obligations or to trade carbon credits, so that emissions reductions with the lowest cost would be implemented first and most easily. The Kyoto Protocol also established a mechanism through which industrialized nations could invest in emission reduction projects in developing countries and receive carbon credits in return, the Clean Development Mechanism (CDM). Numerous countries that had obligations in the first period of the Kyoto Protocol did reduce their emissions, even if there were various reasons why countries did not achieve the climate obligations stated in the protocol. For example, afterwards it turned out that a 5-percent reduction in climate emissions between 1990 and 2012 was not a challenge for eastern Euro-

2. The Kyoto Protocol was negotiated in 1997, but it was not until 2005 that enough countries had signed for it to enter into force.

pean economies, because industrial transformation led to the closure of major sources of emissions. The Kyoto Protocol also meant that international standards were established for measuring and counting climate emissions, and provided a framework that, for the EU, entailed the creation of the EU ETS.

In international law, decision-making is based upon each country's sovereign right to decide upon its economy, its energy choices, rules for industry and taxation of its citizens. The power to decide economic policy is regarded as fundamental to state sovereignty, so it has been difficult to gather countries to talks on issues such as taxes. Agreements on environmental law focus on shared responsibility for the environment and preventing environmental problems that impact multiple countries. Agreements are drawn up between countries for making information available and reducing particular impacts on the environment and political objectives are expressed in terms that describe the desired environmental status or reductions in factors that have a direct impact. Each country then decides how to design measures to meet these objectives. The environmental ministries that negotiate these agreements rarely have the power to commit countries to agreements with more direct control of activities that cause environmental problems, as long as these do not involve direct environmental damage. This means that questions about taxation, direct and sector-specific requirements for activities, and trade regulation, for example, are covered in other negotiations that have other considerations than the environment.

Circling back to the introduction to this report, we can say that international agreements have only slightly touched on *how* their climate objectives should be achieved. This is a problem, because it could have been easier to agree on a reduced price for emissions than to distribute emission volumes between countries. There is an analogy with congestion charges; it is easier to agree on a price for a journey through a charging station than to negotiate how many cars from different suburbs may drive to the city center during each hour of the day.

It is important to note that negotiating how this price is implemented is not essential; whether it is done through emissions trading or a tax is of secondary importance. Equally, there is just as little need to negotiate about what the revenues from the system should be used for. Therefore, there is little risk of state sovereignty being unacceptably curtailed. It is sometimes claimed that agreement on a global carbon dioxide tax is utopian, but it is not much of an exaggeration to say that the issue has never been on the global negotiating table.

The idea of the Kyoto Protocol was to gradually negotiate new periods of commitment between countries and broaden the scope of regulated emissions, so that global emissions would decline by the volume necessary to fulfil the overarching objectives of the Climate Convention. This method, where countries manage and regulate airborne environmental problems using a framework convention and subsequent additional protocol with increasingly tough emissions levels, has been used before. One was the Pan-European Convention on Long-range Transboundary Air Pollution from 1979, which was followed by protocols that set reductions of sulfur and nitrogen emissions, and another was 1985's multilateral Convention for the Protection of the Ozone Layer. That was followed by the Montreal Protocol, which set reductions for- and eventual phasing out of ozone-depleting substances. This type of regulation has had results in combatting environmental problems such as the ozone hole, but has performed more poorly on climate emissions.

At the climate meeting in Copenhagen in 2009, it became clear that the top-down method upon which the previous logic of the Kyoto Protocol was based—with centrally determined figures for countries' commitments to reduce emissions—was not accepted by the USA and China, which accounted for the most emissions. At the same time, it was clear that more countries than the traditional industrialized nations needed to be included, because emissions from middle income countries had begun to increase significantly. The new "logic" was therefore to construct shared regulations based upon countries' own contributions and climate ambitions, i.e. bottom-up, and that all countries needed more defined responsibility for reducing emissions based on their own circumstances. There is support for these methods, including Elinor Ostrom's research on collective action, but it can be problematic when the method is proposed by countries that do not actually want to contribute to the objective.

The new global climate framework, the Paris Agreement, entered into force in 2016 and has now been ratified by 184 states and by the EU; it requires that parties to it have set targets for reducing climate emissions. However, the level of these ambitions is decided by each country, using nationally determined contributions (NDC). The Paris Agreement governs the follow-up of countries' NDCs with common rules for how climate emissions are measured and counted, and ensures that the information is transparent. The agreement does not allow countries to back out of the climate targets they set in their NDC; it instead stipulates that the targets must include gradually increased ambitions.

EU member states coordinate their climate contributions to the Paris Agreement in a shared NDC, which Norway and Iceland have also chosen to join for common implementation. Even if this is the EU's commitment, formally it also applies to every member state. If the EU as a whole does not live up to the agreed reductions, the obligations of the Paris Agreement apply separately to each member state.

The EU has an internal allocation of the agreed reductions in emissions via the EU ETS emission market and the Effort Sharing Regulation, ESR (EU, 2018b). The Swedish climate goals, which we describe in part 3 of this report, are thus not directly part of the Paris Agreement, but naturally fulfil—by a wide margin—the duties given to us by the EU. The Swedish goals are an expression of how Sweden, like other countries, believes that the EU's commitments should have been more stringent, something that Sweden continues to maintain in the revision process.

The Paris Agreement adds detail to the Climate Convention's target of keeping the increase in global temperature below 2 degrees and to strive to limit it to 1.5 degrees. There are statements to the effect that this means global climate emissions must be reduced to zero and then transition to negative levels in the second half of this century. Despite the NDCs that countries provided for the climate meeting in Paris demonstrating clear steps towards how to start reducing global emissions, there is a considerable gap between the level of emissions reductions that have been collectively provided by countries in their first NDCs and those required to achieve the Paris Agreement's target temperatures.

The Paris Agreement's dynamic process for revising and increasing the ambitions of countries' climate contributions aims to reduce and eventually erase that gap. It is too early to know whether it will succeed. Many countries continue to express strong support for the Paris Agreement, despite the USA's decision to withdraw from it, indicating that it remains a force that can provide genuine international coordination on the climate issue and for rules on reduced emissions. The dynamic mechanism of the Paris Agreement is built upon gradual increases to the level of ambition, so it is not possible to say that the commitments made by the countries in the present NDCs are set, rather that the agreement has an important mechanism for promoting the tightening up of these commitments in the near future.

The shift from the Kyoto Protocol's list that governed the allocation of responsibility for reducing climate emissions to the Paris Agreement's system of targets set by individual countries under shared overview, changes the logic of the international coordination on the climate in several ways. The logic of the Paris Agreement builds upon the assumption that enough countries feel sufficient responsibility for limiting climate emissions to prevent decision-making from being dominated by selfish short-term interest. Its basis is also that the sum of individual commitments will be enough to achieve the overarching goal of keeping global warming below 2 degrees. The construction of the agreement helps countries who are good examples to be used as role models for others, who are then pressured to follow their lead. Other, non-state actors—who are thus not formally party to the Paris Agreement—play important roles as partners. The logic is that good examples must be highlighted and given the right conditions to develop.

The issue of how much responsibility each country actually has in reducing climate emissions has also shifted between the agreements. Debate has long focused on establishing principles for a fair distribution of the burden, with different representatives arguing for how this should be done, such as based on historical emissions, the potential as regards assets and welfare, whether responsibility should correlate with the emissions volume per capita and what space future generations should be given for emissions. The Paris

Agreement leaves much of this evaluation to individual countries but, in its principle of the highest possible ambition, it maintains that it is the country's capacity to reduce emissions that should be assessed when the NDCs are reviewed and any naming and shaming done.

The Paris Agreement provides Sweden with several ways of influencing global climate emissions and, even without an agreement, climate innovations that are developed in Sweden, and which proliferate, can have additional impact on those emissions reductions generated by the innovation in Sweden. However, through the Paris Agreement, other countries are pushed to demand such innovations, benefitting their dissemination. The Paris Agreement also creates an arena in which Sweden can profit from its strong work on climate policy, and also use it to influence other countries to introduce reforms and policies for reduced emissions. A prerequisite for the spread of innovation and policy reforms to other countries is that they are also suitable for other countries, which naturally varies. Policy reforms that primarily contribute to Sweden being able to reduce emissions can indirectly support global development, because Sweden's presentation of its emission reductions may provide extra weight to actions that pressure other countries in international talks.

Sweden has also contributed to strengthening the scientific basis for international climate policy and bridging the gaps to less wealthy countries. This has been done though work in the adaptation fund and green climate fund, but also by steering development aid to boost countries' capacities for planning climate adaptation and climate-smart energy. Sweden and Swedish actors have been active in the Clean Development Mechanism, as well as supporting international climate initiatives in other ways, such as ones for the

Arctic, short-lived climate gases, and policy work in the New Climate Economy. The latter is a cooperative project between research institutions and international organizations, such as the IMF and the World Bank. The Global Commission on the Economy and Climate is responsible for the project, and consists of former politicians and business leaders. The commission was formed by seven countries: Colombia, Ethiopia, Indonesia, Norway, South Korea, Sweden, and the UK.

7.3 Coordination within the EU

The EU has an ambitious and fairly comprehensive climate policy. The current long-term goal for the EU is to reduce its greenhouse gas emissions by 80–95 percent by 2050, relative to 1990. In December 2019, the leaders of all EU countries except Poland agreed to tighten up these goals to make the EU climate neutral by 2050.[3] There is also an intermediate goal for a 40 percent reduction in emissions by 2030. This is part of the EU's commitment under the Paris Agreement (NDC). The EU's climate policy framework has three pillars:

- The EU's emissions trading system (EU ETS) covers emissions of carbon dioxide and some other greenhouse gases from energy-intensive industries and energy businesses, as well as carbon dioxide emissions from aviation within the EEA (EU plus Iceland, Liechtenstein and Norway). The system covers around 45 percent of the EU's emissions (excluding international transports).

3. When this report was translated to English, Poland had also agreed to the 2050 climate neutrality goal.

– The Effort Sharing Regulation (ESR) is an agreement that provides a cap on each country's emissions of greenhouse gases from activities that are not included in the EU ETS—primarily non-energy-intensive industry, residential and services as well as domestic transports (EU, 2018b). The agreement covers around 55 percent of the EU's emissions.
– The LULUCF sector (Land Use, Land Use Change, and Forestry) that covers greenhouse gas emissions from land and forestry, and changes in the amount of carbon sequestered in soils and forests (EU, 2018a).

7.3.1 The EU ETS

The EU's emission trading system was introduced in 2005. Businesses under the EU ETS must transfer one emission allowance for every ton of carbon dioxide they emit. If they do not do this, they must pay EUR 100 for each missing emission allowance. Every year, a decreasing number of emission allowances is added to the system through auctions or free distribution. In 2013, 2.1 billion emission allowances were distributed. Every year until 2020, the number of distributed emission allowances will reduce by 38.3 billion, i.e. about 1.8 percent of the 2013 distribution. Reforms in 2018 increased the speed of reductions, which we describe below.

Businesses can trade emission allowances, so companies with high costs can buy emission allowances from companies with low costs to further reduce their emissions, paying a price that means both parties benefit from the transaction.[4] This trade thus reduces the cost of achieving the system's emissions targets. Well-func-

4. Aviation within the EU is allocated special emission allowances that cannot be used outside of the sector. However, the aviation sector may purchase and use or-

tioning trade evens out the companies' marginal costs and the target is achieved at the lowest possible cost. Holders of emission allowances may save them for later use, which also evens out cost differences over time. If participants in the system expect there to be a future lack of emission allowances in relation to demand, perhaps due to increased marginal costs for emission reductions, it may benefit them to save emission allowances. However, such an evening out only occurs in one direction because while saving emission allowances is permitted, borrowing from the future is not.

Initially, the price of emission allowances was at about the same level as today's, around EUR 25 per ton of carbon dioxide (see figure 23). However, during the financial crisis of 2008 their price fell sharply and then remained at a low level for many years. Weak economic growth, combined with an unchanged supply of emission allowances, policy that promoted fossil-free electricity production, and the opportunity to import carbon credits from the rest of the world, meant that companies could build up large savings of emission allowances (in 2017 these amounted to 1.7 billion emission allowances, equivalent to one year of emissions in the system). Together with the low price, this was assessed as being incompatible with the EU's long-term climate goals, so the system was reformed in 2018. The Swedish Government and some Swedish EU parliamentarians have pushed for these reforms. Parts of these are sometimes called "the Swedish proposal." The primary elements of this reform are the following:

1. A faster reduction in the number of emission allowances added to the system every year. From 2021, the number that are distributed will be reduced by 48.4 million every year, which is equi-

---

dinary emission allowances. This means that the prices for these two different emission allowances will not even out as long as the price in the aviation sector is lower.

valent to 2.7 percent of emissions in 2020. If this rate of reduction continues, no emission reductions will be distributed after the middle of the 2050s.

2. The creation of a market stability reserve.
3. The introduction of an automatic cancellation mechanism (EU, 2015, and EU, 2018c).

Items 2 and 3 mean that the number of emission allowances that enter the market depends on how many have been saved. The more saved emission allowances there are, the fewer new ones are issued. This will mean that measures to reduce the demand for emission allowances and—everything else being equal—thereby increase the number of saved emission allowances, also reduce the number issued in the future. One effect of this is that the price of emission

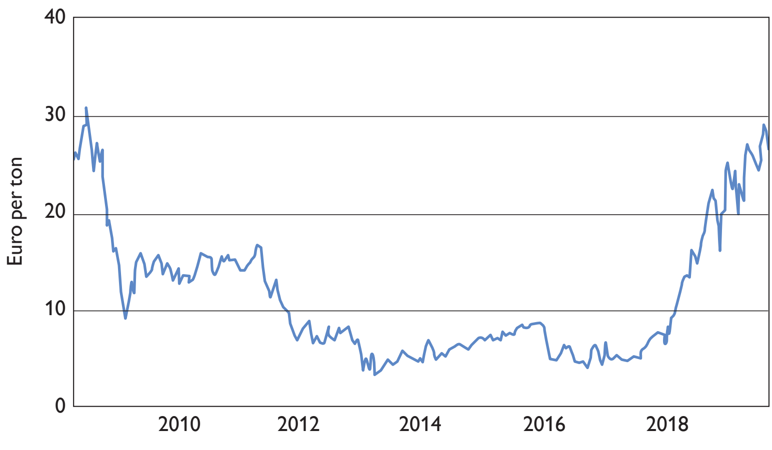

Figure 23 Emission allowance prices 2008–2019, Euro per ton.

Source: https://sandbag.org.uk/carbon-price-viewer/.

allowances will stabilize. If demand falls, the price drops less than it would have done without this regulation of supply, because the supply also falls—and the opposite if demand was to increase. This change has great consequences for the effects of national policy in the EU ETS. We will return to this, but first we describe how this mechanism works.

From 2019, as long as there are more than 833 million saved emission allowances—about half the present number—some of the emission allowances that were intended for auction will instead be transferred to the market stability reserve. The number to be transferred is estimated at 24 percent of the number of saved emission allocations until 2023, and then 12 percent until 2039. Starting in 2023, the reserve will be compared with the number of emission allowances that were auctioned off the previous year. This number is always equal to 57 percent of the total number issued every year which, in turn, follows the declining path we described above.

If the number of emission allowances in the reserve is greater than the number auctioned off in the previous year, the difference is cancelled. The expectation is that large numbers of emission allowances will be cancelled under this rule. The National Institute of Economic Research (2018) calculates that around 2.5–3 billion emission allowances could be cancelled as soon as the 2020s, which is equivalent to more than 1.5 years of current emissions. Silbye and Sørensen (2019) state that an accumulated amount of almost 5 billion emission allowances will have been cancelled by 2050. The faster reduction in the number of allowances that are added every year (item 1 above) probably implies even larger reductions in emissions due to the reforms in 2018.

The reforms will thus significantly increase the scarcity of emission allowances, both by more rapidly scaling down their issue and the forecast cancellations. This has already led to a substantially higher price for emission allowances, as it has quadrupled since the summer of 2017, see figure 23. Despite this, there are calculations showing that the price is low in relation to calculations of future costs for emission reductions. One explanation why this is not evened out by more saving could be that uncertainty about future rules and technologies means that the returns for holding on to emission allowances are very risky: the market demands a high-risk premium for saving emission allowances.

The introduction of a cancellation mechanism has also changed the opportunities for a single country to influence emissions in the EU ETS as a whole. Previously, the total number of emission allowances was not affected by a national policy that reduced the demand for allowances, such as through more support for fossil-free electricity production, as it simply led to companies being able to save more emission allowances, i.e. increase their future emissions or sell them to other emitters. Under the new rules, a policy that reduces the demand for emission allowances not only leads to more emission allowances being saved, but also to more emission allowances being transferred to the reserve—given that the number of emission allowances in circulation exceeds 833 million—and then cancelled. The result of a national demand-reducing policy is therefore a reduction in the total number of emission allowances that are available over time.

It should be noted that when the system is in balance—with fewer than 833 million emission allowances in circulation and the market stability reserve being no greater than the auction volume—the system behaves like the old EU ETS. When this happens, and whether additional rounds of cancellation can occur thereafter, largely depends on the future demand for emission allowances. If, over time, demand falls significantly, for example due to a rapid increase in the renewable energy supply, it may take a long time for the system to become balanced. In other words, emission allowances will then be cancelled over many years. If, on the other hand, there is great demand for emission allowances, perhaps because coal power is difficult to replace, the market stability reserve will shrink more rapidly.

When the EU ETS works in the same way as the old system, i.e. with no cancellation mechanism, measures that reduce emissions in one country simply have the effect of moving them to another country or to the future. For example, taxing the steel industry's emissions so they are further reduced just leads to someone else being able to emit more. Therefore, the effect on total emissions and thus on the climate is zero.[5] Until the cancellation mechanism has ended, the effect is positive. Reduced emissions in one country lead to more saved emission allowances and thus more cancellations, thereby also reducing the total emissions in the system.

The effect of national policy for reducing national emissions in the EU ETS on total emissions thus depends on when it is implemented. As we described, the number of emission allowances transferred to the stability reserve—where they are cancelled after 2023 as long as the reserve is larger than 833 million—is calculated as a share (12 or 24 percent) of the number of saved emission allocations until 2039. Say that the number of saved emission allowances in 2020 increases by 1,000, then the stability reserve increases the

5. However, indirect effects via changes in the EU ETS are possible. If emissions in a country decline, this has a negative effect on the price of emission allowances, so it is conceivable that it is politically easier to gain acceptance for changes to the system of the type that have just been implemented. This mechanism should not be neglected, even if it is difficult to quantify.

following year by 240, all else being equal. This reduces the number of remaining saved emission allowances to 760. Next year, the stability reserve then increases by 24 percent of these 760, i.e. by 180, and so on. The sooner a measure is implemented, the greater the number of such transfers can be done, before they no longer have an effect—because the cancellations have ceased—or the deadline for transfers is reached in 2040.

The opposite also applies: if a country implements measures that increase demand and thus reduce the number of saved emission allowances, emissions will increase more—by reducing cancellation—the earlier they happen. Increased use of electricity produced using coal power is one example of such a measure. Silbye and Sørensen (2019) calculate that measures which are implemented now have an effectiveness of 94 percent, but this sinks to 66 percent if they are implemented in 2030.

Under the old system, it was only possible to reduce the system's total emissions by buying and cancelling emission allowances. Now, purchasing and direct cancellation of emission allowances—at least in the near future—only leads to a reduction in the number of emission allowances that are automatically cancelled. One way of avoiding this effect would be to purchase and keep the emission allowances until the system is permanently in balance and then cancel them, which would lead to the total emissions in the system being reduced by the number of emission allowances cancelled in this way.

One difference between, on the one hand, measures that reduce the national demand for emission allowances and, on the other hand, purchasing, holding, and cancelling emission allowances, is that the first option distorts emissions trading. Measures that affect national demand mean that domestic EU ETS companies encounter a different cost for emissions than that which applies in other countries. However, purchasing emission allowances does not lead to different companies in the system encountering different prices on emissions, but to a somewhat higher price than that which would apply without those purchases.

7.3.2 The EU's Effort Sharing Regulation, ESR

The EU's Effort Sharing Regulation, ESR, covers the majority of emissions outside the EU ETS.[6] It covers the period 2021–2030 and states that the member states' total emissions from activities outside the EU ETS must be 30 percent lower in 2030 than they were in 2005 (EU, 2018b). Within the EU ETS this reduction will be somewhat greater, namely 43 percent.

The agreement also includes that national emission quotas that sum up to this volume are distributed between countries. The reductions in emissions are linear, i.e. a given number of tons per year, so the rate of decrease thus increases with time, as a percentage of actual emissions, in the same way as in the EU ETS.

According to the agreement, countries with a higher per capita GDP are required to reduce their emissions more. For the years 2021–2030, Sweden and Luxemburg are obliged to reduce their annual greenhouse gas emissions to a level that is 40 percent lower in 2030 than in 2005. Poorer countries, such as Bulgaria and Rumania, have received target levels that are at or just below their emissions levels from 2005. It is up to the member states to design national policies that fulfil these commitments. Member states that do not

6. International air and sea transport are not regulated. However, there are ongoing negotiations on the introduction of an emission trading system for these sectors.

do this are penalized by having to reduce their emissions in the following years by 1.8 times more than they missed the previous year.

If member states follow their linear emission reduction pathways, we can expect considerable differences in the different countries' marginal costs for emission reductions. To increase the cost-efficiency of the EU's collective climate policy, there are numerous flexibility mechanisms for the ESR sector. The most important ones are:

- Member states can borrow emission quota units from the future. Up to 5 percent of the emissions permitted in the next five-year period can be borrowed, i.e. more emissions are permitted in the current period, if the equivalent reduction is made in the next period.
- Some member states—including Sweden—may transfer EU ETS emission allowances (up to 2 percent of 2005's emission levels) to their ESR sector. In other words, by reducing the number of emission allowances that are auctioned, countries can increase the emission cap for their ESR sector. The effect this has on the number of saved emission allowances and thus how many are automatically cancelled is removed, otherwise a transfer from the EU ETS to ESR would increase overall emissions.
- Member states may trade emission quotas with each other. A country that falls below its quota can sell some or all its unused emissions quota to other member states. These sales are limited to 5 percent of the country's emissions quota, but there are no limits on how many a country may purchase.
- Member states may transfer a certain amount of LULUCF (land use, land-use change and forestry) credits to their ESR sectors, which means that if the uptake of carbon dioxide in forests and soil increases, it can (with some restrictions) be included so that ESR emissions are increased.

7.3.3 Land use, land-use change and forestry (LULUCF)

In 2018, the EU decided upon rules for land use and forestry (EU, 2018a). They come into force in 2021, with the basic rule being that no country may change its land use and its forestry so that the net uptake of carbon dioxide falls in comparison to the country's reference scenario for 2021–2030. Here too, there are several flexibility mechanisms that aim to ensure costs do not vary too much between the various sectors and countries. For example, a reduction in net uptake may be compensated for through reductions in emissions in the ESR sector. Member states may also trade with each other, so if a country reduces its net uptake it may pay another country to increase its uptake instead.

