A global CO_2 price – Necessary and sufficient

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Abstract

During the last 10 years, I have spent most of my research time on the economics of climate change. Basically all of it has been done together with my colleagues Per Krusell at IIES and Conny Olovsson at Sveriges Riksbank. Being a truly cross-disciplinary field, the close interaction with many natural scientists, in particular Jonas Nycander at the department of meteorology at Stockholm University has been an absolute necessity. In this article, based on a talk at the Finnish Economic Association annual conference in February 2020, I summarize what we have learned over the years. Hopefully it can be of value to other researchers and policy makers. In any case, I am convinced that economics is key for understanding what to do about global warming. The key conclusion is that a global agreement on a (minimum) price on fossil carbon emission is necessary, sufficient and efficient solution to limiting climate change.

The natural science background

Without the inflow of sunlight, life on earth as we know it would be impossible. On average over time and geographic space, earth receives an inflow of energy from the sun of 340 W/m^2. For earth not to accumulate heat, an equal amount has to flow out from earth into space. We call the account of these aggregate flows *earth's energy budget*. When the budget is balanced, in- and outflows are equal, and no heat is accumulated.

The inflow of energy is largely in the form of visible light. Apart from a third of the outflow (being direct reflection of visible light), the outflow is instead largely in the form of infrared radiation. Sunlight passes easily through the atmosphere, but this is not the case for infrared radiation since the atmosphere contains greenhouse gases which trap the infrared radiation. The most important greenhouse gases are water vapor, carbon dioxide (CO_2) and methane. Human activities have increased the amount of CO_2 and methane in the atmosphere. This creates a surplus in the energy budget by reducing the outflow.[1]

A surplus in the energy budget leads to accumulation of energy in the form of heat – the temperature increases. As the temperature increases, more energy is emitted from earth to space and eventually, budget balance is restored, but at a higher global temperature.

Modern models incorporating both the carbon circulation[2] and how changes in the energy budget affect the climate have been shown to imply that the global temperature increase is proportional to the accumulated amount of fossil carbon that is emitted since we started emitting (Matthews et al., 2009). A key feature behind this result is that a substantial share of carbon stays in the atmosphere for thousands of years. Methane, on the other hand, while being a highly potent greenhouse gas, only stays in the atmosphere for a short time (most is gone after a few decades). Thus, in contrast to CO_2, the warming effect of methane depends on the flow of emissions, not the accumulated amount.

Although the models agree on the proportionality between accumulated emissions and the increase in temperature, they do not agree on the proportionality factor (sometimes called CCR – Carbon Climate Response). A key explanation for this disagreement is that science is still unsure of how cloud formation is affected by emissions from fossil fuel. Changes in when and where clouds are formed are important for whether the direct effect of CO_2 on the energy budget is dampened or reinforced. Due to this (and other) feedback mechanisms that are difficult to quantify, there is a large range of uncertainty regarding the proportionality factor between accumulated emissions and global warming. UN's climate panel IPCC suggests a likely interval of 0.8 – 2.5 degrees C per TtC[3]. This is a very large degree of uncertainty. To see this, note that we have so far globally emitted close to 0.6 TtC since we started some 150 years ago. If the proportionality factor is 0.8, we can emit three times as much as we have done so far before reaching an increase of 2 degrees global warming. At the current rate of emission of approximately 0.01 TtC per year, this would take a couple of hundred years. If, on the other hand, the proportionality factor is in the upper end of the interval, we can only emit 0.2 TtC more if we want to stay below 2 degrees. This amount would be emitted in 20 years at the current emission rate.

The increase in the global mean temperature is a key summary measure of climate change. However, climate change is obviously enormously multi-faceted. The same is true of the consequences for human welfare. The direct effect of climate change might be small or even positive in some parts of the world, for example in the Nordic countries. In other parts of the world, often densely populated, climate change may have catastrophic consequences. Also the uncertainty about the consequences of climate change and the possibility to adapt to it is very large and in the same order of magnitude as the

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[1] *More CO_2 in the atmosphere implies that the altitude at which heat radiation can "escape" the atmosphere is pushed outwards towards colder layers of the atmosphere. Since the amount of energy radiated depends on the temperature, less energy is emitted. More CO_2 thus works like putting on a thicker blanket on earth. The first to quantify the relation between CO_2 in the atmosphere and temperature was Svante Arrhenius (Arrhenius, 1896).*

[2] *The circulation of carbon between different carbon reservoirs (carbon sinks) such as the atmosphere, the biosphere and the oceans.*

[3] *Terraton carbon, i.e., 1000 billion ton carbon. Since burning one ton of carbon produces 3.67 tons of CO_2, these numbers can easily be expressed in CO_2 units.*

natural science uncertainty about the CCR. The death of our civilization as a consequence of climate change is science fiction, but cannot be ruled out on logical or scientific grounds.