According to the current accounting system for greenhouse gases, emissions of carbon dioxide from the combustion of biomass and biofuels are not counted in the sectors where they occur—EU ETS and ESR. Instead, the idea is that these emissions should be accounted for as a reduction in the carbon stored in forests and soils. The new rules mean that there is a societal cost when the carbon dioxide sequestered in forests and soils is released, such as by burning biomass. Assume that the new rules' requirement that the net uptake in forests and soil may not decrease is binding. If so, the release of carbon dioxide that occurs if biomass is combusted must be compensated for through measures that increase uptake. This motivates policy instruments that differentiate between different uses of biomass. In relation to the present day, use that does not entail the emission of carbon dioxide, such as construction timber in the building sector, should receive more generous conditions than biofuel, which we return to in our policy proposal.

7.4 Climate clubs

As we have noted in several places in this report, there is a fundamental problem involved in dealing with climate change: the costs of reducing emissions must be carried by the individual emitter, while the benefit—less climate damage now and in the future—is shared between the Earth's current population and its future one. This creates what is called a free-rider problem, which also occurs between nations. Everyone benefits from others' reductions in emissions, but we only pay for our own. The idea of the Paris Agreement is to solve this through agreements and by naming and shaming, with the hope that this will provide enough motivation for countries to fulfil their national commitments (NDCs).

There is reason to fear that this type of highly voluntary commitments and measures will not be enough. Dictatorships such as China and Russia have not shown themselves to be particularly sensitive to naming and shaming on previous occasions, as regards human rights, nuclear weapons, security policy, IP rights and so on. There is therefore reason to ask whether it is possible to construct systems that create stronger incentives for adequately forceful climate policy.

One such system could be climate clubs, a proposal discussed by Nordhaus (2015b). The general theory behind the proposal goes back at least as far as Buchanan (1965), with the basic idea being to create a club in which there is agreement on a specific price for carbon dioxide. After this, a penalty system is introduced for those who are not in the club, for example through tariffs on goods imported from non-members. This idea is also useful in other situations, such as free-trade zones, where there is an agreement not to impose tariffs between member countries. Retaining these tariffs for other countries creates an incentive for membership. These mechanisms have been encouraged within trade due to their usefulness in counteracting trade barriers and trade wars.

Nordhaus (2015b) used an IAM (see section 5.2.3 for a description of these models) to calculate the size of the penalties—tariffs—necessary for all, or at least most, of the world's countries to have an interest in participating in a climate club. This disregards all other forms of penalty, particularly naming and shaming, which is central to the Paris Agreement. The result is that the necessary tariffs are not particularly high for membership to be beneficial for most countries in the world, given that the agreed price is not too high. A price of 50 dollars per ton of carbon dioxide would allow 90-percent participation—in terms of emissions—with a tariff in the order of 5 percent. Calculations show that doubling the price is not feasible. Fifty dollars per ton of carbon dioxide may seem low in relation to the Swedish carbon dioxide tax, which is more than twice as high, but it is almost double the current price of emission allowances in the EU. According to the models we presented in section 5.2.3, a global price of 50 dollars per ton of carbon dioxide would be very effective in limiting emissions.

The above calculation is based on tariffs being imposed on all goods imported from non-participating countries. From an economic perspective, a penalty in the form of tariffs on all goods has some advantages, as any negative effects on member countries are limited. The tariff does not need to be particularly high to have the intended penalizing effect, whereas a tariff on only the carbon dioxide content of imported goods risks being too weak (e.g., McKibbin and Wilcoxen, 2009), and such as tax is very complicated to implement. One major problem is that a tariff on non-members is probably incompatible with international trade regulations. Nordhaus

(2015b) establishes this, and states that the reasonable way forward would be to change international regulations. Given the challenges facing us due to climate change, there is reason to argue that a solution should not be prevented for legal reasons.

The great advantage of using tariffs to correct the carbon dioxide tax is that they could be compatible with international regulations, but as yet there is no consensus on this. There has been wide-ranging discussion about the fees that an importing country might want to impose on products where production has not been burdened with the same level of climate-related taxes as the equivalent domestic production, for example. Some people believe that there is uncertainty about whether tariffs on countries with lower climate taxes would be compatible with the WTO regulation (see National Board of Trade, 2009, for example). This has not been tested through the WTO's dispute resolution, which means there is no legal precedent.

Import duties of this kind must fulfil the requirements of GATT by not being disguised barriers to trade that protect domestic production. This is stated in the founding paragraphs of GATT, articles II and III, both a prohibition on national treatment—that a state gives imported goods poorer conditions than goods produced in that country—and an exception for import fees that correct tax and make the level equal to that imposed on domestic goods.

In principle, it could be possible for a country, within the WTO, to impose a climate-correcting import tariff on specific goods, but that tariff may not exceed the level of the taxes and fees on the equivalent domestically produced product. However, there are several arguments based on trade law, as well on economics and international politics, that point to difficulties in designing appropriate tariffs of this sort.

These design difficulties partly concern determining the exact tariff level for every imported good that leads to an equalization with the domestic climate taxes. There is no established standard for life-cycle analyses of a product's climate impact, and a huge lack of universally trusted data—and partly found in refraining from elements of protectionism in this process. Similar difficulties are discussed as regards anti-dumping measures. Horn and Sapir (2019) state that problems with protectionism are often inadequately highlighted in policy discussions about corrective import charges. However, they believe that it would probably be legally possible to introduce climate-corrective tariffs if they were motivated with the shared and global value of stopping climate change. However, they must be coherent and correspond to the taxation of domestic industry.

The issue of whether it is appropriate to set the same climate price for goods from poorer countries as for goods from the EU and Sweden has also been raised when discussing the appropriateness of such tariffs. Using the fact that the damage caused by carbon dioxide emissions is entirely independent of who emits it, the tariffs should be the same. In the case of climate tariffs and climate clubs, however, the purpose of the tariffs is not really to internalize the damages from climate change, it is to create incentives to join the climate club. Given this, it is possible to argue for different tariff levels for different countries to create enough incentive for membership, with multiple variants of climate-corrective tariffs.

The first variant is defining the climate club as the Paris Agreement, despite there being no agreement on an emissions price. Climate-corrective import tariffs are then introduced on goods from countries that are not party to the Paris Agreement—emphasizing to the USA that the EU wants to stick with the agreement as a negotiating framework, which may motivate other countries not to leave, but to stay and introduce similar charges. However, the climate-corrective tariff should consider the existing taxes on emissions in the country subject to the import tariff. In some cases, such taxes can exceed the price of emissions in some countries participating in the agreement; an import tariff may then be seen as unfair discrimination. A disadvantage of this variant is that the Paris Agreement is a big club to start with, which may make negotiations unmanageable.

Another variant is to use climate-corrective import tariffs only on goods from high- and middle-income countries, ones with similar ambitions for reducing emissions to those of the EU. This means different levels of tariffs on similar goods from China, USA, Brazil, etc., which can be reduced or removed if they join a "climate club" with the EU, in which there is agreement on similar and ambitious climate goals. This may motivate some countries to cooperate more and harmonize their climate objectives, while reducing the risk of weakening poor countries' opportunities for development through trade.

A third variant is to use climate-corrective import tariffs on selected goods where the EU ETS price hits hardest. This option is the one that most clearly equates to the carbon dioxide price for the globally traded goods responsible for the biggest emissions, which may drive development in these product areas.

Given the importance of climate clubs as a central solution to the international coordination problems of climate policy, these opportunities must be further investigated.

PART II

SWEDISH CLIMATE POLICY

CHAPTER 8

Sweden's carbon dioxide emissions

SWEDEN'S USE OF fossil fuels increased until the oil crisis in the 1970s, with the exception of during the Second World War. This trend largely mirrored that of the rest of the world, but the absence of significant fossil fuel deposits in Sweden meant that the impact of the Second World War was felt particularly strongly. From the end of the war until the oil crises, use of fossil fuels grew slightly faster in Sweden than in the world as a whole.

However, since the early 1970s, the trend in Sweden has been radically different from the global trend. While global use continued to grow at roughly the same rate as before, use in Sweden began to decline. From 1970, use fell rapidly for two decades, and by 1990 it was only half the level of 1970. This trend was driven in part by higher oil prices, but particularly by changes to Swedish policy after the oil crises. The large-scale, rapid development of nuclear power and co-generation plants for heat and electric power was a crucial element of this change. The reduction in use continued after this time, but at a substantially slower rate.

This trend is shown in figure 24.

It is important to note that the figures for greenhouse gas emissions here relate to emissions within the borders of Sweden. In Chapter 5, we discussed leakage, which means that emissions transfer from one country to another. Fossil-intensive industries may move to countries with weak climate policies, and from these points sell their goods for consumption in Sweden. One way of measuring these effects is to calculate emissions that can be attributed to the production of goods consumed in Sweden. These calculations are performed by the Swedish Environmental Protection Agency. Although it is not possible to calculate these effects precisely, the results very clearly indicate that Swedish consumption causes sig-

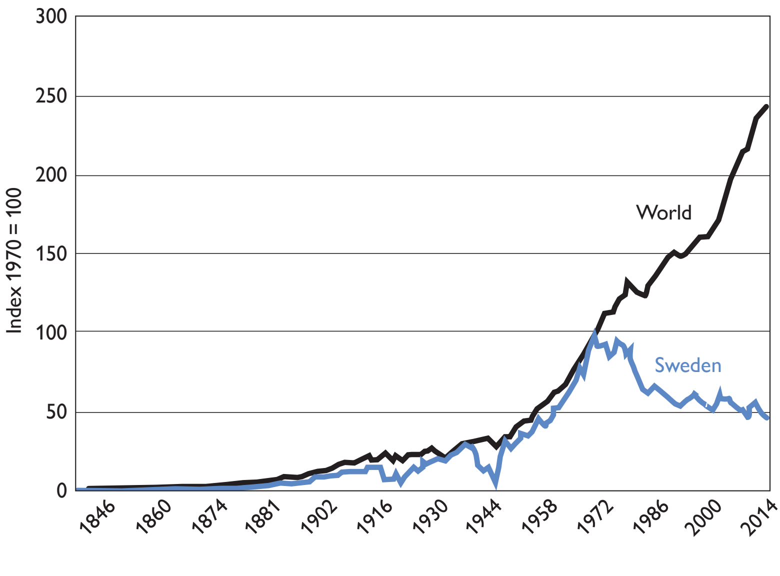

Figure 24 Long-term trend for Swedish and global emissions of carbon dioxide from fossil sources. Index 1970 = 100.

Source: Data from the Carbon Dioxide Information Analysis Center.

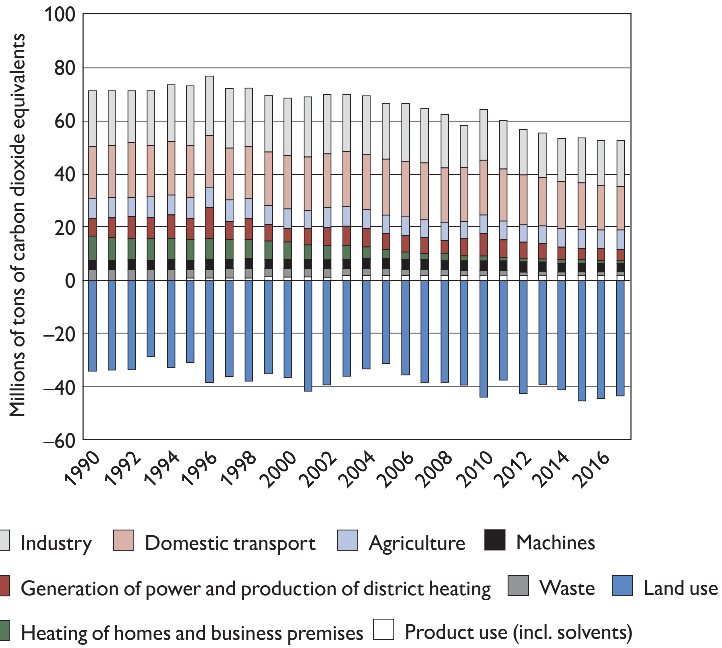

Figure 25 Greenhouse gas emissions in Sweden (excluding transport with foreign destinations) measured in millions of tons of carbon dioxide equivalents.

Source: Swedish Environmental Protection Agency.

nificantly more emissions than those produced directly in Sweden. In addition, there is no clearly discernible downward trend, at least in recent decades.

Figure 25 shows the distribution of Swedish greenhouse gas emissions between sectors in the period 1990–2017.[1] In the period

1. The chart includes emissions of other greenhouse gases than carbon dioxide measured in carbon dioxide equivalents, which serves to describe the contribution of these gases to global warming over a 100-year period. Please note, how-

1990–2015, total Swedish territorial greenhouse gas emissions fell from 71.6 million tons to 52.7 million tons. We can see that emissions in most sectors declined, particularly from heating homes and business premises, where direct emissions dropped by around 90 percent. However, one type of emission that increased significantly is that from outbound foreign travel, but this is not included in Swedish territorial emissions. During this period, emissions from foreign travel increased from 5.1 percent of emissions in 1990 to 20.2 percent in 2017. Figure 25 also shows that the absorption of carbon dioxide by soil and forests increased during this period. This carbon sequestration has risen from 34.4 to 43.7 million tons per annum during the same period.

The net result of emissions and absorption, i.e. Sweden's territorial contribution to increased atmospheric carbon dioxide, fell dramatically in the period 1990–2017. Annual net emissions fell by more than 75 percent from 36.9 to 8.9 million tons.

ever, that most of these other greenhouse gases disappear from the atmosphere in a few decades, while a significant part of the carbon dioxide remains much longer than 100 years.

CHAPTER 9

Sweden's climate policy targets

THE SWEDISH CLIMATE Policy Framework (Government Bill 2016/17: 146) includes one long-term emissions target, two milestone targets, and a separate target for the transport sector. The targets are set for different years and different areas of the economy. The long-term emissions target covers all Swedish territorial emissions. The two milestone targets cover the ESR sector, i.e. emissions in Sweden from the parts of the economy that are not included in EU emissions trading. Emissions in the ESR sector are mainly from domestic transport, agriculture, machines, and industries that are not involved in emissions trading. The target for the transport sector is even more specific and concerns domestic transport, excluding flights.

The long-term target states that Sweden's net emissions of greenhouse gases will be zero by 2045, to then become negative. According to the Climate Policy Framework, this target is to be met by Swedish gross territorial emissions being at least 85 percent lower than in 1990, while the remaining emissions are offset through supplementary measures, i.e., the capture and storage of carbon dioxide from burning biofuel, paying for emission reductions in other countries and increased sequestration from changes in land use and forestry. By setting reduction targets for gross emissions, this is much more ambitious than if it had only been formulated for net emissions, which have already fallen by 75 percent in relation to 1990. Emissions in 2045 may not exceed 10.7 million tons, and these emissions will be offset through supplementary measures. The target concerns all emissions in Sweden, whether in the ESR sector or in the EU ETS. It should be noted that this long-term target is contingent on increased ambitions in the emissions trading system. However, no indication of the necessary increase in ambition is provided, either in the Bill or the report by the Cross-Party Committee on Environmental Objectives (2016).

The interim target for 2030 is that emissions from the ESR sector must be at least 63 percent lower than emissions in 1990. No more than 8 percentage points of the reduction may be the result of supplementary measures; if these are used, the reduction in emissions must be 55 percent. This means that, in 2030, emissions outside emissions trading may not exceed 21.0 million tons of carbon dioxide equivalents.

The milestone target for 2040 is that Swedish emissions from the ESR sector must be at least 75 percent lower than in 1990. No more than 2 percentage points of the reduction may be the result of supplementary measures. This means that the Swedish ESR sector may not emit more than 12.6 million tons in 2040.

The separate target for the transport sector indicates that by 2030 emissions from domestic transport (excluding aviation, which is included in the EU ETS) must have decreased by at least 70 percent in relation to 2010, when they were 19.5 million tons of carbon dioxide equivalents. This means an emission ceiling of 5.9

million tons in 2030. Supplementary measures may not be used to achieve this target.

Figure 26 summarizes the milestone targets and relates them to emissions in 2015. The figure illustrates that the 2030 milestone target for Swedish climate policy demands a much greater reduction from the transport sector than from other parts of the ESR sector. Relative to 2015 emissions, the transport sector must reduce emissions by 66 percent by 2030, while the remaining parts of the ESR sector only need to reduce emissions by 8 percent.

The EU uses regulations to set emissions reductions for member states, so that the EU-wide commitments in the Paris Agreement can be fulfilled. For reasons of fairness, the distribution of emissions

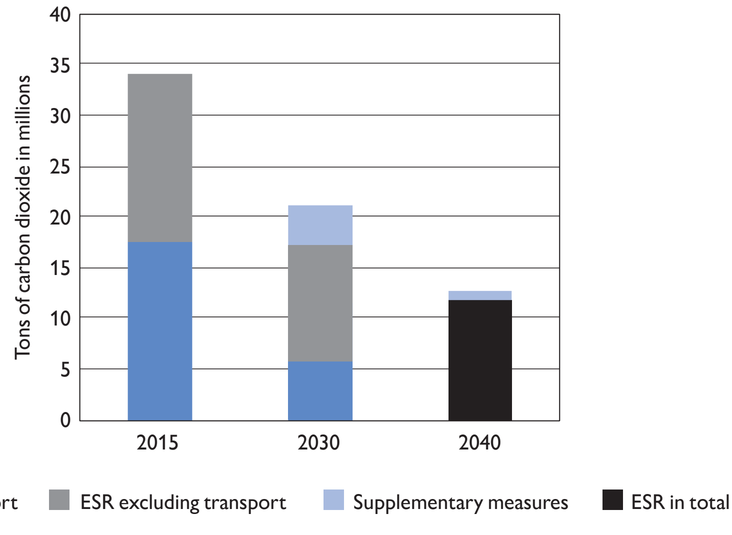

Figure 26 Sweden's milestone targets for emissions outside the EU ETS.

Source: Swedish National Institute of Economic Research (2017b).

targets is based on each country's GDP per capita. Under the effort sharing regulation, Sweden and Luxembourg face the toughest demands: by 2030, emissions must fall by 40 percent relative to the 2005 level. The targets for other countries range from 0 to 39 percent, and total emissions in the ESR sector must decrease by 30 percent relative to 2005.

The agreements within the EU mean that Sweden must reduce emissions within the ESR sector by 40 percent by 2030 and that emissions may not exceed 26 million tons, which is less stringent than the Swedish target of 21 million tons. In addition, Sweden's own target means that the supplementary measures may not exceed 3.7 million tons.

To summarize:

1. Sweden's milestone targets for emissions reductions by 2030 are more ambitious than those in existing agreements within the EU and those for other EU member states. A large part of the biggest reductions in emissions must occur within Sweden.
2. The separate target for emissions reductions by 2030 in the transport sector is much tighter than for other sectors.
3. The long-term target for 2045 also includes emissions from companies in the EU ETS.

CHAPTER 10

Sweden's climate policy instruments

MOST SWEDISH CLIMATE policy measures involve fiscal instruments. We describe the most important of these in this chapter, while aware that other instruments are also used to achieve climate objectives. This is particularly clear when it comes to improving the efficiency of energy, resources and transport, where policy measures include stricter requirements for products' eco-design and energy efficiency, transport infrastructure planning, higher load classifications for roads, adapted road traffic rules for safe cycling, the procurement of night trains to the rest of Europe, and a decision to develop a national ticketing system for public transport.

10.1 Carbon dioxide tax

Various energy sources have long been subject to tax in Sweden. To cite one example, excise duties have been levied on gasoline since at least the 1920s. Based on the experience of rationing in the war years and the energy crisis in 1973, there is a long-held desire to reduce Sweden's dependence on imported fossil fuels. In addition, the problem of environmental acidification has been a much greater issue in Scandinavia than in many other countries, leading to sharp criticism of our fossil fuel dependence as early as the 1970s. When climate change became a major international issue, Sweden responded and was one of the first countries to take action. A carbon dioxide tax was introduced in 1991, along with another energy tax, and these taxes continue to be cornerstones in Swedish climate policy.

The carbon dioxide tax is levied on fossil fuels in proportion to their carbon content, as the carbon dioxide emissions when fossil fuels are combusted are proportional to the fuels' carbon content. This makes measuring actual emissions unnecessary, which greatly simplifies the system. Biofuel combustion is not taxed, although it also generates carbon dioxide emissions. One argument for this is the international agreements that state that biofuel emissions will be managed by recording how much carbon is sequestered in forests and soil instead. The logic is that economic control systems will then affect this storage, although this is not yet happening in practice.

The carbon dioxide tax was introduced in 1991, at a level of SEK 250 per ton of fossil carbon dioxide. This has gradually been increased to reach SEK 1,180 in 2019. This slow increase in the tax rate has allowed households and companies to adapt, which has probably helped boost acceptance of the tax. The Swedish carbon dioxide tax is high from an international perspective—in fact, it is the highest in the world. However, the total tax burden on fossil fuels for consumption in Western Europe is roughly as high. In that sense, Sweden does not stand out positively.

In practice, however, not all emitters have paid the same tax, although a uniform tax is one of the basic principles of the carbon dioxide tax. Tax rates have varied between different areas of use and even from company to company. When the carbon dioxide tax was introduced in 1991, the same tax rate applied to industry as to vehicle owners, for example. However, the industry tax rate was lowered almost immediately.

In recent years, carbon dioxide taxation has once again become more uniform. From 2018, full carbon dioxide tax was imposed on heating fuel in industries outside the EU ETS and in agriculture, forestry, and aquaculture businesses. The deduction for diesel use in mining was abolished in August 2019.[1] However, some sectors and activities are still exempt from taxation. This is the case for domestic shipping, rail traffic, and fisheries, which pay no carbon dioxide tax or energy tax on fuel use.

Carbon dioxide tax revenue is currently SEK 23 billion, while emissions outside the EU ETS total around 32 million tons of carbon dioxide equivalents, which includes emissions of greenhouse gases other than carbon dioxide, primarily methane from agriculture. In 2017, total emissions from the agricultural sector amounted to just over 7 million tons of carbon dioxide equivalents. These were largely methane and nitrogen oxides, which are not subject to carbon dioxide tax. This means that income from the carbon dioxide tax is nearly SEK 1,000 per ton of carbon dioxide emitted in Sweden outside the EU ETS.

The Swedish Environmental Protection Agency stated in 2019 that 80 percent of Swedish greenhouse gas emissions in 2017 (52.7 million tons of carbon dioxide equivalents) were priced by the EU ETS (38 percent) or via carbon dioxide taxation (42 percent, includ-

1. However, co-generation plants in the EU ETS will need to pay carbon dioxide tax in addition to using emission allowances for their emissions.

ing 2 percentage points within the EU ETS). The 22 percent that is non-priced is mainly methane and nitrous oxide emissions from agriculture.

10.2 Electricity certificate system

The electricity certificate system is a way to support the rollout of renewable electricity. It has existed since 2003 and has been shared with Norway since 2012. The system involves allocation of a certificate to certain producers of renewable power—particularly wind-, solar-, and some hydropower—for every MWh of electricity they generate. Electricity suppliers must then buy electricity certificates in relation to the volume of electricity they supply. In 2019, this accounted for 30.5 percent of electricity sold. The cost of the electricity certificates is added to electricity user invoices, although energy-intensive industries facing international competition are exempt; electricity supplied to them entails no requirements to purchase certificates.

The price of electricity certificates is determined by supply and demand. In 2018, the average price was SEK 119 per MWh, i.e. SEK 0.119 per kWh. This meant an average additional cost for electricity consumers of SEK 0.036 per kWh (Swedish Energy Agency, 2019b).

In 2018, users paid for approximately 23 million electricity certificates and, at an average cost of SEK 119, this is a subsidy of SEK 2.7 billion. An important aspect of this support is that it provides the producer with revenue that is less variable than electricity prices, although the electricity certificate price also varies over time.

10.3 Blend-in obligation

An obligation to add biofuel to transport fuel was introduced on July 1, 2018. This entails reductions in greenhouse gas emissions per energy unit by blending in biofuels. One reason for this blend-in obligation is that it is not known whether, in the long term, the EU will permit Sweden to reduce the carbon dioxide tax per liter of transport fuel in relation to how much biofuel is added. Such reductions are currently done in Sweden but are considered state subsidies in EU regulations and require EU approval, which is only granted for a short period at a time. Consequently, the tax system is unable to provide as strong long-run incentives to switch to biofuel as the government would like.

Under the blend-in obligation, fuel companies must ensure that fossil emissions from their sales fall below the emissions that would have occurred if their sales were solely fossil fuel by a specific, increasing percentage. In the second half of 2018, the requirements were 2.6 percent lower emissions for gasoline and at least 19.3 percent lower for diesel. The requirements for 2019 are 2.6 percent for gasoline and at least 20 percent for diesel, while the requirements for 2020 are 4.2 percent for gasoline and at least 21 percent for diesel. No requirements have been published for subsequent years. However, the government believes that the reduction level for 2030 should be 40 percent in order to meet the transport sector target.[2]

The Swedish Energy Agency (2019c) recently proposed that the proportion of biofuel should continue increasing linearly until 2030, when the biofuel admixture should reduce emissions from

2. At the time of translation (Sept. 2020), the government has proposed linear increases in blend-in obligations implying 28 and 66 percent biofuel in gasoline and diesel respectively in the year 2030.

gasoline by 28.0 percent and from diesel by 65.7 percent. The Swedish Energy Agency also proposes reduction levels for 2045 of 80.6 percent for gasoline and 92.9 percent for diesel.

Companies that exceed the requirement in a certain year are not permitted to save the surplus, but it can be transferred to another company with a blend-in obligation for that year. A surplus for blending biofuel in gasoline may not be transferred to another company's deficit for blending biofuel in diesel, and vice versa. Companies that fail to meet the obligation are subject to an emissions reduction obligation charge. This is set by the Swedish Energy Agency, but may not exceed SEK 7 per kilo of carbon dioxide equivalents of the emissions remaining before the obligation is met.

Biofuels are significantly more expensive than their fossil equivalents. Production costs are around SEK 10 per liter for HVO and SEK 8 per liter for FAME (Sweco, 2017), which are the two types of biodiesel currently in use. The corresponding cost for fossil diesel is around SEK 3 per liter. Consequently, it may be assumed that the restriction is binding and that blend-in obligation, in combination with uniform fuel taxation, means higher fuel prices for users.

10.3.1 Bonus-malus

In 2018, Sweden introduced a 'bonus-malus' system for new vehicles, replacing the previous system of green car premiums. Vehicles with low specific carbon dioxide emissions (per kilometer) are awarded a premium (bonus), while vehicles with emissions over a certain level are subject to increased tax (malus) for the first three years. The system is designed to supplement the more general fuel taxation and aims to increase the proportion of green vehicles with lower carbon dioxide emissions (Government Bill 2017/18:1).

More precisely, the system means that zero-emissions vehicles, such as electric cars, are awarded a bonus of SEK 60,000, which is paid out six months after the date on which the vehicle was registered. The bonus decreases in relation to the vehicle's specific emissions of carbon dioxide per kilometer; this reduction is SEK 833 per gram of carbon dioxide per kilometer. Consequently, a vehicle with emissions of 60 grams of carbon dioxide per kilometer receives a bonus of SEK 10,000. A vehicle with emissions higher than 60 grams of carbon dioxide per kilometer receives no bonus. A malus, in the form of increased annual vehicle tax, kicks in if emissions exceed 95 grams of carbon dioxide per kilometer. This increases in line with the vehicle's emissions.

For the first three years, the tax increases by SEK 82 for each gram over 95 grams, up to an emissions level of 140 grams of carbon dioxide per kilometer. Above this, it increases by SEK 107 per gram of carbon dioxide per kilometer. From the fourth year, the increased vehicle tax is calculated instead as SEK 22 per gram of carbon dioxide per kilometer over 111.

The system offers significant incentives for choosing vehicles with low carbon dioxide emissions. The bonus part has been budgeted as SEK 1.25 billion in 2019 and SEK 1.64 billion in 2020. However, overall, the system is estimated to produce a surplus of SEK 0.43, 0.09 and 0.58 billion in 2018, 2019 and 2020, respectively. Nevertheless, revenue and costs in the system depend on the extent to which consumers make choices based on these subsidies and taxes.

10.4 Klimatklivet ("Climate Stride")

Klimatklivet is a funding program for local and regional climate investments. It was established in 2015 and allows companies, municipalities, housing cooperatives, and county councils to apply for funding for climate investments in the ESR sector. In 2015–2018, funding was granted to just over 3,200 projects, of which 66 percent were charging stations for electric vehicles. However, these applications are relatively small. Total funds granted amount to SEK 4.8 billion, of which approximately 9 percent was for charging stations, and 36 percent for investments in energy efficiency and energy conversion, such as boiler replacements. Just over 20 percent was for biogas plants and just over 20 percent for biofuel stations.

10.5 Other funding programs

In addition to the above funding, there are presently and have been a number of smaller programs. One of these is Industriklivet ("Industry Stride"), the aim of which is to contribute to the Swedish climate policy targets and enhance the competitiveness of Swedish industry. From 2019, funding was increased to SEK 300 million per annum. Other funding is for households that install solar cells, which can receive a grant of 20 percent of the investment cost. In 2019, the budgeted cost of this program was SEK 736 million. The previous funding available for e-bikes and electric outboard motors for boats was removed in 2019.

CHAPTER 11

Analysis and discussion

11.1 Milestone target for 2030

As we discussed above, the Swedish milestone target for 2030 is more ambitious than Sweden's ESR undertaking, and is designed in a way that limits the opportunity to use flexible mechanisms, such as buying emission reductions in other EU member states or negative emissions. This leads to increased costs for Sweden; partly the cost of further reducing our carbon footprint and partly the additional costs of doing more within Sweden's borders, rather than funding emission reductions in other countries with lower costs. It is essential to understand these costs in order to relate them to the revenue generated by climate policy.

Naturally, it is difficult to calculate the costs of the ambitious Swedish targets. We cannot expect to perform these calculations with great precision, but we maintain that they are a valuable foundation for political discussions and decisions as they provide an idea of the scale involved.

It is important to note that the costs of climate policy cannot be calculated as the sum of the climate taxes paid by individuals and companies. These payments are state revenue, which can be used to fund various utilities or to lower other taxes. It is equally impossible to calculate the benefit of climate policy using the money allocated. Instead, particularly if it is poorly formulated, the costs of climate policy arise from its leading to the inefficient use of societal resources. Economists call these effects distortions, and their result is that we fail to utilize the full potential of our production resources.

To study the costs of climate policy, we need a general equilibrium model that describes the entire Swedish economy. Such models describe the entire economy's functions, such as production, consumption, investments, markets, etc., and are regularly used by the Swedish Ministry of Finance and bodies such as the Riksbank and the Swedish National Institute of Economic Research. When the focus is on climate policy, the model must be quite detailed and realistic in its description of energy use, because this is the primary source of emissions and where policy has an effect.

The National Institute of Economic Research has developed a general equilibrium model that is suitable for studying the consequences of various versions of climate policy on the Swedish economy. This model is called EMEC and is described by the Swedish National Institute of Economic Research (2015). A report from the Swedish National Institute of Economic Research (2017b) analyzes different methods for achieving the carbon footprint stipulated in the Swedish milestone target for 2030. More specifically, it studies three different combinations of carbon dioxide taxation and flexible mechanisms. In scenario A, a carbon dioxide tax is introduced so that Sweden meets the requirements for Swedish emission reductions under EU rules. In addition, emission allowance units are purchased from other EU member states, which are then cancelled to achieve the carbon footprint stated in the milestone target. In scenario B, the interim target is achieved in accordance with the climate policy framework, i.e. flexible mechanisms are used for the equivalent of 8 percentage points of the emission reduction and carbon dioxide tax is increased so that emissions from the Swedish ESR sector are 55 percent lower in 2030 than in 1990. In scenario C, a carbon dioxide tax is levied, so that the milestone target is met solely by means of domestic emission reductions, i.e. emissions are 63 percent lower than in 1990.

The total carbon dioxide emissions are the same in these three scenarios, but what varies is the proportion of the reduction that occurs in Sweden due to a higher carbon dioxide tax versus the proportion that comes from Sweden's funding of emission reductions in other EU member states. The latter is assumed to be achieved at a price of SEK 400 per ton of carbon dioxide. The results of the analysis are not very sensitive to the level of this price; the consequences are marginal, even if the price halves or doubles.

An analysis by the National Institute of Economic Research using EMEC (National Institute of Economic Research, 2017b) shows that the consequences of the Swedish targets depend on how much of the reductions in emissions occurs in Sweden. Scenario A, which meets EU requirements and the higher Swedish targets for emissions by funding emissions reductions in other countries, leads to a 0.5 percent reduction in GDP in relation to a reference scenario that uses the current policy. With the existing milestone target (scenario B), the fall in GDP almost doubles to 0.9 percent. If no supplementary measures are applied (scenario C), so that emissions are reduced by 63 percent, the fall in GDP is as high as 2.2 percent.

The analysis by the National Institute of Economic Research also shows that carbon dioxide tax needs to be increased dramatically to meet the targets in scenarios B and C, while this is not needed in scenario A. The extent of the tax increase depends partly on how price-sensitive fuel demand is and how fast vehicle fuel efficiency increases. Applying the parameters that the National Institute of Economic Research consider most reasonable, carbon dioxide tax needs to increase by a factor of more than 5 in scenario B and by a factor of 15 in scenario C.

The analyses by the National Institute of Economic Research only use a carbon dioxide tax to adjust domestic ESR emissions, assuming a fixed volume of biofuels and some autonomous enhancements to energy efficiency. The reduction obligation that was introduced in 2018 may increase the volume of biofuel above this assumption. In these cases, the taxes required to keep emissions at the target levels in the scenarios will be lower. However, the total cost is likely to be higher for two reasons: a carbon dioxide tax promotes cost efficiency better than reduction obligations, and the potential for tax-shifting policies is decreased.

The effects of climate policy on GDP are not the same as the costs of climate policy, although it is not unreasonable to assume that they are of the same order of magnitude. In our case, there are currently no better calculations of the costs, which need to be compared with the benefits that are generated. These are not fully included in the calculations by the National Institute of Economic Research, and many of them are difficult to quantify. This is true, for example, of the increased potential to affect the outcome of international negotiations if Sweden applies a more ambitious climate policy. However, even in the absence of quantitative studies, it is still necessary to assess the feasibility of policy. Our assessment is that Sweden's ambitions to reduce emissions by 2030 to a greater extent than is required by EU agreements need not be unreasonably expensive if they build upon on carbon dioxide tax and supplementary measures, such as buying and cancelling emission allowance units from other EU Member States.[1]

11.2 Transport sector target

There are multiple arguments for a separate target for the transport sector, which accounts for around half of Sweden's emissions. Since 1990, these emissions have decreased by 15.7 percent, which is less than the corresponding figure for Sweden's total emissions, 26.1 percent. Technology exists to reduce emissions from the transport sector and, as domestic transport necessarily takes place in Sweden, there is little risk that tougher taxation of this sector would lead to its moving abroad. Therefore, it is possible to argue that the transport sector can 'cope with' higher climate taxes and a greater pressure to become climate-friendly.

There is an element of network externalities if reductions in emissions come from electrification, in that a network of charging stations is necessary. This generates an argument for policy. This is that there will be no demand for electric vehicles if there are not enough charging stations and, if there are no electric vehicles, there are no private incentives to develop a network of charging stations. If the transition to electric vehicles and the construction of charging stations are stimulated through political decisions, these things can occur relatively quickly. In this context, a specific target for the

1. Trading in emissions allowance units is one of the EU systems for balancing the costs of emissions reductions outside the EU ETS. The system is based on member states being able to buy and sell allowances for emissions that occur in the sectors not covered by the EU ETS.

transport sector can anchor this planning process. Another argument in favor of a Swedish target for the transport sector is that it could also help drive technology development on a global scale.

The target set for the transport sector, that emissions must fall by 70 percent by 2030, means that this sector's emissions must fall faster than those in the ESR sector as a whole. As we noted above, in 2030 the transport sector may emit 5.9 million tons of carbon dioxide equivalents, and the remainder of the ESR sector 15.1 million tons (see figure 26). The transport sector's proportion of emissions will then be 28 percent, compared with around 50 percent today. The pressure on the transport sector to become green therefore risks being greater than in other sectors.

The National Institute of Economic Research (2017b) has attempted to quantify how much greater the pressure to become green could be as a result of the transport sector target, using a calculation of emissions in 2030 based on existing policy. This revealed that in 2030 emissions from domestic transport (excluding aviation) would be just over 12 million tons if no new instruments were introduced. This would be a reduction of 23 percent on 2017, but still exceed the target by more than 6 million tons. New policy thus needs to reduce transport sector emissions by half of the emissions that existing policy results in. However, the adopted policy is sufficient for the ESR sector, excluding transport, to meet the target.

Consequently, to meet both the milestone target for the ESR sector as a whole and the specific target for the transport sector, the tax levied on transport emissions must be increased dramatically, although it can be left unchanged or even reduced for other areas in the ESR sector. With normal assumptions, the differences in carbon dioxide tax between the transport sector and the remaining areas will be very high. According to calculations by the National Institute of Economic Research, carbon dioxide tax may need to be as much as six times higher in the transport sector.

Emissions from the transport sector can be reduced in three ways: by replacing fossil fuels with biofuels or fossil-free electricity, by new vehicles having lower greenhouse gas emissions per kilometer than older vehicles, and by reducing the volume of transport (vehicle kilometers).

Each of these mechanisms brings challenges. The challenge inherent in reducing emissions through the increased use of biofuel is that there is a limited supply of biofuel. Sweden already uses a high proportion of the biofuels available on the world market, which is contributing to driving up the global market price of biofuel. To the extent that this promotes production of sustainable biofuels, this is positive. However, imports to Sweden and the EU also include palm oil and other biofuels; this probably has a negative net effect on the climate that could be reduced or eliminated through certification. Given global limits on the production of biofuels and the need to use them where alternatives are difficult to develop, for example in aviation, it is hard to see a major focus on vehicle biofuels as a solution that other countries can adopt to any great extent. One motivation for the increased use of biofuel could be to stimulate the development of process technology for the production of aviation fuels that are made in the same processes. Such technology should be scalable but, for the foreseeable future, aviation will probably be dependent on carbon-based fuels. It is only in the long term that these could be produced from another source of carbon combined with hydrogen from renewable electricity.

One important argument against the transport target is that it aims to reduce the use of gasoline and diesel made from fossil oil. In section 4.3, we described how the supply of conventional oil is not sensitive to pricing. All such oil will most likely be used and presumably has a high enough socioeconomic value to justify its use, even when factoring in negative climate effects. The reduced use of conventional oil in Sweden will therefore probably lead to use increasing somewhere else. This is usually called the 'leakage' of emission reductions. Even though leakage reduces the effect of emission reductions, it does not necessarily eliminate it. A reduced demand for oil lowers the price on the world market, so decreasing incentives for the development of technology to exploit non-conventional reserves of oil and gas.[2] If the availability of oil increases for China, for example, it may reduce their use of coal. Such effects cannot be ruled out but seem uncertain and risk being weak; a rapid phase-out of oil use will have little effect on carbon dioxide emissions.

Electrification may have undesirable side effects via the EU ETS, particularly if it progresses more rapidly than carbon-based electricity generation is phased out in countries to which Sweden exports electricity. Although Swedish electricity generation is largely fossil-free, Swedish electricity generation is interlinked with generation in the rest of the EU. All things being equal, it can be expected that increased Swedish electricity use will reduce net exports to our neighbors, several of which, particularly Poland and Germany, still have a high level of fossil-based electricity generation. Reduced electricity exports will then lead to increased demand for German and Polish carbon-based electricity generation and, after the most recent reforms to the EU ETS, this will lead to increased allocation of emission allowances and thus higher emissions. This means that reducing emissions from vehicles in Sweden leads to higher emis-

2. For example Arctic oil and gas, and reserves extracted using new methods such as fracking.

sions in Poland and Germany. It is important to note that these problems arise if electrification occurs too early, partly because the fossil content of Polish and German electricity will probably eventually decline, and partly because the link between demand and allocation of emission allowances will only exist as long as there are emission allowances saved in the system.

The National Institute of Economic Research has calculated these effects. The results are shown in figure 27, which shows how much the accumulated emissions within the EU ETS are expected to rise if emissions increase by two million tons, depending on

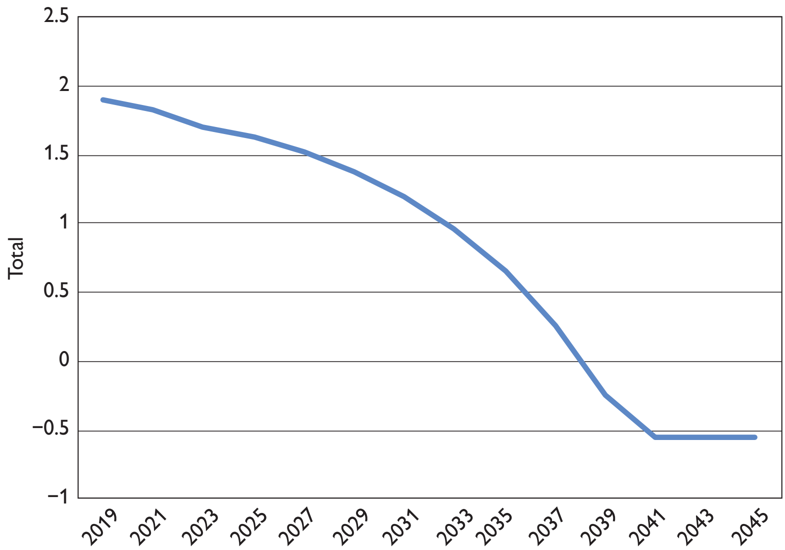

Figure 27 Effects on total emissions of a one-off increase in emissions of 2 million tons within the EU ETS, depending on when the increase occurs.

Source: The National Institute of Economic Research (2020).

when this increase occurs. As we can see, the curve is downward. It starts near 2, i.e. increased emissions lead virtually one-on-one to increased emissions as fewer emission allowances are cancelled. The further into the future the emissions occur, the less the cancellations are affected and thus total emissions.

Electrification and/or a transition to more efficient vehicles requires the vehicle fleet to be replaced. This takes a relatively long time and the aim of the bonus-malus system is to accelerate this process, but the problem is that a rapid transition risks leading to major loss of capital or to exportation of used fossil fuel vehicles for use in other countries, which would limit any global climate benefit. It is also doubtful whether Swedish measures in this area have any effect on total EU emissions from the transport sector. The EU sets strict requirements for the average climate emissions for new vehicles and significant sanctions are imposed on vehicle manufacturers that fail to meet these requirements. To comply with them, a significant proportion of new vehicles will need to be electric vehicles and plug-in hybrid vehicles. Vehicle manufacturers are therefore under great pressure to sell large numbers of such vehicles and may even be forced to subsidize them to make it possible to sell other, more profitable, vehicles. Vehicle manufacturers will be very thankful if Sweden manages to stimulate sales of green vehicles through the use of subsidies, as Sweden then covers the cost of the subsidies instead of the vehicle manufacturers. However, given EU requirements, the climate properties of the new vehicles would not be better than they would have been anyway.

The third way of achieving the emissions target for the transport sector is to reduce transport volumes. Reducing road transport by raising the price of transportation via higher fuel taxes is possible, but it requires significant price increases. Road transport has a relatively low price elasticity that most studies estimate at around –0.3. This means that the cost of driving must double if the volume of road transport is to fall by 30 percent, which would be roughly in line with the Swedish Transport Administration's scenario for achieving the transport sector target. The political and distribution-related difficulties of such a measure are considerable. Reducing car use by improving alternative means of transport (public transport, walking, cycling) usually has small effects in relation to costs, particularly outside cities, where public transport already accounts for a fairly high proportion of journeys. Buses also produce emissions and, as the occupancy of buses outside cities is already low, it is far from certain that increasing the supply of buses would lead to net reductions in emissions.

As we described in section 5.3, there is a clear negative relationship between population density and car use. In principle, rapid population relocation to densely populated areas could reduce car use and thus emissions. However, this relationship is not particularly strong. An individual who lives in a municipality with a population density that is twice as high as another municipality, drives an average of 300 kilometers less than someone in the second municipality, according to the relationship we demonstrated in section 5.3. A 30 percent reduction in driving distance corresponds to around 2,000 kilometers per person. Given the estimated relationship, a reduction of 2,000 km per person requires population density to double almost seven times, which corresponds to a hundred-fold increase. Although continued urbanization may, in the long term, form part of climate policy, it does not appear to play a decisive role in achieving the 2030 transport sector target.

In this context, it is important to stress that such a significant reduction in road traffic cannot be achieved by reducing commuting by car in metropolitan areas and instead using bicycles and public transport. City commuters account for less than 5 percent of Sweden's car traffic; other journeys, such as shopping, leisure activities, and service provision account for a much higher proportion of car use than commuting. Car use outside cities is the by far dominant share of car traffic in Sweden. Consequently, in practice, it is impossible to achieve significant reductions in car use in Sweden solely by reducing commuting in cities, quite simply because these journeys make up such a small part of the total.

11.3 The long-term emissions target for 2045

Sweden's long-term national emissions target states that, in 2045, total emissions from the Swedish ESR sector and Swedish EU ETS companies must be at least 85 percent lower than in 1990. Sweden should also be fossil-neutral in 2045, by neutralizing remaining emissions through supplementary measures. Although Sweden accounts for only 0.1 percent of global carbon dioxide emissions, it will set an example by becoming a fossil-neutral welfare state before the middle of this century.

Sweden has provided two political motivations for its climate initiatives and for why the EU should take the lead globally. First, there is a moral responsibility to act in the way you wish others to act; the objective is to influence development in other countries, so they introduce more ambitious climate policies. If Sweden puts its own house in order, there may be greater political will in other countries to not be worse. This is a central idea in the Paris Climate Agreement, which aims to be effective through naming and shaming countries that fail to take moral responsibility for the climate. Progress in other countries may also be promoted by developing new technologies to facilitate the transition of other countries, as the speed of the global transition may increase if change is cheaper. If there are uncertainties about the cost of transition, a country can also do some good by taking the lead and hopefully showing that the transition is not unreasonably expensive (see Graeker, Golombek, and Hoel, 2019, for a detailed analysis of these arguments).

Second, being at the cutting edge of technological developments towards climate neutrality is expedient. Given that the global transition is accelerating, the first countries to make this transition can benefit through greater competitiveness. Sometimes this motivation is clearly expressed, such as in the announcement of Industriklivet, a funding program for processing industry companies to reduce Swedish emissions of greenhouse gases. To be granted funding, projects must 'contribute to greater long-term competitiveness for industry.'

It has rarely been clear which of these two motivations was the reason for individual reforms and it is far from obvious that they lead to the same policy designs. For new technology to have any impact on global emissions, it must be possible for it to be copied quickly and cheaply in other countries. However, strong competitiveness would present reasonable demands for legal or other restrictions on use of the newly developed technology by companies in other countries.

If the aim is to have an impact on global emissions by showing that the transition does not have to be as expensive as others fear, it is vital to formulate policy so that socioeconomic costs are low and clear enough to convince the skeptics. In this regard, it is obvious that Swedish policy leaves much to be desired, as discussed in section 11.4 below. It should also be noted that Sweden has very favorable conditions from an international point of view. If Sweden wants to credibly show that it is taking the lead, it must employ measures other than those based on its very favorable natural resources, such as hydropower and forest assets.

However, the moral influence mechanism does not necessarily have to be based on transferable technology and low costs. Setting ambitious targets for national climate policy and seeking out solutions that deliver emission reductions, regardless of whether they are transferable, may be a way of motivating other countries to do the same. Sweden's vision of becoming the world's first fossil-free welfare state includes that argument in challenging other countries to follow its lead or be first themselves. Therefore, not falling behind the leading country is the motivation for other countries raising their ambitions, but the ways in which that country has chosen to achieve the target do not necessarily have to be transferable to others.

One fundamental problem with the Swedish long-term target for 2045 is that it also includes emissions within the EU ETS. As stated above, the idea of an emissions trading system is that companies that have the lowest costs for reducing emissions do so, while those with higher costs can buy emission allowances. Within the system, this makes it possible to control total emissions and ensure that they occur at the lowest possible socioeconomic cost. Emission allowances are traded between the countries involved in the system, regardless of national borders, so the system has no opportunities for governing in which countries emissions occur. This is not a shortcoming of the system, quite the opposite—it is fundamentally important for the system's ability to deliver cost-efficient reductions in emissions.

The EU ETS means that the EU has full control of emissions within the EU. The scale of future emissions in each country is not governed and is therefore extremely uncertain and, because the Swedish target for 2045 covers both the ESR sector and emissions within the EU ETS, this uncertainty is spread to the ESR sector via communicating vessels. An increase in emissions from Swedish ETS companies not only means that someone else within the ETS has to reduce their emissions, which is the idea of the system, but the formulation of the Swedish target also means that emissions from the Swedish ESR sector have to decrease by the same amount. Consequently, there is uncertainty about the level of emissions that will be permitted in the ESR sector and the costs this will entail.

It is important to note that emissions in a certain country do not necessarily decrease due to a company in that country developing efficient technology for emissions reduction. Assume that production of a certain product leads to carbon dioxide emissions, but that some companies use a technology that leads to lower emissions per produced unit. If a price on emissions is introduced via an emissions trading system, the companies using this technology will be more competitive than other companies. Therefore, even if the emissions price leads to a fall in overall sales, it is entirely possible that the companies that are least emissions-intensive will increase production and thus their emissions. Once again, this is not a shortcoming of the system. It is exactly what is intended. Companies with high emissions are forced out, while those with low emissions can expand.

The analysis above was based on the assumption that Sweden will respect the fundamental principle of the EU ETS and not introduce its own instruments for Swedish companies' emissions within the ETS. However, the national emissions target for 2045 gives

Swedish planners a strong incentive for using instruments to try and reduce emissions by Swedish ETS companies. The marginal cost of emission reductions in the Swedish ESR sector is much higher than the price of emission allowances, and can be expected to remain so. This offers compelling reasons for Sweden to apply further national controls to emissions from Swedish EU ETS companies. It should be noted that such control means that Swedish companies will take emission reduction measures at higher costs than other ETS companies, i.e. it distorts the trade in emission allowances.

One important reservation in the above reasoning is that it assumes that emissions in the EU ETS will not have fallen to zero by 2045. Under current rules, the allocation of emission allowances will end in 2057 and there is ongoing discussion in the EU about additional acceleration in phasing out them out. We hope that this will be the case, and do not exclude this possibility. If this leads to emissions within the EU ETS falling to zero by 2045, then the uncertainty about how much is emitted in the system in Sweden also disappears.

Nevertheless, the conclusion of this reasoning is that the long-term Swedish target for 2045 is problematic; there is a contradiction between the principles of emissions trading and the fact that the Swedish targets include emissions in Sweden within the EU ETS. If this contradiction is not resolved through emissions in the EU ETS being zero by 2045, it needs to be dealt with. The principles for this should be established now, and seen as clarification of a decision made by the Swedish Parliament, the preparatory work for which states: 'The target assumes increased ambitions in the EU ETS' (Government Bill 2016/17:146, p. 125). We see three possible ways forward.

1. Reformulate the Swedish emissions target so that it does not include Swedish territorial emissions within the EU ETS. This could be compatible with the target of making Sweden carbon dioxide-neutral by 2045, if Sweden commits to supplementary measures that correspond to the emissions within Sweden. The cost of this is uncertain and is influenced by the volume of emissions generated by Swedish companies in the EU ETS. However, if supplementary measures were allowed without restrictions, including those in other countries, costs would decrease. Sweden should also advocate for faster reductions in the allocation of emission allowances within the EU ETS, which could reduce Swedish costs.
2. Introduce supplementary control of the EU ETS sector in Sweden, which could be done in various ways. One approach involves general measures, such as imposing a carbon dioxide tax on emissions or subsidizing emission reductions. Another approach might be legislation that requires emission reductions in line with current Swedish climate targets. It is probably also necessary to review permits for new plants and make it possible to deny permits for new businesses that make achieving the Swedish climate targets more difficult.
3. Leave the EU ETS, which would be a radical measure. All companies operating in Sweden would then be subject to Swedish climate legislation, making it possible for Sweden to achieve its targets for emissions in Sweden cost-efficiently. The legal aspects of this would, of course, need to be investigated before such a measure were taken.

11.4 Major differences in costs for emissions reductions

As we discussed in Chapter 5, to avoid the costs of climate policy becoming unnecessarily high, it is important that all emitters of carbon dioxide meet the same emissions price. There are exceptions to this principle, but there should be specific, defined circumstances in which such exceptions are considered. In keeping with this principle, Swedish carbon dioxide taxation has become more uniform over time. It is particularly significant that the once significant reductions in carbon dioxide tax for industrial emissions have largely been abolished.

However, Swedish climate policy consists of a range of instruments besides carbon dioxide tax. In many cases, these instruments are superimposed on each other without the total effect being considered or even calculated. The National Institute of Economic Research (2017b) demonstrates that this leads to extreme differences in the socioeconomic cost per reduced kilo of carbon dioxide emissions. Where fuel choice for passenger cars is concerned, the cost varies from SEK 1,800 to SEK 4,900 per ton of reduced carbon dioxide emissions. One element of these differences arises because reductions in energy taxation on biofuels mean that their use does not cover the costs of road wear and poorer air quality.

As reductions in energy taxation on biofuel contravene EU regulations, they are gradually being replaced by a blend-in obligation, i.e. fuel companies are being forced to blend an increasing proportion of biofuel in their fuels. This solves the legal problem of tax reductions on biofuel and results in the use of biofuel being taxed in such a way that it covers the costs of road wear and poor air quality. Therefore, policy will to a lesser extent be at the expense of poorer internalization of the external costs of road traffic. At the same time, the blend-in obligation means that a certain volume of biofuel will be sold on the market regardless of what this costs, which could be very high if biofuel becomes more expensive to produce than expected.

Current policy also offers strong incentives to choose electric cars. In some cases, the total incentives to choose an electric car instead of an average gasoline-powered car are calculated to be SEK 6,000–7,000 per ton of carbon dioxide that is avoided in the ESR sector. Funding is also available for charging stations through Klimatklivet. The Swedish National Audit Office (2019) showed that the total cost of reduced emissions in the ESR sector from switching to electric cars is SEK 8500 per ton of carbon dioxide. This includes the funding for charging stations, the bonus-malus system, energy tax reduction in relation to diesel, and costs due to both administration and the financing of funding through tax revenues.

11.5 Inadequate incentives to store carbon

In addition to reducing emissions, the increase in atmospheric carbon dioxide levels can be reduced by sequestering carbon from the atmosphere in soil and forests. As we described in Chapter 2, there is a high natural flow of carbon from the atmosphere to soil and forests and in Sweden the net absorption of carbon in soil and forests is high. As mentioned in Chapter 9, in 2017 the net absorption in the LULUCF sector was 43.7 million tons; in 1990 it was 34.4 million tons. These figures should be compared with Sweden's territorial emissions, which were 52.7 million tons in 2017. Consequently, absorption is over 80 percent of emissions. From a policy viewpoint, it is key that this absorption depends on human activities like changed land use and forestry, and is thus affected by financial incentives. The fact that there are currently no financial incentives for increased storage of carbon in soil and forests is therefore alarming. One example of the distortion this causes is that it creates excessive incentives to burn biomass for heat and electricity production. This is exempt from carbon dioxide taxation under the ESR and does not require emission allowances if it occurs within the EU ETS. The idea behind this exemption is that effects on atmospheric carbon dioxide should be managed using incentives to increase and retain the volume of carbon stored in soil and forests. However, this is not the case at present.

Increased sequestration of carbon in forests and soil generates negative emissions and should therefore receive subsidies that equal the price of carbon dioxide emissions. Given a carbon content of around 50 percent in wood, this corresponds to SEK 2,160 per ton of wood if we use the Swedish carbon dioxide tax as the price for negative emissions.[3] There are no such subsidies, with the result that there is a fiscal stimulus for the incineration of biomass, but not for carbon sequestration. As a result, storage levels are too low and emission levels too high.

The weak or non-existent financial incentives for separating carbon dioxide from flue gases using CCS technology (carbon capture and storage) is another area with great potential for reducing Swedish and global net emissions. As mentioned in Chapter 4, with current technology, the cost of CCS is around SEK 1,000 per ton of carbon dioxide. This is not particularly expensive compared to many other Swedish measures to reduce emissions. The equivalent of

3. A carbon dioxide price of SEK 1,180 per ton corresponds to 1,180 x 3.66 ≈ SEK 4,320 per ton of carbon

just under half of Sweden's total carbon dioxide emissions could be eliminated if CCS technology was introduced at the 27 Swedish industrial plants with emissions that exceed 500,000 tons a year (not including co-generation in the energy sector). Roughly 23 million tons of carbon dioxide could be separated from these plants, 9 million tons of which are of fossil origin and 14 million tons are from biomass. The cost of this would vary between roughly SEK 500 and SEK 1,500 per ton of carbon dioxide.

At an average cost of SEK 1,000 per ton, halving Swedish carbon dioxide emissions would cost SEK 23 billion per year. This equals the current revenue from the Swedish carbon dioxide tax, which equates to an annual cost per capita of the Swedish population of SEK 2,300. This appears to be a relatively cheap method of getting halfway to the target of carbon dioxide neutrality. Of course, if the technology were also introduced at large co-generation plants and plants with annual emissions below 500,000 tons, even greater emissions reductions could be achieved.

Storage of the sequestered carbon dioxide would have to be done in Norway, at least initially. This is because there is extensive storage space in the North Sea and specific plans to develop infrastructure for transport and storage. There is also potential for storage in Sweden, south-east of Gotland, but geological surveys are required to establish the area's characteristics and provide a better assessment of Swedish storage opportunities.

CHAPTER 12

Policy proposals

12.1 Clearer link to global emissions

The link between Swedish climate policy and global emissions must be made much clearer. Individual policy components are currently justified by their contribution to achieving Swedish climate targets and, as these targets are formulated for emissions in Sweden, it is often unclear how different parts of policy contribute to global climate benefit. We believe that claiming that reduced emissions in Sweden have an impact on global climate is a legitimate argument, in that Sweden is 'cleaning up its own backyard' and thus setting a good example for others to follow. However, this cannot justify every measure to reduce Swedish emissions. It is sometimes obvious that there is a conflict between Swedish climate targets and global climate benefit, such as when Swedish policy leads to emissions moving from country to country. This occurs under the EU Emissions Trading System or due to leakage mechanisms, when reduced emissions in one country result in a lower world market price for oil and thus higher oil use in the rest of the world.

Swedish climate policy should therefore come with the clarification that Swedish climate targets are intermediary and that their aim is to help the world become climate neutral. Where a conflict between Swedish emissions targets and global climate benefit is identified, the latter should be prioritized. At the Economic Policy Council, we are not in complete agreement about the extent of these target conflicts, but we do agree that they can occur and that the relevant authorities should be tasked with quantifying them.

In the opinion of the Economic Policy Council, the objective of Swedish climate policy should be derived from global climate benefit. This objective is currently entangled with the objective that Swedish industry should be competitive on the global market. Certain funding, for example Industriklivet (Industry Stride), has the explicit aim of enhancing Swedish companies' competitiveness, which risks turning Swedish climate policy into something of a disguised industrial support policy. This is unfortunate, because it can easily lead to irresolvable conflicts between the objectives. Within the framework of climate policy, climate-friendly technology should only be subsidized if it can be assumed to contribute to global climate benefit and, for that to be the case, it must be able to be copied quickly and cheaply by companies and consumers in other countries. Obviously, the technology that best enhances the competitiveness of Swedish companies does not fit this description.

The Economic Policy Council believes that taking the lead in the transition to a green economy can benefit Sweden and Swedish companies. However, this should be seen as a positive side effect and not become the policy objective.

The Economic Policy Council also believes that reports stating that Swedish instruments have become too varied and complex must be taken seriously. As described in section 11.4, there is strong evidence that the cost per ton of reduced emissions varies greatly between societal areas. These differences appear to have limited justification in rational arguments relating to global climate benefit. Instead, they are often caused by overlapping instruments, where no attention is paid to the sum of incentives and costs, leading to unnecessarily high costs. It can be argued that Sweden is a rich country and that the climate is too important an issue for arguments about money. However, our assessment is that Sweden's potential to influence the rest of the world increases significantly if Sweden demonstrates that the transition to climate neutrality can be done at a reasonable cost and with reasonable sacrifices. We are convinced that this is possible, but it requires a greater focus on cost-efficient climate policy than we have seen so far.

12.2 The long-term target for 2045

The opinion of the Economic Policy Council is that the target that Sweden should be carbon-neutral by 2045 should remain in place. Reducing the level of ambition in Swedish climate policy would be both unfortunate and out of step with the fundamental principles of the Paris Agreement. We also believe that this target should be set *without* self-imposed limits on the range of supplementary measures. Measures in other EU member states, where it is possible to ensure that emission reductions actually take place in a reassuring, credible manner, as well as technologies for capturing and storing carbon dioxide, are vital to effective climate policy and should not be limited. Comprehensive action in this area is part of Sweden's ambition to be a leading country. We also believe that if limits on supplementary measures are reduced, it should be entirely possible to increase the ambitions of Swedish climate policy so that Sweden is carbon-neutral much earlier than 2045.

However, there are divergent opinions about this issue on the Council. Council member Åsa Romson is of the following opinion:

Unlike the rest of the Economic Policy Council, I do not believe that Sweden's long-term climate target for carbon neutrality by 2045 should be changed. In section 5.3.1, the Council argues that changing targets risks significantly reducing their instrumental effect. It is also valuable to global climate policy for countries such as Sweden to be able to set a good example and specifically reduce their territorial emissions. Another argument against buying emission reductions in other countries is that acceptance of tax-based investments in climate-smart technologies is probably higher if they are made in Sweden. Investing tax revenue in other EU *member states rather than in Sweden as a basis for Swedish climate policy may be cheaper in the short term, but is not based on—and does not contribute to—a good transition in Sweden. As all countries gradually need to scale down to zero climate emissions, it is also of greater value to the state to invest in Sweden.*

The EU*'s current climate target and undertakings in the Paris Agreement were a political compromise in which the level was kept down by countries that did not agree that faster independence from fossil fuels would benefit* EU *innovation and competitiveness. The discussion in the* EU *has since been about whether it is reasonable to tighten up this target. Ahead of the first round of new undertakings to be made in 2020, the main proposal is also for the* EU *climate target to be tightened. Sweden's climate target reflects both its role as a prime mover in the* EU *for the* EU*'s common* NDC *to be enhanced and its good capacity to reduce emissions at home as Sweden has* *great potential for renewable energy, corporate innovation, and an environmentally aware population. Overall, in my opinion, the weight of these arguments is enough to suggest that the target should not be changed.*

The Economic Policy Council also maintains that the current conflicts between the target for Sweden's total territorial emissions and the EU ETS' principle of borderless emissions are problematic. Although it is possible that these conflicts may cease to exist , if the rate of reduction of the issue of emissions allowances in the EU ETS increases, principles should be established for how the conflicts are to be managed if they do arise. However, we believe that these conflicts can be managed without Sweden's introduction of new instruments aiming to influence Swedish emissions within the EU ETS. Instead, Sweden should commit to supplementary measures that compensate for increased emissions in Sweden within the EU ETS.

If supplementary measures are used to compensate for Swedish emissions in the EU ETS, the costs of Swedish climate policy will depend on the level of emissions within the Swedish EU ETS sector. However, we believe that this uncertainty is limited, because the marginal costs of such supplementary measures will probably not increase as fast as they would if the measures had to occur in Sweden. The costs associated with this uncertainty are an acceptable price to pay, both for being a leading country and for not distorting the EU ETS. The cost also creates an incentive for Swedish politicians to push the EU for a faster reduction in the distribution of emission allowances.

12.3 The separate target for the transport sector

As regards the target for the transport sector, we emphasized above both the potential costs and the value of the target. In the absence of a uniform price for emissions, quantitative targets for individual sectors or regions may be justified under certain circumstances. Sector targets generally imply differential transitional pressure in the form of varied marginal costs for emission reductions from sector to sector. Where the Swedish target for the transport sector is concerned, there is a risk that this problem is particularly significant, as the cost of taking the lead in the transport sector's green transition could be very high. Relative to 2015's emissions, the transport sector must reduce emissions by 66 percent by 2030, while the remainder of the ESR sector only needs to reduce its emissions by 8 percent. This will lead to very unevenly distributed transitional pressure, especially given that emissions in the transport sector are already priced higher than in other sectors. It is quite likely that current policy, including the Swedish carbon dioxide tax, is far from sufficient to create the transitional pressure necessary to achieve the transport sector target.

There is much to indicate significant uncertainty as to whether meeting the Swedish target will generate any additional climate benefit. Due to effects on the world oil market, lower oil use in Sweden will lead to higher use in other countries. The Swedish market is also far too small to drive technical development in the transport sector. If the target is met through electrification in Sweden before power generation in countries such as Germany and Poland has become less fossil-intensive, it will lead to increased emissions in other countries. The climate benefit is also uncertain if the target is met through the use of biofuels, particularly if Sweden continues to import large quantities of biofuel.

It is sometimes stated that the separate target for the transport sector is linked to network externalities, i.e. that the primary reason for the delay in transforming to become fossil free is because no systems for charging electric vehicles have been developed. At the same time, there are no private incentives to build charging systems until there are enough electric vehicles on the roads. In such a situation, the economy may end up in a bad equilibrium. A target for the transport sector could be an effective way out, by coordinating expectations for the equilibrium with electric vehicles. Although this argument is logical, there are, of course, other ways of avoiding this bad equilibrium, for example by subsidizing charging stations. Such funding already exists and may need to be expanded. However, influencing developments in the EU is much more important. Sweden should instead contribute to the European transport system becoming fossil-free as quickly as allowed by the development of fossil-free power in the EU. We should push this development, but not go faster than the rest of the EU. It is difficult to see that the Swedish target for the transport sector is an effective instrument for this.

However, changing a target also comes with costs. Planning has already been based on the existing target, and Sweden's reputation as a role model may suffer. At the same time, similar costs will be incurred if the target is left unchanged but not met.

The opinion of the Economic Policy Council is therefore that Sweden should consider abolishing or reformulating the separate target for the transport sector. However, opinions on this issue diverge among the Council. Council member Jonas Eliasson abstains from voicing an opinion on the issue of whether the transport sector target should be reformulated.

Council member Åsa Romson is of the following opinion:

My opinion is that it would be wrong to consider abolishing the separate target for the transport sector. The framework for Swedish climate policy was adopted after joint analysis by most of the Swedish parliamentary parties, and the climate target and its interim targets were adopted in such a way that they generate confidence in many different quarters of society. In section 5.3.1, the Council discussed how long-term climate targets can facilitate the transition. We emphasized there that targets require stability to be effective. The instrumental effect of climate targets is at risk of disappearing if they are changed just one year after the climate policy framework took effect.

The transport target plays a particularly important role in the climate policy framework and thus for Sweden's contribution to global climate policy, as it stakes out a specific transition in the short term. Transport has high climate impact and is governed largely by sector-specific regulations and societal initiatives (vehicle rules, infrastructure planning), for which reason it is logical for it to be treated separately in the policy. As stronger strategies in all three of these areas would probably produce important societal benefits in addition to reductions in greenhouse gases, for example new industrial development, lower impact on health from poor air and noise, and improved land management with lower construction costs for homes, there are several reasons to promote the strategies. If the transport target is removed or weakened, we would not see the potential for climate benefits or other transport benefits that Sweden has.

In this area, changing the target would reasonably also be interpreted as lowering the level of ambition, which would be the wrong *direction to take, considering the general tightening of climate policy that is needed globally.*

12.4 Carbon capture and storage–CCS

Capturing and permanently storing a ton of carbon dioxide has the same societal value as reducing emissions by one ton. Consequently, properly functioning climate policy should offer the same incentives to both activities.

An emissions price for emissions of carbon dioxide of fossil origin creates an incentive to capture and store carbon dioxide, whether this is based on a tax or emissions trading. This is because capture and storage mean that the emitter need not pay the tax. However, there are no incentives to capture and store non-fossil emissions, for example from the incineration of biomass, as no carbon dioxide tax is levied nor do any emission allowances have to be used. Sweden should grasp this opportunity to lead the way and introduce a price for the capture and storage of carbon dioxide, including capture from biogenic sources of emissions.

The potential for capturing and storing carbon dioxide from large point source emissions (steel industry, co-generation plants, wood and paper pulp plants, and cement production) is huge, both in Sweden and elsewhere. As described in section 6.4.4, the technology for this already exists, and the cost is between SEK 500 and SEK 1,500 per ton of carbon dioxide for a limited number of major Swedish emitters which, together, account for 23 million tons of carbon dioxide emissions. At an average cost of SEK 1,000 per ton, halving Swedish net carbon dioxide emissions would therefore cost SEK 23 billion per year.

In terms of climate benefit, it is irrelevant whether the carbon dioxide captured and stored is of biogenic or fossil origin. There may nonetheless be arguments for Sweden to treat them differently, since emissions of fossil carbon dioxide from large point sources are within the EU ETS, so these emissions are consequently paid for via emissions trading. The current price of emission allowances (around SEK 250 per ton) is insufficient to create an incentive for capture and storage. Swedish funding for CCS might therefore be regarded as distorting the emissions trading system. Although we are not convinced by this argument, it is clear that it does not apply to biogenic carbon dioxide, since it is not included in the EU ETS. Emissions caused by biomass incineration by the 27 largest emitters of carbon dioxide in Sweden total approximately 14 million tons per annum. If only these emissions were captured and stored, the result would be almost the same reduction in emissions as if all road traffic became fossil-free (15.5 million tons). Sweden should therefore introduce funding for the capture and storage of biogenically produced carbon dioxide; there should be legislation to guarantee that its price follows the Swedish carbon dioxide price. There should also be studies of whether this system can be extended to other types of capture and sequestration via forestry and land use.

12.5 Reform of the EU ETS

The opinion of the Economic Policy Council is that the EU ETS is an essential and effective element of EU climate policy. The most recent reforms, particularly a faster reduction in the allocation of emission allowances, are very valuable and quickly resulted in a much higher emissions price, which not only reduces emissions at a European level but also makes it easier to implement a rational climate policy in Sweden. Consequently, a central tenet of Swedish climate policy is to campaign for further tightening of the system.

The system of automatic cancellations of surplus emissions allowances that was introduced in 2018 has effects that are somewhat reminiscent of a price floor. How strong these effects are and how long they will be operative is very uncertain. There are no long-term guarantees that the price will not crash to such low levels that the system will largely cease to have any effect on emissions. This has already happened twice, in 2007 during the system's commissioning period, when the price fell to zero, and in 2013–2017, as shown in figure 23 on page 215.

Such a price crash could be due to the unexpectedly rapid development of alternative energy sources or unforeseen external events, such as a financial crisis. This uncertainty is crippling when the aim is to secure long-term investment to reduce emissions. Sweden should therefore campaign for the introduction of a price floor; it should not be too difficult to persuade other countries to accept a floor slightly below the current price level, perhaps EUR 20 per ton. The price should be raised in line with the nominal rate of increase in GDP in the EU.

One essential aspect of the EU ETS is that it can affect other countries and regions. The fact that a properly functioning system that generates the desired emissions reductions in a cost-efficient manner exists sets both a moral example and a technical example. There is therefore reason to adjust and improve the system along the way, even though there are costs involved in changing an established system to which the involved parties have conformed.

12.6 International agreements

The introduction of a global price for emissions of carbon dioxide would be a cheap and effective way for the world to achieve climate neutrality before climate change has an unacceptable impact. Significant problems, such as companies moving to countries with lower taxation, would be avoided under uniform emissions pricing. It is sometimes heard in public debate that global emissions pricing is a utopian idea and incompatible with national demands for sovereignty over taxation. We believe that this is wrong, and that the main reason for which there has been no global progress on this is that no serious negotiations on emissions pricing have been held as of yet. No agreements need to be drawn up about what the revenue from the pricing of emissions is used for, and Sweden should point out that this means that agreements on minimum pricing for emissions are fully compatible with national sovereignty.

In international climate negotiations, Sweden should therefore focus on trying to establish international agreements on minimum permitted emissions pricing. Important steps in this direction would be to increase the proportion of global emissions that are priced[1] and reduce subsidies for the production and use of fossil fuels. This approach should be taken on the foundation of existing frameworks. For example, it would be quite wrong to dismantle the EU ETS in the hope that an agreement on carbon dioxide tax can be reached. Instead, Sweden should campaign for transparent mechanisms for a price floor and price cap to be introduced in the EU ETS, which supplements the system but does not replace it. In addi-

1. According to World Bank calculations, 11 Gt CO_2 was priced via taxes or emission prices in 2019. This is equivalent to 20 percent of global greenhouse gas emissions. See https://carbonpricingdashboard.worldbank.org/map_data.

tion, Sweden should also campaign in the EU for minimum levels of emissions pricing to be included in negotiations for free trade agreements, which could be one way towards the creation of broad climate clubs with uniform emission prices and adequate incentives to eliminate free-rider mechanisms.

Outside the EU, Sweden should work to ensure that the Paris Agreement is supplemented with commitments to minimum prices for emissions. We should also try to influence the WTO to clearly accept the principle that concern for the world's climate is an adequate reason for tariffs on countries that do not have acceptable emissions pricing.

PART III

SEVEN QUESTIONS

CHAPTER 13

Introduction to the questions

IN THIS SECTION we will answer seven questions to illustrate how we believe the system understanding we described in Part 1 should be applied. We have chosen these questions because they are salient and relevant, and because we believe that they provide good examples of how we think it is possible to apply the systematic approach that we advocate.

The questions are:

1. Can the climate targets of municipalities and businesses contribute to an effective climate policy? If so, how should they be designed?
2. Should climate targets be set separately for different economic sectors, or should all sectors have the same cost pressure on transformation?
3. How effective is climate aid as a climate policy?
4. Is buying emissions allowances and not using them good climate policy?
5. Should Sweden strive to create a surplus of fossil-free electricity for export?
6. Should nuclear power be kept for climate reasons?
7. Should Sweden provide funding for investments in carbon dioxide separation and storage?

CHAPTER 14

Can local climate targets contribute to an effective climate policy? If so, how should they be designed?

14.1 The short answer

Local climate targets can contribute to boosting knowledge and commitment in relation to climate change. Local emissions targets can also facilitate meeting national and EU climate policy targets. Swedish climate policy is largely implemented through the decisions made in municipalities and regions and so, for Swedish climate policy to be realized, it is necessary for municipalities and regions to adapt their planning. Local climate targets can help with this. However, it is essential that local decisions mesh with national planning. Despite this, many local climate targets are formulated in such a way that they inadvertently counteract the national targets. In other words, local targets can contribute to effective climate policy but, if they are to do so, those who set them must pay far greater attention to their effects on emissions outside the area for which those targets are set than they do at present.

Where there are political demands to do more than implement national climate policy, the way the local targets affect emissions outside the local area should be analyzed and, even though it is difficult to perform such an analysis accurately, it should be relatively easy to distinguish between measures that are expected to have desirable effects and those that are not. Efficiency-focused urban and transport planning, the development of charging infrastructure and a generous approach to providing suitable land for wind turbines are among the former, while the latter include municipality-specific energy standards, biofuel subsidies, requirements for 'green electricity,' and similar funding for renewable power generation and targets for emission reductions within the municipality.[1]

14.2 Background

Many municipalities and regions, as well as companies and organizations, have set their own climate targets. These vary: most municipalities and regions have targets for emissions generated in their geographic area, and a few have targets for consumption-based emissions; some are targets per inhabitant, others concern total emissions; some have targets for all emissions in their area, while others have targets for specific sectors.

Most municipalities' targets or measures focus on reducing emissions within the municipality from energy provision, heating buildings, transport, and various types of consumption-based emissions from their own organizations, such as school meals, travel, and transportation.

---

1. Council member Åsa Romson is of a different opinion on this issue. See the final section of the chapter.

The question is whether such targets can contribute to a climate policy that is adequately effective without unnecessary costs and, if so, how.

14.3 Policy objectives

The overall objective of the policy is to reduce global emissions and thus limit climate change. The intermediate objective of the policy is to reduce emissions within a geographic area. In our analysis, we ignore objectives that do not concern the climate issue, which could be to improve the municipality's image or to favor specific political or economic interests.

14.4 Analysis

Local climate targets are one way of demonstrating commitment to the climate and to an ambitious climate policy, and can contribute to increased commitment and knowledge. Consequently, the mere existence of a local climate target may have a positive effect. To achieve a more direct impact on climate change, however, the essential factors are how the targets are formulated and the measures taken to meet them.

It is easy to find examples of targets that reduce local emissions, while emissions in a wider area (Sweden, the EU or globally) remain unchanged due to compensation and leakage mechanisms (see Chapter 4). There are also examples of the reverse: measures that, while not reducing *local* emissions (or even increasing them), may still serve to reduce emissions in a *wider* area.

Local targets must not exclude or counteract the latter measures. Where local measures are assumed to work through a demonstration effect, it is also important for them to be scalable, which means they can be copied by others; any newly developed planning or technology must be usable by other cities or countries. For example, Swedish waste management, urban planning, and transport planning are often cited as good examples internationally, and are scalable measures in the sense that other countries can imitate them.

Another example of a scalable measure is the development and implementation of methods for capturing and storing carbon dioxide (CCS, see section 6.4.4), which could lead to the cost of CCS methods falling for those who subsequently use them. If the cost of a measure, in any sense, decreases for subsequent users, there is positive externality from pioneers to followers, and such measures have the potential to provide considerably greater climate benefit than the 'visible' benefit in the organization's own emissions. However, the transport sector's use of biofuel is a measure with doubtful scalability, since the supply of biofuel is severely limited on a global scale.

Local climate targets can therefore be problematic in three ways:

1. If they lead to the implementation of (expensive) measures that reduce local emissions, but not the total emissions in a wider area.
2. If measures that affect total emissions in a wider area are not implemented because they do not affect local emissions.
3. If no consideration is paid to whether measures are scalable or have positive externalities.

Our assessment is that a large proportion of local climate targets are formulated solely to reduce emissions in the local geographic area, with no consideration for the three points above.

Simply formulating targets solely in terms of local emissions resembles the way in which the Paris Agreement is structured: each country or group of countries is responsible only for their own emissions. However, it is important to realize that individual municipalities or organizations do not separately report their emissions reductions under the Paris Agreement. They do so as part of something bigger which, in Sweden's case, is the EU.

Consequently, from the point of view of the Paris Climate Agreement, local climate targets must help reduce total EU emissions, or at least Swedish emissions, to be relevant.

The conditions for climate-smart solutions and low emissions may often be better in urban areas. If people live there, instead of in more sparsely populated areas, demand for emissions may fall and it may be easier to achieve national emissions targets. However, a municipality's own emissions do not need to decrease if this strategy leads to an increase in the municipality's population. This is a general problem with local climate targets, particularly if they are expressed in total emissions instead of emissions per inhabitant. Or, put differently: it is, of course, good for national emissions if municipalities with low emissions per inhabitant (which primarily involves climate-efficient heating and low vehicle use) increase their population in relation to municipalities with high emissions per inhabitant. However, such a development may conflict with the growing municipality's own local climate targets. These are more difficult to meet if the population increases. Local climate targets expressed as reductions in total emissions therefore risk doing more harm than good.

It is difficult to perform a complete analysis of the effects on emissions beyond the boundaries of a municipality and this will not lead to exact results. Nevertheless, we believe that it is possible to distinguish between measures based on their expected contribution to emissions reductions in a wider area. We go through a few such examples below.

14.4.1 Fossil-free electricity generation

If Sweden increases its fossil-free electricity generation, it can be expected to reduce total EU emissions as Swedish electricity exports increase, thus displacing carbon-based electricity in importing countries. After the 2018 reforms of the EU ETS, total EU emissions from electricity generation then fall, at least if the reductions take place while a surplus remains in the system, and the cancellations do not lead to more emissions being permitted in the ESR sector. Even if this does not reduce Sweden's emissions, the measures contribute to reducing global warming and to meeting the EU's obligations under the Paris Climate Agreement.

However, a single municipality or region cannot affect the total volume of fossil-free electricity, excluding nuclear power, that Sweden generates, as this is controlled by the Electricity Certificate System, which has operated in Sweden and Norway since 2012.

In brief, electricity certificates work as follows: those who want to sell non-renewable electricity must buy a corresponding quantity of electricity certificates, and these certificates are distributed to those who generate renewable electricity from wind-, hydro-, and solar energy. Consequently, producers of renewable electricity receive additional income from certificate sales, a sort of cross-subsidy from non-renewable electricity to renewable electricity. The price of electricity certificates is set so that the volume of renewable electricity generated meets predetermined targets. If there is a large number of renewable electricity producers, the certificate price falls, and vice versa.

A municipal energy company's decision to generate renewable electricity although it is not financially profitable, considering the investment and operating costs, demand, electricity price, and certificate income, results in a consequential reduction of the certificate price. As a result, other producers of renewable electricity will reduce their production—since they will be paid less for it—precisely to the extent that total generation of renewable electricity in Sweden does not change. However, the total electricity price, including certificate costs, will fall for all consumers so that the municipal electricity company will have subsidized the electricity price for all Swedish consumers. One significant impact of the subsidy is that generation of renewable power is distorted. Inefficient generation is subsidized and more efficient generation is forced out.

However, municipalities can and should contribute by helping reduce the actual costs, apart from subsidies, of renewable electricity generation. They could do so by facilitating the establishment of such electricity generation. The problem currently is that many municipalities oppose wind power instead. The municipal veto stops half of wind turbines before they even reach the environmental impact assessment stage (Dagens Samhälle, 2017). Recently, for example, Kristianstad rejected an offshore wind farm although it could have reduced emissions by twice as much as total emissions in the municipality. This approach may, ultimately, make it difficult to meet the renewable electricity generation target.

Municipalities with their own energy companies can also contribute to the development and implementation of CCS (carbon capture and storage) technology, for example by fitting CCS at their combined heat and power plants. This would both help reduce total net emissions in Sweden and the EU and be an extremely scalable measure as experience and technological development can be used worldwide. However, as discussed in section 11.5, there are still no market mechanisms to make this financially profitable.

Municipal targets should therefore be formulated in such a way that they facilitate the establishment of fossil-free power generation and cause the actual costs of such generation to fall. However, subsidies and emissions targets for the municipality's own power generation are not the right way to go.

14.4.2 Heating buildings

Energy requirements for new buildings, in addition to what the developer would voluntarily fulfill for financial reasons, lead to higher construction costs. They must be related to the expected future reductions in emissions. It is conceivable that the developer will not be adequately remunerated for building an energy-efficient building if the buyer does not adequately take into account the present value of future heating costs. If this is the case, it could justify rules for energy consumption.

However, such rules should not be introduced at the municipal level, as having different rules in different municipalities leads to unnecessarily high construction costs when construction methods and materials cannot be standardized and used in many different places. However, the opportunities for the housing and service sector to help reduce climate impact directly are limited, as energy supply for these uses is already largely carbon-free. Consequently, it is often difficult to justify energy efficiency measures purely on the basis of their climate impact. On the other hand, the focus on the climate impact of new construction has greatly increased, although emissions largely occur in the production of base materials (cement), i.e. in the sector covered by the EU ETS emission market.

14.4.3 Transport planning

The Swedish national target for reduced emissions from transport is based both on a transition to electricity and biofuels and on a reduction in overall road transport. Consequently, municipalities can contribute to meeting the national target by means of urban and transport planning to reduce road transport and by supporting the transition to electric vehicles and biofuel vehicles in various ways. However, central government has the most effective and efficient instruments at its disposal: fuel taxes, vehicle taxes, rules for travel deductions, and company car taxation, charging infrastructure along the national road network, etc.

Decisions made in municipalities and regions about urban planning, transport planning and public transport do have an impact on total road transport, though. Good urban and transport planning often causes a reduction in road transport, for example through efficient public transport, attractive urban environments, and physical planning to reduce the need for vehicle use. The state influences municipal planning through state regulations and taxes in the transport sector. It seems reasonable that municipalities and regions should not only adapt to these instruments but also contribute to the implementation of effective climate policy in other ways. However, this assumes that local decisions mesh with state policy. A municipality or region might also want to do more than contribute to the implementation of state climate policy. If the aim is to have an impact on total emissions, national or global, it is essential to analyze how local decisions affect them.

Despite this, as far as we know, no municipalities or regions have formulated climate targets that take account of whether the *national* emissions are actually reduced by the measures they take. Let us take a specific example. Stockholm aims to reduce total emissions within its boundaries, partly by reducing road transport. However, vehicle use per person is low in Stockholm, much lower than in most other municipalities in Sweden. This means that, if people move from other municipalities to Stockholm, national emissions are very likely to fall, while emissions in Stockholm increase. An emissions target in Stockholm therefore does not mesh with the national targets and even risks working against them. However, if the target were formulated as reduction in emissions per inhabitant, inward migration would not have a negative impact. It would be even better to have a target that took account of how total national emissions are affected by inward migration.

This is not an insignificant question. Instruments such as higher fuel taxes stimulate relocation to areas with lower vehicle use per person, i.e. primarily to the centers of large cities. And relocation is responsible for a non-negligible part of the effect these instruments have on traffic reduction. Therefore, it is important to prevent local targets from continuing to work against the overall targets.

14.4.4 Biofuels and electric vehicles in own vehicle fleets

Many municipalities and regions promote biofuel vehicles in various ways as part of their climate initiatives, for example by running buses, their own vehicles, and machines with biofuels or by requiring biofuel in procurements. However, the problem is that it is mainly the supply of biofuels that is lacking, not demand. Higher demand may, however, make it more profitable to increase biofuel supply by establishing new installations. In this way, municipal demand stimulus may contribute to reducing national emissions.

And if municipalities produce biofuel, thus increasing total biofuel supply, there may be a net reduction in emissions at national, European and global levels, provided that this displaces fossil fuels, which is unfortunately not a given. If oil supply elasticity is low, oil consumption simply moves to other countries outside the EU (see section 4.3.1). Local biofuel subsidies are therefore difficult to justify.

Municipalities can stimulate demand for electric vehicles by developing the public charging infrastructure and through various types of benefit, for example dedicated parking spaces for charging. In Norway, electric vehicles are also permitted to use bus lanes. It is too early to know the effect of such measures on electric vehicle demand, but experience from Norway and from the congestion charge exemption for green cars in Stockholm, in place 2006–2012, indicate that they may have some impact. Such measures may therefore permit municipalities to help reduce national emissions from the transport sector. In section 12.3, we argued that the national target is not well formulated. However, the task of the municipalities is, arguably, to help meet national targets.

14.5 Conclusions

The responsibility for Swedish climate policy lies at the level of central government. However, this policy is largely implemented by decisions made in municipalities and regions. The effectiveness of

Swedish climate policy therefore depends on these local decisions meshing with central government planning. Despite this, many local climate targets are formulated in such a way that they may even work against the national targets. One example is a target for reduced emissions within the boundaries of the municipality instead of a target for emissions per person.

Where there is political demand to do more than just implement national climate policy, an analysis of how the local targets affect emissions at a higher level is required. Although it is difficult assess the exact effects, it is relatively easy to distinguish between measures that probably have a desirable effect and measures that probably do not. The former include urban and transport planning designed to reduce transport, development of charging infrastructure and a sympathetic approach to wind turbines. The latter include municipality-specific energy standards, biofuel subsidies, requirements for 'green electricity' and similar funding for renewable power generation and targets for emissions reductions within the boundaries of the municipality.

On this issue, divergent opinions are represented on the Council. Council member Åsa Romson is of the following opinion:

> *Swedish municipalities' local climate targets must be analyzed based on the resources available to the municipalities and what tools the municipalities can develop to contribute to the long-term climate transition of the local community. Areas that are particularly strategic from a climate perspective are that the municipalities' planning monopoly largely determines the development of transport in urban areas, and, as the contracting authority, the municipal sector also controls the market for climate-smart products and services, and the municipality can contribute to*

important system gains in energy systems. In my opinion, it would have been more interesting, in the report, to analyze whether there is a shortage of clear rules that municipalities must promote a sustainable, climate-smart community, and whether municipalities have adequate tools to perform such work effectively. Swedish climate targets may be more difficult to achieve if the municipalities do not work within their areas.

I also believe that it is incorrect to conclude that municipal climate targets aiming to reduce emissions in absolute terms impede climate-smart urbanization, and think it is difficult to see such targets as a problem for climate policy. The situation is rather that the active work on climate issues by several municipalities meant that there was a driving force in Sweden that resolved opposing party-political interests and led to a more ambitious climate policy at national level.

CHAPTER 15

Should emissions targets be set separately for different economic sectors, or should all sectors have the transformation pressure?

15.1 Quick answer

Sector-based emissions targets will, in practice, lead to different marginal costs of emissions reductions and thus to different transformation pressure in different sectors. The more long-term and inflexible the targets are, the higher these differences tend to be. They therefore lead to less emission reduction for a given cost.

For sector-based targets to be justified, therefore, such differences in transformation pressure must generate values other than the direct emission reductions. In addition, it must be difficult or impossible to achieve these values in other ways. Examples of such other values are if emission reductions in a specific sector generate the development of new technologies or have particularly adverse distributional consequences for the population. If such technological development cannot be stimulated in any other way and means to compensate for the adverse distributional consequences are missing, arguments for sector-based targets can be made. We do not believe that these conditions exist with respect to the interim target for the Swedish transport sector.[1]

15.2 Background to the question

If maximum emissions reduction is to be achieved for a given transformation cost, it is necessary for the marginal costs of emissions reductions to be the same regardless of the sector of the economy in which they are achieved. Differences in costs between sectors are therefore an indication that larger emissions reductions could be achieved at the same cost. In Sweden and the EU, the understanding of this has led to emissions trading and carbon dioxide tax being the central components of climate policy. Such systems lead to the marginal costs of emissions reductions being equalized within each system, since all emitters pay the same price for emissions. However, there are significant departures from this. Within the EU, emissions trading covers roughly half of emissions. In Sweden, the climate framework for 2030 indicates a specific target for the transport sector and an interim target of minus 70% for the sector that is not subject to the EU ETS. The question is whether such departures are justified.

1. Council member Åsa Romson has a divergent opinion on this issue. See the last section of the chapter.

15.3 Analysis

The transition to climate neutrality means that emissions of greenhouse gases must eventually decrease to near zero everywhere. Consequently, emissions must also decrease radically in virtually every area of activity. One way of ensuring commitment to an intangible global target may be to divide it up into tangible sub-targets. This applies both geographically and sectorially.

This strategy certainly has its merits. However, it is also easy to give arguments against sector targets. Climate concerns do not require that emissions decrease at exactly the same rate in all sectors. A transition to long-term sustainable technology may generate significant emissions during the transitional phase. Sector-based targets obviously risk conflicting with potential needs for a different rate of emission decrease in different sectors. They may then lead to excessive costs, which risk making the transformation so expensive that it is difficult to gain political acceptance for it.

It is worth mentioning one case in which this argument is not applicable, namely when a rapid total ban on the use of a certain product or technology is the appropriate policy. However, this is clearly not the case when it comes to the emission of greenhouse gases and the use of fossil fuels.

Sector-based targets must be determined before emissions occur and their costs are realized. Consequently, in practice it is impossible to set them so that the costs of marginal emissions reductions are the same in all sectors. The extent of the differences is influenced by how far in advance the targets are set. There is a risk that, if targets are many years in the future, they will lead to very large differences in costs and to the total emissions target being achieved at much higher costs than if a target or price were set for the entire economy.

In practice, it is impossible to avoid sector-based targets for emissions reductions leading to differences in transformation pressure[2] in different sectors. The arguments for sector-based targets must therefore be based on such differences being good or at least acceptable. It is possible to argue that the value of emissions reductions is not always the same in all sectors. However, for this to be the case, there must be values of the emissions reduction other than the direct values, i.e. the effect of the emissions reduction on the climate. In addition, there should not be other, more effective ways of achieving these values.

If emissions reductions in a certain sector are made through technological innovations that can be spread to other users within or outside the sector, such emissions reductions have higher value than otherwise. In principle, the values that arise through such technological development could be achieved through technology subsidies. However, it is possible to imagine situations where it is difficult to design such subsidies, in which case it could be justified to have a higher transformation pressure. A similar reason is if emissions reductions in a certain sector have a special demonstration value, whether real or symbolic.

Another example of where emissions reductions create other values is if the redistributional consequences of the transition to climate neutrality vary from sector to sector, or differ across geographic regions. Emissions reductions in one sector could, for example, lead to costs for mainly high income earners, while the opposite is true in another sector. Given a desire to transfer resources from high

---

2. The term transformation pressure does not have an exact definition. Loosely speaking it is the (marginal) cost increases incurred by a sector or a firm due to climate policy. When policy only takes the form of a tax on emissions, transformation pressure can be interpreted as the level of this tax.

income earners to low income earners, the economic cost of emissions reductions is therefore lower in the first sector. However, for this to justify a higher transformation pressure in the sector, it is necessary for the redistribution to be unachievable in any other efficient way. Thus, in the EU, different member states are subject to different targets for emissions reductions. Richer countries are obligated to do more. However, trading in emissions reductions between countries is permitted, which means that the transformation pressure can be evened out while the distribution policy targets are achieved. Within countries, it appears reasonable to assume that there are mechanisms for compensating adverse distributional consequences of a uniform transformation pressure. If this is the case, this argument for sector-based targets ceases to apply.

That redistributional concerns may lead to departures from the principle of uniform transformation pressure not only applies to the case where the concern focuses on individuals with low incomes. Individuals and firms in certain sectors may sometimes be able to block effective climate policy if their profits are reduced by climate policy. Setting lower requirements in these sectors could make an ambitious climate policy politically feasible. Again, however, there are typically other ways to placate blocking political interests. For example, a large number of emissions allowances in the EU ETS are given free to companies with large previous emissions. This reduced their interest in blocking the introduction of the system without actually reducing the transformation pressure on these companies. On the margin, the value of reducing emissions is given by the price of emission allowances, even if a company has been given them for free. By reducing emissions, the firm that was given the allowances can sell them on the emission allowance market.

Another argument for sector targets that is sometimes presented is that they may be effective in stopping the economy from getting stuck in a bad equilibrium. The transition to electric vehicles is an example where this reasoning may be applied. The logic is that people need a system of charging stations before they will buy electric vehicles. However, if no one has an electric vehicle, there are no private driving forces behind developing such a system. There are two market equilibria here. One is that no one buys electric vehicles and no charging stations are built. The other is that everyone buys electric vehicles, which creates sufficient demand for it to be profitable to invest in charging stations. The market does not provide a mechanism for everyone coordinating on the second (good) equilibrium. However, a sector target for emissions in the transport sector could be one way of eliminating the first equilibrium so that the second is achieved automatically.

Sweden has only one sector target for emissions reductions. It applies to the transport sector and is for this sector's emissions to fall by 70 percent by 2030 in relation to 2010. This is a much larger reduction than that required in the other sectors in Sweden. According to calculations in the Swedish National Institute of Economic Research (2017b), new policy needs to be introduced because current policy only reduces transport sector emissions by half of that required by the target. For the remaining sectors, on the other hand, existing policy is sufficient. Given these calculations, the Swedish target for the transport sector will lead to very large differences in transformation pressure across sectors with a much larger pressure in the transport sector than elsewhere.

We are not convinced by the theoretical argument that a target can permit a fast, easy transition on account of network externalities which, without a target, could lead to bad equilibria, as discussed above. There are such externalities in relation to the transport sector. However, there are other efficient ways of managing them, for example by subsidizing charging stations. Such subsidies already exist and may need to be increased. The transition to a green transport sector also needs to be coordinated within the EU if it is not to be excessively costly. Furthermore, it is not clear that battery technology will dominate alternative technologies, for example those based on hydrogen. The risks of ending up at a dead end are lower under a coordinated EU transformation than if Sweden chooses technologies on its own. In addition, unlike Sweden, the market within the EU is sufficiently large to drive technological development. Sweden should therefore make the transition in step with the EU but insist that this transition should be fast.

15.4 Conclusions

Arguments for sector-based targets must be based on the fact that deviations from the principle of a uniform marginal cost of emissions are desirable or at least acceptable. For this to be the case, it is necessary for values to exist other than the direct emissions reductions and that they cannot be achieved in any other way. Examples of such values are avoiding the relocation of industry outside the jurisdiction in which the policy applies, or the redistributional consequences of a uniform policy that cannot be managed otherwise for legal, political or other reasons. In practice, these conditions are rarely met and sector-based targets should therefore be avoided.

Divergent opinions on this issue are represented on the Council. Åsa Romson is of the following opinion:

I believe that different sectors in society should sometimes have different transformation pressure at different times. Sector targets are a good way of managing such differences. Placing greater responsibility for emissions reductions on the transport sector in the near future makes clear that other emissions in the non-traded sector such as agriculture are subject to less transformation pressure and therefore this sector has longer to achieve zero emissions. I also believe that it may well be relevant to introduce a ban on the use of fossil technologies and fuels in the transport sector, for which reason the sector-based approach is logical.

CHAPTER 16

How effective is climate aid as a climate policy?

16.1 Quick answer

It is difficult to assess the effects of climate aid with any degree of precision. However, available studies show that Swedish climate aid to date has reduced emissions at a cost that is much lower than average costs of emission reductions in Sweden. Many poor countries have also made their plans for emissions reductions conditional on foreign financial aid. There are thus strong arguments for climate aid. However, effective climate aid is much more complicated than just "sending money." Consequently, it cannot grow too fast, nor should climate aid be counted as part of the foreign aid budget as, if targets are mixed up, the result is often that none of them is achieved. As Sweden also needs to become climate-neutral itself, a higher budget for climate aid should not reduce the level of ambition of Swedish climate policy.

16.2 Background

In most of the world, climate policy is less ambitious than in Sweden. Almost by definition, this means that the marginal costs of reducing emissions are lower in other countries. This is particularly true in developing countries which, for various reasons, have not come so far in the transition to climate neutrality. Major studies such as *Stern Review* (Stern, 2006) have established that there is great potential for cheap emissions reductions in poor countries.

Sweden has also been financing climate projects in developing countries for many years. In 2001–2018, for example, the Swedish Energy Agency spent SEK 1.5 billion financing such emissions reductions. According to the agency, this resulted in emissions reductions of 22.5 million tons of carbon dioxide (Swedish Energy Agency, 2019e). The average cost was therefore around SEK 70 per ton, which is much lower than the Swedish carbon dioxide tax of SEK 1,180 per ton and also less than one third of the current price of emissions allowances in the EU ETS. Climate aid has become an increasingly important part of bilateral aid, including from Sweden. However, it is also well known that climate projects in developing countries can go wrong. Emissions reductions may be lower than planned and there may be undesirable side effects.

16.3 Objective of policy

The aim of climate aid is to contribute to effective climate policy, both by achieving cost-efficient emissions reductions in other countries and by making it easier for countries with more limited economic resources than Sweden to undertake the transition to climate neutrality.

16.4 Analysis

Given that the cost of emission reduction is low in developing countries, there are obvious arguments for climate aid. There are also several arguments for climate aid generating values other than the direct emissions reduction:

1. Climate policy must be global to succeed. In poor countries, there is a significant risk that it is not possible to prioritize long-term, complex issues like climate without external aid.
2. Poor countries tend to be hit hardest by climate change. Climate aid can have positive side effects, for example by improving energy supply and the local environment or simply by freeing up resources for other purposes in the recipient country.
3. In the international climate agreements, the richer countries have assumed responsibility for contributing to the transition in poor countries. Several poor countries have also made their measures to reduce emissions conditional on receiving financial help. In addition to the direct value of Swedish climate aid, we can also hope that we are contributing to the provision of more climate aid by example.

In the public debate, arguments like the ones above are sometimes used to suggest that Swedish climate policy should be changed completely and mainly focus on climate aid. For a number of reasons, we believe that this is entirely the wrong approach.

Firstly, Sweden also needs to become climate-neutral, which requires an ambitious domestic climate policy. Secondly, the difficulties of actually achieving emissions reductions in other countries are often underestimated. It is presumably true that, if Amazonian forest owners were paid an amount equivalent to the Swedish carbon dioxide tax for the carbon dioxide captured in their trees, the financial incentives for deforestation would disappear. However, given the social, legal and other conditions, it is not as easy as just "sending money" to achieve a functioning system for such payments in another country. Thirdly, a Swedish policy change risks leading to a reduction in the level of ambition in our climate policy at the same time as climate aid will not increase by much.

We also believe that we need to be careful about justifying climate measures with claimed positive effects on development and welfare in the recipient country. Such side effects do occur, but it is not reasonable to assume that climate aid is automatically also good aid policy. It is a lot to ask of a project that it should be both effective at reducing carbon dioxide emissions and, at the same time, reduce poverty. Köhlin et al. (2015) contains a summary of evaluations in two important areas, forestry and household energy, to document target achievement there. The report confirms the impression that an increasing proportion of aid is going on climate initiatives and that too few evaluations are being made. It does find a number of positive examples, but emphasizes the problem that aid is governed more by the preferences of the donor than those of the recipient. It recommends solid evaluation so that future climate aid can be based on scientific evidence of both climate benefit and welfare improvements. The evaluations must take account of local characteristics in the economy, culture and biotopes and be of high scientific quality. They must be interdisciplinary and should preferably involve many local researchers to ensure legitimacy and understanding of local conditions and to make it possible to incorporate the results in local political practice.

As with all aid, it is important to find good projects and countries to work with. Aid is governed in part by historically established channels with certain recipient countries. However, this has changed a great deal in recent years. In relation to climate aid, most of the ideas that run through this report remain central. It is necessary to think at the system level. For example, helping countries to increase their capacity to analyze and execute policy in the climate field is a good idea. Many developing countries lack the capacity to analyze the climate-related, economic and political consequences of the global climate change that will threaten them and for which they need to prepare. In many cases, they find it difficult even to participate fully in the international negotiations on the IPCC, the UNFCC, and in other forums that are so important to their future.

A number of countries have shown great interest in and positive commitment to the climate negotiations. Ethiopia is one example, which has also been one of Sweden's major partner countries for many years. Ethiopia's undertakings under the Paris Climate Agreement are very far-reaching. Very briefly, its objective is to grow very fast economically to become a medium-income country, but without increasing its emissions of climate gases.

16.5 Conclusions

There is substantial reason to believe that emission reductions in other countries are cheaper than in Sweden. The potential for Swedish aid to produce significant emission reductions is therefore high. Climate aid can also produce other benefits, such as contributing to economic development and to less injustice between poor and rich countries. In their climate plans, many poor countries have stated that they need foreign economic aid, which creates strong arguments for increasing Swedish climate aid. However, it is also obvious that climate aid is much more complicated than just "sending money." Consequently, the climate aid budget cannot increase too fast. In our opinion, it is also unwise to take increased climate aid as a pretext for lowering the level of ambition of Swedish climate policy.

CHAPTER 17

Is it good climate policy to buy emissions allowances and not use them or to influence emissions in the EU ETS in some other way?

17.1 Quick answer

Following the 2018 reform of the EU ETS, buying and immediately cancelling emissions allowances most likely has little or no effect on emissions of carbon dioxide or on the price of emissions allowances. The reason for this is that the number of new emissions allowances created in the system will automatically be adjusted upwards after any such cancellation and thus largely negate the emissions reduction.

Emissions reductions could be achieved if one were to buy emissions allowances and wait to cancel them until the surplus of saved emissions allowances in the EU was exhausted. However, this could take quite some time. According to calculations by the Swedish National Institute of Economic Research and other researchers, a reasonable forecast is that surplus exhaustion will occur sometime between 2030 and 2050. Purchases with delayed cancellation would reduce emissions under the current rules. However, the emissions reduction would be spread out over a long time scale and mainly occur several decades into the future. As climate change is governed by the volume of emissions accumulated over time, this spread need not be of any disadvantage to the climate. Political aspects such as the need to show that policy has effects on emissions in the short term may, however, mean that spreading emissions reductions over time is worse than measures with more direct effects.

17.2 Background to the question

The EU Emissions Trading System (EU ETS) covers just under half of emissions of carbon dioxide in the EU and means that companies in the system must supply one emissions allowance to the EU for every ton of carbon dioxide they emitted in the previous year. Major emitters in the industrial, power, and heating sectors are in the EU ETS, while the transport sector is one of those that is not. A certain number of emissions allowances are issued every year, 43 percent of which are issued free to emitting industries. The argument for issuing emissions allowances free of charge is to reduce the risk of companies moving to countries outside of the EU that have less restrictive climate policy. The remaining 57 percent are auctioned off, and the income flows back to EU Member States. The EU ETS permits the EU to manage the volume of emissions of carbon dioxide within the system. There is a market for trading in emissions allowances, which means that there is always a price for emissions allowances. This price is also the price for emitting carbon dioxide for all companies in the system. Holders of emissions allowances may save them for future use. One consequence of this is that the price depends on expectations of the future. (See section 7.3.1 for more about the EU ETS.)

The EU ETS has been a feature of the debate about Swedish climate policy for several reasons. One is that in 2016 Sweden decided to buy emissions allowances in the EU ETS to then cancel them.[1] The price of emissions allowances is low in relation to many measures to reduce emissions in Sweden. Buying and cancelling emissions allowances could therefore be a clever way of achieving the greatest possible reduction in emissions per krona invested. However, does it work after the reforms of the system that were introduced in 2018?

17.3 Objective of policy

The objective of buying emissions allowances and cancelling them is to reduce global emissions of greenhouse gases. As the price of emissions allowances is relatively low, this could be done at low cost. The reduction would occur as a result of the cancellation increasing the price of emissions allowances, which also has indirect effects on emissions via technical development and transformation. Given that reduced emissions in the EU actually reduce total global emissions, the objective is in line with the general objectives of climate policy. As the cost of the policy is borne by taxpayers via their tax assessments, the distribution policy consequences are small. The risk of conflict with other objectives is relatively low.

1. The decision was rescinded in 2018 before it took effect.

17.4 Analysis

The basic principle of the EU ETS is that, every year, the companies involved must report their emissions volume during the year and supply emissions allowances corresponding to these emissions. A certain number of emissions allowances are issued every year. Each of these entitles the holder to emit one ton of carbon dioxide. The number issued is reduced by a specific number every year. In 2018, it was decided to increase this rate of reduction from 2021: 48 million fewer every year instead of 38 million before. The new annual reduction roughly corresponds to Sweden's current annual emissions, and, if it continues, no emissions allowances will be issued after 2057. The higher rate of reduction means that approximately 9 billion fewer emissions allowances will have been issued by the time they stop being issued.

A central feature of the EU ETS is that emissions allowances may be bought and sold on a well-functioning market. This is similar to a stock exchange, with a price that is constantly determined by supply and demand. If two companies in the system have different costs for reducing their emissions, the company with the highest cost will want to pay most for the emissions allowances. Companies that have lower marginal costs for emissions reductions than the price of emissions allowances will want to reduce their emissions rather than use emissions allowances.

Consequently, the system leads both to the total volume of emissions being limited and to emissions reductions taking place at the lowest possible total cost. The latter would not occur if each company were awarded a certain number of emissions allowances but could not sell them or buy more. In such a system, the costs per ton of emissions reduction would differ between companies and thus not be the lowest possible cost. Leaving it to the market to distribute emissions reductions ensures that they take place in a cost-efficient manner.

Another central feature of the system is that anyone who holds an emissions allowance may save it for use or sale at a later time. There are currently saved emissions allowances on the market equivalent to approximately one year's emissions in the system. One important consequence of the ability to save emissions allowances is that the companies in the system are able to decide themselves what constitutes cost-efficient distribution of emissions reductions over time. If a company has high costs now but will have lower costs in the future, it can decide to make higher emissions reductions in the future. In this way, the regulator leaves it to the market to decide when emissions will occur. The balance of the emissions allowances market leads to the price of allowances rising over time so that holders receive a market return on their saved emissions allowances.[2]

One effect of the existence of saved emissions allowances is that, if the volume of emissions allowances issued is reduced, the emissions reduction can be spread over the entire time for which there are saved emissions allowances in the system. Under reasonable conditions, it will also be in the interest of companies to do this.

Suppose that that the system was designed so that a specific number of emissions allowances were issued every year. A state or any

---

2. However, with a reasonable estimate of what emissions allowances will be worth when the current surplus is exhausted, the current low price means that market operators require a quite high expected return to save emissions allowances, perhaps 7–10 percent (Silbye and Sorensen, 2019). One explanation may be lack of faith in adherence to the system's rules if the price increases dramatically. The result is that emissions reductions will probably occur later than when they would be best in terms of the economy. However, given that the volume of saved emissions allowances is currently at the order of one year's emissions, this effect is not large.

other operator would then be able to reduce emissions in the system by buying and cancelling emissions allowances. The emissions reduction would be spread out over the time for which there were saved emissions allowances in the system. The system was designed in this way until 2018, when an important change was introduced. This meant that the number of emissions allowances issued from 2023 will depend on how many saved emissions allowances there are. As long as there are more than 833 million tons of saved emissions allowances, a percentage of new emissions allowances will be placed in a Market Stability Reserve (MSR) instead of being released onto the market.[3] From 2023, there is a ceiling on the size of this reserve.[4] If the reserve reaches its ceiling, emissions allowances in the reserve are cancelled so that the ceiling is not exceeded.

It is highly likely that this automatic cancellation will take place for several years. If a state or other operator buys and cancels emissions allowances now, this will lead to fewer automatic cancellations in the future. The effect of the first cancellation is then largely negated by later automatic cancellation. The mechanism is that cancellations today lead to a smaller number of saved emissions allowances. Fewer emissions allowances are then transferred to the reserve, and there are therefore fewer automatic cancellations. This also means that there is no effect or very little effect on the price if someone buys and cancels emissions allowances, provided there is an automatic cancellation at a later time.

---

3. This percentage is 24 percent of the volume of saved emissions allowances up to 2023 and 12 percent after 2023. If the number of saved emissions allowances is lower than 400 million, 100 million are released back onto the market from the MSR.

4. The ceiling is equal to the volume of emissions allowances auctioned off the year before.

17.5 Complications, uncertainties, and extensions

As we saw in the analysis above, cancellation has no effect in the new system, *given that there are saved, unused emissions allowances in a sufficiently high volume*. The opportunity then arises to buy emissions allowances and wait to cancel them until the surplus of saved emissions allowances has disappeared. How long will there be a surplus? This is more difficult to answer, as it depends on how demand for emissions allowances develops. This, in turn, depends on technological developments, future economic growth, and other variables that are hard to forecast over long timeframes.

As fossil-free alternatives in industry and power generation emerge, demand will fall, postponing the time at which the surplus is over. Electrification of vehicles will increase demand as electricity is in the EU ETS, while diesel and gasoline for vehicles are not. According to a calculation by Silbye and Sørensen (2019), the surplus and the automatic cancellation will remain until mid-2050. With slightly more pessimistic assumptions (for example in the Swedish National Institute of Economic Research, 2018), the surplus disappears a decade or two earlier.

Another complication is that the system may change in the future. A policy that involves buying emissions allowances contributes to an increase in the price of emissions allowances. This is good for the transformation pressure in the economy but could also lead to the rules being changed in the wrong direction.

The conclusion is that purchasing emissions allowances today and not using them will lead to emissions reductions that are spread out over several decades into the future, but only if it is possible to credibly commit to not using them or cancelling them during this period.

An important point in Silbye and Sørensen (2019) is that, if a policy of buying and cancelling allowances does not work, a policy that reduces demand for emissions allowances does work instead. This policy may involve taxing fossil fuels within the ETS or subsidizing fossil-free alternatives. The logic is that lower demand leads to more saved emissions allowances and thus greater automatic cancellation. Previous conclusions to the effect that measures to reduce demand in the ETS sector in a country have no impact on total ETS emissions are therefore overturned. Provided that automatic cancellation continues, measures that reduce demand for emissions allowances will lead to more cancellations not, as previously, only to the price of emissions allowances falling without any reduction in emissions. If demand for emissions allowances in the future becomes so high that the surplus of unused allowances rapidly shrinks, the automatic cancellation will disappear. In this case, reductions in demand will not have any impact.

It is also important to note that the market automatically distributes a given target for emissions reductions cost-effectively over time. Demand reduction measures should also be distributed over time in a manner that does not make them unnecessarily expensive.

17.6 Conclusions

A policy that entails buying and cancelling emissions allowances in the EU ETS will only have an impact if the buyer is able to credibly commit to not using the allowances or cancelling them until after the surplus in the system is exhausted. It is not impossible that this may take several decades. This, combined with the fact that the price of emissions allowances is now significantly higher than before the 2018 reforms, has clearly reduced the effectiveness of such a policy. However, the price of emissions allowances remains much lower than the cost of many emissions reduction measures in Sweden and only around one-fifth of the Swedish carbon dioxide tax. Consequently, buying emissions allowances should not be entirely ruled out. However, the arguments for doing so are not as strong as they were before the 2018 reforms.

CHAPTER 18

Should Sweden aim to create a large surplus of fossil-free electricity for export?

18.1 Quick answer

The reformed EU ETS gives Sweden a new opportunity to reduce the system's total (accumulated) carbon dioxide emissions by influencing the number of emissions allowances that disappear in the automatic cancellation that enters into force in 2023. To the extent that Sweden values such additional emissions reductions, there may be reasons for promoting net exports of electricity with political means. When the EU ETS is in balance again, the system will behave as previously, and Swedish electricity exports will no longer influence total ETS emissions. It is difficult to anticipate when this will occur, but the window may very well be open for a decade or longer. However, it appears questionable to invest in building up a long-term electricity surplus larger than the one resulting from current policies and to further invest in increased transmission capacity to countries with carbon-intensive electricity generation.

The extent to which Sweden should promote increased electricity exports depends largely on the value placed on additional emissions reductions in relation to domestic emissions reductions. Electrification of the transport sector will reduce emissions from the transport sector in Sweden, but lead to lower Swedish electricity exports and presumably to higher emissions from the EU ETS.

18.2 Background to the question

As described in Chapter 17, the automatic cancellation mechanism offers a new opportunity for a single country to influence the accumulated emissions in the EU ETS. From 2019, provided there are more than a given volume of saved emissions allowances, a percentage of the allowances that were intended to be auctioned off are instead transferred to the market stability reserve. Starting in 2023, the reserve will be compared with the auction volume in the previous year and if the former is larger, the difference will be cancelled. The effect of this is that, provided there is a sufficiently large surplus of saved emissions allowances, a number given by a percentage of them will be cancelled.

In the new system, measures that reduce demand for emissions allowances will increase the number of saved emissions allowances and thus increase the number that are cancelled. The earlier such emissions reduction measures are introduced, the more emissions allowances will be cancelled. Unless the rules are changed, this automatic cancellation will disappear when the number of saved emissions allowances has fallen to a specified level. It is, however, very uncertain when this will be. It depends in part on the pace of the transition to fossil-free electricity generation and how demand for electricity develops. Depending on the assumptions made, the window of automatic cancellations may last up to the middle of the century. However, it may also be much shorter. After this, the system will behave like the old EU ETS insofar as national measures that reduce demand for emissions allowances will no longer influence the accumulated emissions in the system.

Compared with other countries, Sweden has low carbon intensity in electricity generation. By exporting electricity that displaces more carbon-intensive power generation in our neighboring countries, Sweden is able to influence demand for emissions allowances in the EU ETS and thus how many allowances will be cancelled and, by extension, the accumulated emissions in the system. There are great differences in carbon intensity between countries. The average carbon dioxide content of electricity that is consumed in Sweden is 47,000 tons of carbon dioxide per TWh, while it is much higher in the neighboring countries to which we export, apart from Norway (see Table 4).

This begs the question of whether there is reason to increase Swedish net exports of electricity, i.e. increase production capacity, reduce domestic electricity consumption, and/or increase transmission capacity to countries with carbon-intensive electricity generation: the Baltic States, Denmark, Finland, Poland, and Germany. The potential is huge. If one Swedish TWh of electricity can replace one Polish TWh, which emits up to 980 thousand tons of carbon dioxide when produced, emissions will fall by 980 – 47 = 943 thousand tons, nearly a million tons of carbon dioxide. This is equivalent to almost twice the emissions from all domestic flights in Sweden or more than the annual emissions from half a million cars.[1] Although such a one-to-one ratio is not necessarily achieved, this back-of-the-

1. Calculated based on 120 grams of carbon dioxide per kilometer and 15,000 kilometers per annum, producing 1.8 tons per annum.

Table 4 Carbon dioxide content of final electricity consumption in some EU Member States.

Country	*Thousand tons of carbon dioxide per TWh*
Denmark	377
Estonia	944
Finland	211
Latvia	1,168
Lithuania	390
Poland	980
Sweden	47

Source: Moro and Lonza (2018).

envelope calculation shows that the potential emission reductions are large.

Sweden has been a major exporter of electricity for many years. We export around 30–35 TWh every year, of which roughly two thirds goes to Denmark, Finland, Poland, and Germany. At the same time, we also import large volumes of electricity, mainly from Norway and Denmark. Net exports in 2017 were 19 TWh (Swedish Energy Agency, 2018). The large net export is partially explained by the Swedish/Norwegian electricity certificate system, which has fed in additional production capacity for many years, regardless of the electricity balance. The 2016 energy agreement between five parties in the Swedish Parliament is considered to add additional production capacity. The fact that the new rules for the EU ETS imply that electricity export reduces the accumulated emissions in the EU ETS may be regarded as an unexpected and very significant climate benefit of Swedish energy policy. What we are discussing here is whether there are reasons for further increasing Swedish net exports of electricity in order to reduce emissions from the EU ETS.

18.3 Analysis

The reformed emissions trading system gives Sweden a direct opportunity to reduce emissions in other countries. If Sweden places more value on emissions reductions than the price of emissions allowances, which is currently less than one quarter of the Swedish carbon dioxide tax, such higher valuation should be reflected in the prices and costs facing Swedish companies. Specifically, Swedish power companies should be paid for the emissions reductions to which they contribute in other countries or be stimulated to export in some other way.

The earlier net exports of electricity increase, the greater the reduction in emissions will be—for several reasons. More emissions allowances will be fed into the reserve, where they are cancelled. The rate at which emissions allowances are transferred into the reserve will be halved in 2023. Moreover, partly as a consequence of the quintupling of the price of emissions allowances since fall 2017, we can expect falling carbon intensity in our neighboring countries' electricity generation over time.[2] The climate returns on Swedish electricity exports will therefore fall over time.

2. We can already see that the energy sector is reducing its emissions, while aviation and industry have not yet obviously reacted.

In the short term, maximum production and transmission capacity must be considered to be fixed. In the longer term, the situation is harder to assess. The opportunities for promoting Swedish electricity exports certainly increase over time due to the short-term transmission capacity constraint, for example. On the other hand, there is greater uncertainty about the impact of Swedish electricity exports on the volume of emissions allowances that will be cancelled. As stated above, this will decrease over time. The major uncertainty concerns when the period of cancellations will end, and the rate of the transition to fossil-free power generation in our neighboring countries is also uncertain (the Swedish National Institute of Economic Research, 2018). In the very long term, Swedish electricity exports will have no impact on total emissions from the EU ETS. The arguments for not discontinuing fossil-free electricity generation if it leads to lower electricity exports in the short term are therefore much stronger than for investing in a long-term higher electricity surplus.

18.4 Conclusions

There are reasons for Sweden to investigate the opportunities for rapidly increasing Swedish electricity exports in relation to currently adopted plans. Increased net exports of electricity to countries with more carbon-intensive electricity generation than that in Sweden can dramatically reduce total emissions from the EU ETS. This effect is not reflected in the market prices, so there are reasons for political management. Measures to increase Swedish net exports in the short term, up to 2023, will have the greatest impact.

The situation is not as clear in the longer term. There is great uncertainty about when the period of cancellations will end and how fast the fossil content of electricity will fall in the countries to which we export. It is therefore more difficult to find strong arguments for investing in building up a long-term electricity surplus and increasing transmission capacity. In other words, Sweden should not adopt any such strategy in the present situation.

CHAPTER 19

Should nuclear power be kept for climate reasons?

19.1 Quick answer

The nuclear power industry decided to shut down Ringhals 1 and 2 for commercial reasons. The remaining nuclear power will presumably be profitable for a certain time, but risks coming under pressure in the longer term.

However, the fact that a decision is made to close nuclear power plants for commercial reasons does not automatically mean that it is the right decision from a socioeconomic point of view. A commercial need to drive up electricity prices from a price level that does not pay nuclear power in full for its services by closing some plants indicates that the economic value of nuclear power may be higher than its commercial value. It is particularly important to note that the closure of Ringhals 1 and 2 may reduce exports of electricity to countries such as Germany and Poland, where there is a risk of it being replaced by carbon-based power. This may lead to significant increases in total emissions within the EU. There should be urgent analysis of the strength of these arguments and whether they should affect the decisions on closure.[1]

However, the Council's assessment is that investments in new nuclear power are of no commercial interest today and would require very large government commitments. Given the long lead times and very high costs if current technology is used, an investment in new Swedish nuclear power does not appear reasonable at present.

19.2 Background

Along with hydropower, nuclear power has accounted for the greater part of Swedish electricity generation for several decades. Currently approximately 40 percent of electricity generation comes from nuclear power and just as much from hydropower, which is shown in Figure 28. Nuclear power was developed before the electricity market was deregulated. With hydropower, these two sources of energy meant that both Swedish industry and Swedish households benefited from considerably lower electricity prices than those in other European countries. In addition, the demand for nuclear power turned out to be smaller than was initially anticipated, which lead to direct electric heating being installed widely in Sweden. A maximum of approximately 17 TWh was used for direct electric heating.

Electricity from nuclear power is currently produced in seven nuclear reactors: three in Forsmark (F1-F3), one in Oskarshamn

1. Åsa Romson and Thomas Sterner have divergent opinions on this issue. See the last section of the chapter.

(O3) and three in Ringhals (R1, R3, R4). There were previously also two reactors in Barsebäck, which were shut down in 1999 and 2005, and two reactors in Oskarshamn, which were shut down in 2015 and 2017. Reactor 2 at Ringhals was shut down at the end of 2019, and reactor 1 is planned to be shut down by 31 December 2020.

Oskarshamn 3, which entered commercial operation in 1985, our most recent nuclear power plant, is undergoing modernization with the aim of continued operation after 2020. Ringhals 3 and 4 have undergone significant modernization works and measures to enhance safety, with the aim of being able to operate the reactors for

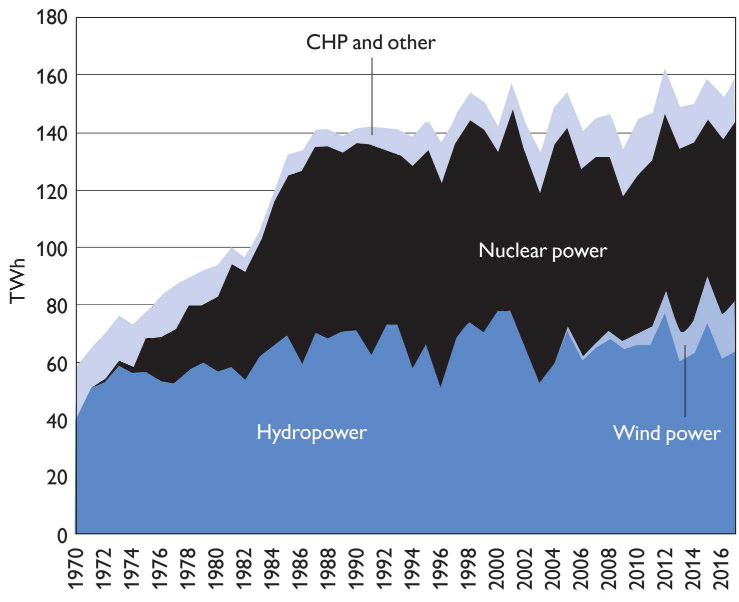

Figure 28 Electricity generation at Swedish power plants, by type of power.

Source: Swedish Energy Agency (2019d).

up to a service life of 60 years, which means up to 2041 and 2043, respectively.

Nuclear power has suffered from poor profitability for a number of years, due to low electricity prices and a specific nuclear power tax. Several nuclear power plants have seen substantial losses. The nuclear power tax has been lifted as part of political multi-party energy agreement.

Nuclear power has relatively low marginal costs, but they are not as low as those of solar and wind power. For existing Swedish nuclear power, the original investment has likely been economically depreciated. However, there have been a large number of investments in safety upgrades and increased output over the years. With these included, production costs are estimated to be approximately SEK 0.25 per kWh (Sweco, 2016).

19.3 Analysis

As we described in Chapter 4, an increasing proportion of unplannable electricity leads to greater price variations, all other things being equal. This applies, in particular, to wind power, and can be observed in our neighboring countries, primarily Denmark and Germany, which already have significant volumes of wind and solar power.

Greater price variations mean higher profitability for various measures that reduce them. Such measures involve making both supply and demand more flexible. The value of storage also increases, as it is based on buying electricity when it is cheap and selling it when it is expensive. Hydropower is a flowing source of energy, but Swedish hydropower has large reservoirs in which energy can be stored between seasons. In practice, therefore, Swedish hydropower constitutes plannable electricity generation, although its contribution varies greatly between dry and wet years. Nuclear power, on the other hand, is designed to be operated as base load power plants, i.e. with high, continuous output. This makes it difficult to integrate in an energy system with high price variations.

Parts of nuclear power will probably remain commercially profitable, provided that unplannable electricity does not lead to electricity prices becoming too variable. In a future energy system with large volumes of unplannable electricity generation, however, there is much to suggest that nuclear power in its current form as base load will find it difficult to compete. Given that the proportion of wind power and other unplannable electricity generation is increasing, it will primarily be electricity generation that can easily change its output and storage, as well as measures to enhance flexibility of demand, that will be commercially profitable. This will also put pressure on existing and new combined heat and power plants to be more flexible.

Given the previously low profitability of the nuclear power industry, the owners decided to shut down two of the reactors at Ringhals. As we described in Chapter 6, however, it is not obvious that the profit incentives of nuclear power companies entirely coincide with the interests of the economy as a whole.

Nuclear power plants are certainly large enough installations for their operation to significantly affect prices. It is not possible to rule out that the companies' decisions are made based on an assessment that closure will increase prices and thus increase profitability for the remaining electricity generators. Moreover, it is possible to argue that nuclear power producers are not fully paid for the services they provide. Nuclear power contributes to maintaining the stability of the frequency (50 Hz) of alternating current by providing grid inertia. This increases the value of nuclear electricity in relation to electricity from wind power and solar panels. Despite this, the same price is paid for the electricity regardless of source. The increased costs of transmission—owing to the fact that wind power is generated when the wind blows—also reduces the value of wind power in relation to nuclear power. However, it is currently unclear whether pricing these extra values of nuclear power would have any significant impact on its commercial profitability.

As explained in Chapter 18, it would likely be of major importance for commercial profitability if the value of electricity exports to countries with a high proportion of carbon-based power generation were priced. The reduction in exports due to the closing of Ringhals 1 and 2 risks leading to large increases in emissions in the rest of the EU. In particular, electricity exports in the years before 2023 will have the greatest impact on emissions, providing an argument for postponing the shutdown.

Continuing to operate Ringhals 1 and 2 until at least after the first cancellation rounds in 2023–2024 would reduce emissions from the EU ETS. As pointed out above, the volume of reduction depends on several uncertain factors, including the carbon intensity of the electricity generation that would be displaced and how fast the EU ETS achieves a balance without a large pool of saved emissions allowances.

It is difficult to calculate exactly how much closing down Ringhals 1 and 2 will affect emissions. However, the following back-of-envelope calculation may give an indication of the order of magnitude. Ringhals 1 and 2 jointly generate approximately 13 TWh a year. If higher exports and lower imports mean that this generation displaces half as much, i.e. 6.5 TWh, of carbon-based condensing power in neighboring countries, this is equivalent to approximately 6 million tons fewer carbon dioxide emissions every year. Calculations by Silbye and Sørensen (2019) show that such measures would, via increased automatic cancellations, reduce emissions by between 83 and 94 percent if they were introduced between 2020 and 2025. Although these calculations are probably in the upper part of the uncertainty interval for how the automatic cancellations work, they indicate very large impacts. Six million tons is equivalent to the annual emissions from 3 million cars, or roughly 40 percent of emissions from Swedish road traffic.

Whether Sweden should extend the operation of the reactors in Ringhals depends largely on the costs of doing so. These costs include not only operating and modernization costs for the reactors, but also the costs of storing additional nuclear waste. These costs must be compared with the value Sweden places on additional emissions reductions in the EU ETS. If the value of these reductions is SEK 1,180 per ton, the Swedish carbon dioxide tax, the total is approximately SEK 7 billion per year.

The nuclear power sector is liable for the costs of storage and final storage of spent nuclear fuel and other radioactive residual products. These costs are covered by a fee paid by the power plant owners. The level of these payments is determined in practice in a game played by the nuclear power industry, public authorities, and politicians. It cannot, however, be ruled out that these fees are lower than they should be, providing an argument against continued operation.

New nuclear power is currently far from commercially viable. It involves very high investment costs, and the difficulty estimating electricity prices and their variability far into the future means that the financial risk is too high. Some form of government guarantee would therefore be required to build new nuclear power plants. Lead times for nuclear power are also very long. If new nuclear power plants are to be considered, it is probably necessary to develop Gen-III technology, the technology being built in Finland and France, to permit these costs to be reduced. The importance of doing this, as well as developing SMR (Small Modular Reactors), is emphasized in the recently published MIT study *The Future of Nuclear Energy* (MIT, 2018). Fourth generation technology (Gen-IV technology) could also be developed. The benefits of this new generation primarily concern safety and reduced waste, while the costs are hard to predict. It will probably be a long time before such technology is available commercially.

19.4 Conclusions

Nuclear power currently accounts for around 40 percent of Sweden's electricity supply. Reasonable forecasts for how the electricity supply will change indicate rapid growth of the proportion of unplannable electricity, primarily wind power. This will increase the demand for flexible power generation and other measures that are able to balance the variability of the unplannable electricity supply and varying power demand. Nuclear power is not well suited to this, which means that it will presumably be under commercial pressure in the long term. However, it is not a given that the lack of commercial profitability in the nuclear power industry is synonymous with a low economic value to society. This reasoning applies, in particular, to closures of existing nuclear power plants, which risk leading to quite substantial increases in emissions in neighboring countries such as Poland and Germany as exports of fossil-free electricity to them decrease and are replaced with carbon-based power. Furthermore, it cannot be ruled out that a commercial motive for closing Ringhals 1 and 2 is to increase profits by reducing supply and thus push electricity prices upwards. The value for society of the continued operation of all existing nuclear power reactors should therefore be urgently investigated.

However, there are divergent opinions on this issue on the Council. Åsa Romson and Thomas Sterner are of the following opinion:

> *We believe that there are a wide range of incorrect incentive structures on the market for the generation and distribution of electricity. The biggest problem associated with the transition to a green economy is that our energy system currently wastes a huge amount of energy, partly because the electricity and heating sectors do not collaborate better. It is therefore strange to consider it interesting to study the existence of any difference between energy companies' business assessment and the economic assessment of the time for closing existing nuclear reactors. Nor is it logical to consider that Germany would import electricity generated by nuclear power in Sweden on a large scale to replace carbon-based power when it has already shut down a large part of its former nuclear power plants, or that Denmark, which has decided against nuclear power, would do this.*

In the (unanimous) assessment of the Economic Policy Council, new nuclear power plants with current technology would be far from commercially profitable. Given this, long lead times, and uncertainty about when new nuclear power technologies may be commercially viable, investment in new Swedish nuclear power plants does not appear reasonable in the short term.

CHAPTER 20

Should Sweden provide funding for investments in carbon capture and storage?

20.1 Quick answer

In principle, payment for carbon capture and storage (CCS) should be equalized to the taxation of carbon dioxide emissions. Furthermore, the UN climate panel, IPCC, also points to a major need to develop and use CCS. As the costs of the technology per ton or carbon dioxide stored are comparable with the Swedish carbon dioxide tax, it may be regarded as a cost-efficient way of reducing Sweden's carbon dioxide emissions.

The potential for CCS is high in Sweden, particularly for major emitters in industry. The equivalent of just under half of total carbon dioxide emissions in Sweden could be eliminated if CCS technology were to be introduced at the 27 Swedish industrial plants that emit the most, if both fossil and biogenic emissions were included. This reduction is greater than if the entire Swedish transport system were fossil-free. At an average cost of SEK 1,000 per ton, it would cost

SEK 23 billion per annum to halve Swedish carbon dioxide emissions in this way. A funding system is required to make this possible. It is not obvious what this should look like, but the costs of such funding do not appear to be insurmountable.

20.2 Background

Carbon capture and storage, CCS, has been on the agenda for many years, with research and development programs in the EU, in particular in the UK and Norway. The Swedish energy company Vattenfall has carried out a CCS project in Germany. However, several projects have been discontinued, primarily for financial reasons. CCS technology is energy-intensive, and therefore reduces the efficiency of the power plant. The value created, less climate change, has no commercial value without taxes and subsidies. It will therefore always be entirely dependent on politically created systems for its funding —not only for investments, but also for continuous operation.

The EU ETS is the most important climate policy instrument at the EU level. Emitters of carbon dioxide of fossil origin in the system would not need to pay for emissions allowances if they introduced CCS, but the price of emissions allowances is still too low to make CCS commercially profitable. With current technology, the cost of CCS is on the order of SEK 1,000 per ton of carbon dioxide for major emitters of point source emissions. The cost is comparable with Sweden's carbon dioxide tax, approximately SEK 1,180 per ton, but considerably higher than the ETS price, which is currently approximately SEK 250 per ton. For small emitters such as cars, there is currently no developed technology for capturing carbon dioxide. The same applies to capture directly from the air, although this is being developed.

On a global scale, fossil-burning power plants are the biggest potential area of application for CCS, but in Sweden we only use small volumes of fossil fuels for electricity generation. The major Swedish point source emissions are dominated instead by base industries: cement, iron and steel production, petrochemicals, and paper and pulp factories. Combined heat and power plants, which primarily burn forestry waste, also emit large volumes of carbon dioxide. Emissions from biofuels are outside the ETS and are not subject to carbon dioxide tax either. To date, therefore, there are no adequate incentives for capturing and storing the carbon dioxide emitted.

Carbon capture and storage has the same impact on the climate, whether the carbon dioxide is of fossil origin or not. However, there is currently no policy instrument in place that provides incentives for capture and storage of biogenic emissions (Bio-CCS). Overall, the incentives for applying CCS to Swedish point source emissions are far too low at present, although the potential is high and the cost is on par with that of the Swedish carbon dioxide tax. Bio-CCS is also a supplementary measure identified by the government for achieving net zero emissions, i.e. the 15 percent reduction required in addition to the 85 percent from fossil emissions.

Many of the major point source emissions in Sweden are near the coast, which is beneficial for the transport of captured carbon dioxide by ship. This reduces the initial investment and the risk of building up a transport system to storage locations, which will probably be below the North Sea. Also, the cost of ship transport is relatively weakly dependent on the transport distance.

A feature of base industry emissions is that a quite limited number of plants account for a significant proportion of total emissions. Roughly 23 million tons of carbon dioxide can be captured from the 27 Swedish industrial plants that emit more than 500,000 tons per annum. Of these emissions, 9 million tons are of fossil origin, and 14 million tons are from biomass. 23 million tons is equivalent to just under half of total fossil carbon dioxide emissions in Sweden and is 50 percent more than the emissions from all Swedish road traffic. The potential for CCS is therefore high, and it could be even higher if it were used more widely.

Reducing carbon dioxide emissions from these 27 plants to almost zero could be done at a cost ranging from approximately SEK 500 to SEK 1,500 per ton of carbon dioxide, i.e. on par with the Swedish carbon dioxide tax of SEK 1,180. This cost estimate is based mainly on the use of the type of CCS technology that is currently available commercially. It is probable that these costs can be reduced by applying other CCS technologies and combining CCS with other measures.[1] It should also be possible to lower the cost by using alternative CCS technologies such as oxyfuel technology in cement production and the introduction of various forms of electrification which, in a scenario with high volumes of electricity from wind power, could exploit electricity generation that would otherwise have to be wasted.

Although the cost of eliminating emissions from base industry is on par with the Swedish carbon dioxide tax, it is not obvious how the introduction of CCS and other measures would be funded or how a market pricing system would be constructed. CCS involves significant investments and increased operating costs for the industrial processes. It is unlikely that CCS will be incentivized by the policy instruments in existence today. For fossil emissions, the price of emission allowances is too low, and there is no incentive whatsoever

1. If the reduction were achieved solely with CCS technology, the full reduction potential would not be achieved, as CCS is usually assumed to capture 80–90 percent of emissions.

for reducing biogenic emissions through CCS. To make investments in CCS technology commercially interesting, there needs to be sufficient confidence among investors that the instruments affecting the ongoing commercial value of CCS, for example carbon dioxide tax and subsidies for the ongoing capture and storage of carbon dioxide, are high enough and are in place throughout the life of any investment.

20.3 Analysis

Should Sweden introduce a system to fund CCS? On one hand, the cost per ton of carbon dioxide captured in Sweden is presumably higher than in the biggest coal-fired power plants in Germany and Poland. However, with the carbon dioxide tax, we have set such a high domestic price for emissions in Sweden that CCS may still be reasonable. Even if CCS in Sweden is more expensive than potential emissions reductions in other countries, it may very well be cheaper than other ways of reducing emissions here. Moreover, the fact that Sweden has unusually high potential for capturing carbon dioxide from non-fossil energy sources is an argument for introducing a funding system for CCS.

For the sake of simplicity, if we set the cost at SEK 1,000 per ton, it would cost SEK 23 billion per annum to capture and store the 23 million tons of carbon dioxide that the 27 biggest Swedish point sources emit every year. SEK 23 billion is equal to the income generated by the carbon dioxide tax in Sweden at present. SEK 23 billion seems an acceptable cost for halving Swedish carbon dioxide emissions. The potential to reduce emissions using CCS is therefore high in Sweden.

At the same time, in several cases, the investments required to reduce carbon dioxide emissions from base industry to almost zero would only produce a marginal increase in the cost of the end products in which these materials are used. If CCS and other measures were applied to cement and steel production to reduce carbon dioxide emissions to almost zero, and these costs were absorbed by end consumers, it would mean that the price of a building or a car would need to increase by half of one percent (Rootzén and Johnsson, 2016, 2017).

The problem is that there are currently no instruments that enable emitters to compare CCS with other emissions reduction methods. As mentioned repeatedly in this report, a uniform emissions price, including payment for negative emissions, is what is required for the market to be able to deliver a cost-efficient reduction in emissions. It would be rational to treat CCS in the same way, regardless of the fuel used, as the climate benefit depends only on how much carbon dioxide is stored. Sweden should therefore work towards changes in the ETS rules so that negative emissions as a result of the capture and storage of carbon dioxide of non-fossil origin are subject to the same financial incentives as for emissions from fossil fuels. This could be done by making non-fossil CCS exchangeable for emissions from fossil fuels, i.e. by paying for it with emissions allowances. This would probably not yet provide adequate incentives for large-scale CCS, but technological developments and rising prices for emissions allowances could change the conditions for profitable CCS.

An alternative for Sweden would be to make the combustion of biofuel subject to carbon dioxide tax in order to create an incentive for non-fossil CCS. The logic behind this would be that all emissions of carbon dioxide generate the same climate consequences.

To prevent the elimination of the comparative advantage of biofuels over fossil fuels, which is the purpose of the carbon dioxide tax, other capture of carbon dioxide must then be exchangeable for carbon dioxide tax, such as in the form of sustainable production of biofuel.

If a tax is not viable as a means to incentivize bio-CCS work, it is necessary to consider subsidies. In this case, it would mean that the government pays a storage subsidy for every ton of carbon dioxide captured and safely stored. It would be paid whether the carbon dioxide comes from fossil fuels or biofuels. It would also be technology-neutral. There are a number of technological solutions for CCS, and it is difficult to know in advance which is best for each type of plant. The best approach is to let the operators on the market decide. It is also conceivable that there will be voluntary partnerships across sectors, in which sectors that find it difficult, i.e. expensive, to dramatically reduce emissions pay for negative emissions with CCS in the industrial and district heating sectors.

The storage subsidy should absorb part of the difference between the ETS price and our carbon dioxide tax. It should not be so high that there is a risk of plants being operated for the primary purpose of obtaining a storage subsidy, with the result that it increases the level of combustion instead of reducing emissions. This could happen, given that the price of emissions allowances is considerably lower than the carbon dioxide tax. It is conceivable that a plant could burn coal and pay for it by buying emissions allowances. Via the storage subsidy, capture generates an income that, in the current situation, would be considerably higher than the cost of emissions. If the cost of buying and burning coal were sufficiently low, this could be a lucrative but economically harmful activity. However, if the emissions price were as high as the storage subsidy, these problems would not arise. They illustrate negative side effects that can arise because differences in taxation often generate undesirable arbitrage opportunities.

The lead time for building a CCS plant is probably at least five years. For such investments to be made, there must be a long-term government commitment to help fund ongoing operations. Given the arbitrage problem that a sufficiently high storage subsidy could generate, it may also make sense for the government to contribute to development and build pilot plants in partnership with industry.

20.4 Conclusions

CCS could make an important, cost-efficient contribution to dramatically reducing Swedish carbon dioxide emissions. The potential is high. Emissions reductions of more than 50 percent of current emissions could be achieved at a cost per ton equivalent to the Swedish carbon dioxide tax. Large-scale Swedish development of CCS could help make the technology cheaper and less financially risky. The international ripple effect could then be significant.

For CCS to become commercially viable, financial incentives must be provided for capture and storage. Initially, this should involve storage subsidies. However, public co-funding of investments may also be needed. The question of how such systems should be designed is not trivial. However, in our opinion, it is entirely possible to answer it.

REFERENCES

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous (2012). "The environment and directed technical change". *American Economic Review*, 102(1): 131–166.

Anderson, B. G., and M. Bell (2009). "Weather-related mortality: How heat, cold, and heat waves affect mortality in the United States". *Epidemiology*, 20: 205–213.

Berndes, G., M. Goldman, F. Johnsson, A. Lindroth, and A. Wijkman (eds.) (2018). "Forests and the climate. Manage for maximum wood production or leave the forest as a carbon sink?". *Kungl. Skogs- och Lantbruksakademiens Tidskrift*, 157(6).

Black-Samuelsson, S., H. Eriksson, D. Henning, G. Janse, L. Kaneryd, A. Lundborg, and L. Niemi Hjulfors (2017). "Bioenergi på rätt sätt – om hållbar bioenergi i Sverige och andra länder". Report by Swedish Forest Agency, Swedish Energy Agency, Swedish Board of Agriculture and Swedish Environmental Protection Agency. Rapport 10, Swedish Forest Agency.

Börjesson, P. (2016). *Potential för ökad tillförsel och avsättning av inhemsk biomassa i en växande svensk bioekonomi. Rapport nr 97*. Lund: Lund University, Department of Technology and Society, Environmental and Energy Systems Studies.

BP Statistical Review of World Energy 2019. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf.

Buchanan, J. M. (1965). "An economic theory of clubs". *Economica*, 32(125): 1–14.

Campbell, J. E., J. A. Berry, U. Seibt, S. J. Smith, S. A. Montzka, T. Launois, S. Belviso, L. Bopp, and M. Laine (2017). "Large historical growth in global terrestrial gross primary production". *Nature*, 544: 84–87.

Carattini, S., S. Kallbekken, and A. Orlov (2019). "How to win public support for a global carbon tax". *Nature*, 565: 289–291.

Coady, D., I. Parry, N.-P. Le, and B. Shang (2019). "Global fossil fuel subsidies remain large: An update based on country-level estimates". IMF Working Paper 19/89.

Dagens Samhälle (2017). "Kommunalt veto stoppar vindkraft". 30 March 2017.

Dell, M., B. F. Jones, and B. A. Olken (2014). "Temperature shocks and economic growth: Evidence from the last half century". *American-Economic Journal: Macroeconomics*, 4(3): 66–95.

Dunne, J. P., R. J. Stouffer, and J. G. John (2013). "Reductions in labour capacity from heat stress under climate warming". *Nature Climate Change*, 3: 563–566.

EU (2015) Decision (EU) 2015/1814 of the European Parliament and of the Council.

EU (2018a). Regulation (EU) 2018/841 of the European Parliament and of the Council.

EU (2018b). Regulation (EU) 2008/842 of the European Parliament and of the Council.

EU (2018c). Directive (EU) 2018/410 of the European Parliament and of the Council.

Fu, S. H., A. Gasparrini, P. S. Rodriguez, and P. Jha (2018). "Mortality attributable to hot and cold ambient temperatures in India: A nationally representative case-crossover study". *PLoS Medicine*, 15(7): 1–17.

Golosov, M., J. Hassler, P. Krusell, and A. Tsyvinski (2014). "Optimal taxes on fossil fuel in general equilibrium". *Econometrica*, 82(1): 41–88.

Göransson, L., and F. Johnsson (2018). "A comparison of variation management strategies for wind power integration in different electricity system contexts". *Wind Energy*, 21(10): 837–854.

Government Bill 2016/17:146. Ett klimatpolitiskt ramverk för Sverige.

Government Bill 2017/18:1. Budgetproposition för 2018.

Graeker, M., R. Golombek, and M. Hoel (2019). "Global impact of national climate policy in the Nordic countries", in Calmfors, L., and J. Hassler (eds.), *Climate Policies in the Nordics*. Nordic Economic Policy Review 2019. Copenhagen: The Nordic Council of Ministers.

Hassler, J., P. Krusell, and C. Olovsson (2018). "The consequences of uncertainty: Climate sensitivity and economic sensitivity to the climate". *Annual Review of Economics*, 10: 189–205.

Hassler, J., P. Krusell, and C. Olovsson (2019). "Directed technical change as a response to natural-resource scarcity". Working Paper, Institute for International Economic Studies (IIES), Stockholm University.

Hassler, J., P. Krusell, C. Olovsson, and M. Reiter (2019). "Integrated assessment in a multi-region world with multiple energy sources and endogenous technical change". Mimeo, Institute for International Economic Studies (IIES), Stockholm University.

Heinisch, V., M. Odenberger, L. Göransson, and F. Johnsson (2019). "Prosumers in the electricity system – household vs. system optimization of the operation of residential photovoltaic battery systems". *Frontiers in Energy Research*, January 10 2019.

Horn, H., and A. Sapir (2019). "Border carbon tariffs: Giving up on trade to save the climate?" Bruegel blog post, https://bruegel.org/2019/08/border-carbon-tariffs-giving-up-on-trade-to-save-the-climate/.

Howard, P., and T. Sterner (2017). "Few and not so far between: A meta-analysis of climate damage estimates". *Environmental and Resource Economics*, 68: 197–225.

IEA (2019). "CO_2 emissions from fuel combustion – 2018 highlights". International Energy Agency.

Im, E.-S., J. S. Pal, and E. A. B. Eltahir (2017). "Deadly heat waves projected in the densely populated agricultural regions of South Asia". *Science Advances*, 3(8).

IPCC (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T. F., et al. (eds.)]. https://www.ipcc.ch/report/ar5/wg1/.

IPCC (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B. et al. (eds.)]. https://www.ipcc.ch/report/ar5/wg2/.

IPCC (2018). *Global Warming of 1.5°C. An* IPCC *Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V. et al. (eds.)]. https://www.ipcc.ch/sr15/.

IPCC (2019a). *Climate Change and Land.* IPCC *Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. https://www.ipcc.ch/report/srccl/.

IPCC (2019b). *Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O. et al. (eds.)]. https://www.ipcc.ch/srocc/download-report/.

IRENA (2018). *Renewable Energy Policies in a Time of Transition*. IRENA, OECD/IEA and REN.

IVA (2019). *Så klarar det svenska energisystemet klimatmålen. Rapport* IVA-*M 504*. Stockholm: Royal Swedish Academy of Engineering Sciences.

Johnsson, F., J. Kjärstad, and J. Rootzén (2019). "The threat to climate change mitigation posed by the abundance of fossil fuels". *Climate Policy*, 19(2): 258–274.

Keenan, T. F., I. C. Prentice, J. G. Canadell, C. A. Williams, H. Wang, M. Raupach, and G. J. Collatz (2016). "Recent pause in the growth rate of atmospheric CO_2 due to enhanced terrestrial carbon uptake". *Nature Communications*, 7, article no 13428.

Kriström, B., R. Brännlund, J. Nordström, and S. Wibe (2003). *Fördelningseffekter av miljöpolitik*. Bilaga 11 till Långtidsutredningen 2003/04, SOU 2004:19.

Krusell, P. (2019). "The role of economic analysis in combatting climate change". Presentation at Bank of Canada, May 2019.

Köhlin, G., S. K. Pattanayak, E. Sills, E. Mattsson, M. Ostwald, A. Salas, and D. Ternald (2015). *In Search of Double Dividends from Climate Change Interventions: Evidence from Forest Conservation and Household Energy Transitions*. Report 2015:09 to The Expert Group for Aid Studies (EBA), Stockholm.

Li, P., C. Peng, M. Wang, W. Li, P. Zhao, K. Wang, Y. Yang, and Q. Zhu (2017). "Quantification of the response of global terrestrial net primary production to multifactor global change". *Ecological Indicators*, 76: 245–255.

van der Linden, S. L., A. A. Leiserowitz, G. D. Feinberg, and E. W. Maibach (2015). "The scientific consensus on climate change as a gateway belief: Experimental evidence", *PLOS ONE* 10(2): e0118489.

McGlade, C., and P. Ekins (2015). "The geographical distribution of fossil fuels unused when limiting global warming to 2 °C". *Nature*, 517: 187–190.

McKibbin, W. J., and P. J. Wilcoxen (2009). "The economic and environmental effects of border tax adjustments for climate policy". *Brookings Trade Forum*, 2008(1): 1–34.

Mehling, M., and E. Tvinnereim (2018). "Carbon pricing and the 1.5°C target: Near-term decarbonisation and the importance of an instrument mix". CCLR *Carbon & Climate Law Review*, 12(1): 50–61.

MIT (2018). *The Future of Nuclear Energy in a Carbon-Constrained World – An Interdisciplinary* MIT *Study*. Massachusetts Institute of Technology.

Moro, A., and L. Lonza (2018). "Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles". *Transportation Research Part D: Transport and Environment*, 64

National Board of Trade (2009). *Climate Measures and Trade. Legal and Economic Aspects of Border Carbon Adjustment*. National Board of Trade 2009:2.

National Institute of Economic Research (2015). "EMEC – en populärvetenskaplig beskrivning". PM March 26 2015.

National Institute of Economic Research (2017a). "Kostnader och intäkter i Sverige av långsiktiga klimatförändringar – en litteraturöversikt". Specialstudie 60.

National Institute of Economic Research (2017b). *Miljö, ekonomi och politik 2017*. Stockholm: National Institute of Economic Research.

National Institute of Economic Research (2018). " EU ETS, marknadsstabiliseringsreserven och effekter av annulleringar". Special Study. KI-no 2018:10.

National Institute of Economic Research (2020). "Annulleringsmekanismen, prisbanor och konsekvenser av en storskalig elektrifiering av transportsektorn", memorandum, forthcoming.

Näyhä, S. (2005). "Environmental temperature and mortality". *International Journal of Circumpolar Health*, 64(5): 451–458.

Nordhaus, W. D. (1994). *Managing the Global Commons: The Economics of Climate Change*. Cambridge, MA: MIT Press.

Nordhaus, W. (2007). "A review of the Stern Review on the Economics of Climate Change". *Journal of Economic Literature*, 45(3): 686–702.

Nordhaus, W. (2015a). *The Climate Casino. Risk, Uncertainty, and Economics for a Warming World*. New Haven and London: Yale University Press.

Nordhaus, W. (2015b). "Climate clubs: Overcoming free-riding in international climate policy". *American Economic Review*, 105(4): 1339–1370.

OECD/IEA (2019). "Update on recent progress in reform of inefficient fossil-fuel subsidies that encourage wasteful consumption". https://oecd.org/fossil-fuels/publication/OECD-IEA-G20-Fossil-Fuel-Subsidies-Reform-Update-2019.pdf

Owen N. A., O. R. Inderwildi, and D. A. King (2010). "The status of conventional world oil reserves – Hype or cause for concern?". *Energy Policy*, 38(8): 4743–4749.

Poterba, J. M. (1991). "Is the gasoline tax regressive". Chapter in Bradford, D. (ed.), *Tax Policy and the Economy*, volume 5. MIT Press: Cambridge, MA.

Rootzén, J., and F. Johnsson (2016). "Paying the full price of steel – Perspectives on the cost of reducing carbon dioxide emissions from the steel industry". *Energy Policy*, 98: 459–469.

Rootzén, J., and F. Johnsson (2017). "Managing the costs of CO_2 abatement in the cement industry". *Climate Policy*, 17(6): 781–800.

Rosenzweig, C. et al. (2018). "Coordinating AgMIP data and models across global and regional scales for 1.5°C and 2.0°C assessments". *Philosophical Transactions of the Royal Society A*, 376: 20160455.

Ruane, A. C. et al. (2018). "Biophysical and economic implications for agriculture of +1.5° and +2.0°C global warming using AgMIP Coordinated Global and Regional Assessments". *Climate Research*, 76(1): 17–39.

Silbye, F., and P. Birch Sørensen (2019). "National climate policies and the European Emissions Trading System". Chapter in Calmfors, L., and J. Hassler (eds.), *Climate Policies in the Nordics*. Nordic Economic Policy Review 2019. Copenhagen: Nordic Council of Ministers.

Sinn, H. W. (2012). *The Green Paradox: A Supply-Side Approach to Global Warming*. Cambridge, MA: MIT Press.

SMHI (2010). "Klimatförändringarnas effekter på svenskt miljömålsarbete". Klimatologi no 2/2010.

SOU 2007:60. *Sverige inför klimatförändringarna – hot och möjligheter."*

The Commission on Climate and Vulnerability.

SOU 2016:21. *Ett klimatpolitiskt ramverk*. Delbetänkande från Miljömålsberedningen." The Cross-Party Committee on Environmental Objectives.

Stern, N. (2006). *Stern Review on the Economics of Climate Change (pre-publication edition). Executive Summary*. London: HM Treasury.

Sterner, T. (2012). "Distributional effects of taxing transport fuel". *Energy Policy*, 41: 75–83.

Stoknes, P. E. (2015). *What We Think About When We Try Not To Think About Global Warming*. White River Junction, VT: Chelsea Green Publishing Co.

Svensk Vindenergi (2019). "Svensk Vindenergis vindkraftstatistik och prognos – kvartal 3, 2019". https://svenskvindenergi.org/statistik/2017-3.

Sweco (2016). "Ekonomiska förutsättningar för skilda kraftslag". En underlagsrapport till Energikommissionen 2016.

Sweco (2017). "Konsekvenser av Sveriges klimatpolitik i transportsektorn – en analys av 2030-målet och reduktionsplikten". A report for Confederation of Swedish Enterprise.

Swedish Energy Agency (2018). Press Release February 9 2018.

Swedish Energy Agency (2019a). "Energiläget 2019 – en översikt". ET 2019:2.

Swedish Energy Agency (2019b). "En svensk-norsk elcertifikatsmarknad. Årsrapport för 2018". ET 2019:4

Swedish Energy Agency (2019c). "Kontrollstation 2019 för reduktionsplikten", supplemented October 23 2019.

Swedish Energy Agency (2019d). "Energiläget i siffor 2019".

Swedish Energy Agency (2019e). "Årsrapport 2018 för Sveriges program för internationella klimatinsatser". ER 2019:5.

Swedish Environmental Protection Agency (2018). "Allmänheten om klimatet: En kvantitativ undersökning om den svenska allmänhetens syn på lösningar för klimatet." (Gullers Grupp Rapport).

Swedish Environmental Protection Agency (2019). *Underlag till regeringens klimatpolitiska handlingsplan*. Report 6879.

Swedish National Audit Office (2018). *Nedsatt moms på livsmedel – priseffekt, fördelningsprofil och kostnadseffektivitet*. RiR 2018:25.

Swedish National Audit Office (2019). *Klimatklivet – stöd till lokala klimatinvesteringar*. RiR 2019:1.

The Commission on Climate and Vulnerability (2010). *Sverige inför klimatförändringarna – hot och möjligheter*. SOU 2007:60.

The Cross-Party Committee on Environmental Objectives (2016). *Ett klimatpolitiskt ramverk*. Delbetänkande från Miljömålsberedningen. SOU 2016:21.

UNEP (2018). "Emissions gap report 2018". United Nations Environment Programme, November 2018.

van Vuuren, D. P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S, J. Smith, and S. K. Rose (2011). "The representative concentration pathways: An overview". *Climatic Change*, 109:5.

Weber, E. (2015). "Climate change demands behavioral change: What are the challenges?". *Social Research*, 82: 560–580.

Weitzman, M. (2014). "Can negotiating a uniform carbon price help to internalize the global warming externality?". *Journal of the Association of Environmental and Resource Economists*, 1(1/2): 29–49.

THE AUTHORS

JOHN HASSLER (chair) is professor of economics at the Institute for International Economic Studies at Stockholm University. His research concerns public finances, social mobility, growth, and climate change. In 2013–2016, he was chair of the Swedish Fiscal Policy Council. In 2009–2018 and from 2020 he is a member of the Prize Committee for the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel. He is a board member of the Stockholm Resilience Center. He is a member of the Royal Swedish Academy of Sciences and of the Royal Swedish Academy of Engineering Sciences.

BJÖRN CARLÉN has a PhD in economics and is a researcher at the Environmental Economics unit of the National Institute of Economic Research. His research primarily concerns instruments of climate policy and energy policy. In 2005–2010, he was secretary of the Swedish Ministry of Finance's expert group on environmental studies and, in 2010–2012, the group's deputy chair.

JONAS ELIASSON is a visiting professor in transport systems at Linköping University and accessibility director at the Swedish Transport Administration. His research concerns the impact of the transport system on travel and transport patterns, the environment and social development, and economic analysis of infrastructure and transport policy. In 2016–2018, he was transport director for the City of Stockholm and, in 2007–2017, a professor at KTH Royal Institute of Technology.

FILIP JOHNSSON has been professor of sustainable energy systems at Chalmers University of Technology since 2003. His research focuses on the transformation of energy and material systems, for example how wind and solar power can be effectively integrated in the energy system. He also studies supply and value chains from base materials to end products within the framework of a Mistra project (Mistra Carbon Exit) and how the cost of emissions reduction measures can be highlighted furthest out in the value chain.

PER KRUSELL is professor of economics at the Institute for International Economic Studies at Stockholm University, where he has worked since 2008, after more than twenty years in the US. In 2003–2013 and 2017–2019, he was a member of and, in 2011–2013, chair of the Prize Committee for the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel. He is member of the Royal Swedish Academy of Sciences. In 2020 he is president of the European Economic Association.

THERESE LINDAHL has a PhD in economics and is a researcher and program leader at the Beijer Institute of Ecological Economics. Her research concerns the overlap between environmental and behavioral economics and focuses on various aspects of human behavior linked to environmental and climate issues. She has been one of the stream leaders for the Biosphere Stewardship stream at Stockholm Resilience Center since 2015.

JONAS NYCANDER is professor of geophysical hydrodynamics at the Department of Meteorology at Stockholm University. His research concerns oceanography, climate and the global carbon system. He is a member of the Royal Swedish Academy of Engineering Sciences.

ÅSA ROMSON is a doctor of laws and a researcher in environmental law and environmental policy at IVL Swedish Environmental Research Institute, focusing on climate law and environmental policy instruments. She has 15 years of experience of environmental politics at local and national levels and was Minister of the Environment in 2014–2016.

THOMAS STERNER is professor of environmental economics at the University of Gothenburg. His research concerns climate economics and the design of environmental economics instruments in various socioeconomic contexts. He was previously president of the European Association of Environmental and Resource Economists (2008–2009), chief economist at the Environmental Defense Fund (2012–2013) and elected to the College de France (2015–2016).

CLIMATE POLICY IS a complex area that requires input from many different perspectives. The SNS Economic Policy Council 2020 comprises nine researchers from a range of disciplines, with different backgrounds and with varied opinions on the debate surrounding climate policy.

They analyse Swedish climate policy in a global context, describing the causes and consequences of climate change and focusing on how policy can achieve the desired reductions in carbon emissions. The report also provides answers to questions that are frequently discussed in the Swedish debate, such as the effectiveness of climate aid and whether Sweden should generate a larger surplus of fossil-free electricity for export.

The members of the SNS Economic Policy Council 2020 are John Hassler (chair), Björn Carlén, Jonas Eliasson, Filip Johnsson, Per Krusell, Therese Lindahl, Jonas Nycander, Åsa Romson, and Thomas Sterner.

ISBN 978-91-88637-59-8