Economics and economists are needed

Most researchers who are active in the area of climate change are natural scientists. However, economists are needed to provide key answers to the questions about how to reduce emissions. If it were the case that the reasonable response to the climate change problems was to impose a global, total and immediate ban on fossil fuel, economists would not be required. Arguably, however, such a medicine would kill the patient and cannot be prescribed. Instead fossil fuel needs to be phased out over time and perhaps at different speeds in different parts of the economy and differentially for different fossil fuels. Doing this by central planning where the emissions of each emitter is prescribed by a global emission agency is not practical, to say the least.

Instead we need to realize that emissions are the consequences of economic activities such as consumption, investment, and production. Behind these activities are humans and firms that make decisions, largely on markets. How such decisions are made and how they can be affected by various policies is what economists study.

A key economic lesson going back to the work of Pigou exactly 100 years ago is that markets will not deliver good outcomes when there are externalities (Pigou, 1920). With this we mean a situation where an activity on a market has direct consequences for other parties than the ones involved in the transaction behind the activity. Emission of CO_2 is a perfect example of such an externality. When I ride my motorcycle and burn the gasoline I bought at the gas station, the emitted CO_2 quickly (time scale of weeks) spreads in the global atmosphere and affects the climate everywhere and for a very long time. These effects are not part of the price I pay for the gasoline unless there is policy that makes me pay for them. Without a price that makes me pay for the externalities, the market fails to deliver the socially right outcome. I use too much gasoline.

An alternative way of describing the market failure is to note that the atmosphere's capacity to absorb CO_2 is a resource in limited supply. If this resource is free to use for everyone, we will get overuse in the same way as free access to the fish in the ocean or trees in the forest leads to overuse. Economist call this phenomenon the Tragedy of the Commons.

It is sometimes claimed that the causes of our problems with climate change is economic and/or population growth. Is this correct? Well both yes and no. No since the root cause of the problem is the lack of a price on emissions – the atmosphere capacity to absorb CO_2 is freely up for grabs. Yes since growth exacerbates the negative consequences of the absence of a price on emissions. Again, this is very similar to the case of fish in the oceans. We get overfishing if everyone is allowed to fish as much as they want without a price or a fishing quota. But the amount of overfishing certainly increases with growth in technology (larger boats), in population and GDP. However, the solution to the problem is not to go back to small fishing boats bound to the coastlines. It is to regulate the fishing industry with prices or quotas. The same thing is true for CO_2 emissions.

Integrated assessment models

One hundred years ago, Arthur Pigou provided the key conceptual insight required to understand what to do with the externalities – a price equal to externality must be imposed on the agents who control the activity leading to it. However ingenious Pigou's idea was, it is not sufficient to give policy advice. For this, we need quantitative answers about how high the price should be. To provide incentives for policy makers to follow our advice, we need to show what happens under different, also suboptimal, polices. For this, we need what is called *Integrated Assessment Models*, IAM's. William Nordhaus received the Nobel Economics Prize in 2018 for being the first to construct such models.

IAM's consist of three modules.

1. A carbon circulation module that describes the circulation of carbon between different carbon sinks such as the atmosphere, the biosphere and the oceans.

2. A climate module. This is built around the energy budget described above and describes what happens with various aspects of the climate over time when there is a budget imbalance.

3. A global economy module where production, consumption and emissions are determined and climate damages incurred.

The modules are linked in the following way; in the economy module a dynamic path of emissions of CO_2 are determined together with a number of other variables like income, production, consumption and investment. Emissions enter as an input to the carbon circulation module. There, a path of atmospheric CO_2 concentrations is determined. This becomes the input into the energy budget in the climate module in which the dynamics of the climate is determined. Finally, to close the loop, the climate is affecting the economy that incurs various damages caused by climate change.

All IAMs are built in this way, but they of course differ with respect to e.g., the degree of complexity of the various modules. Regardless of this, all modules need to be consistent with observations and our understanding of how the world works. This is of course as important when it comes to the economy as it is for the natural science modules.

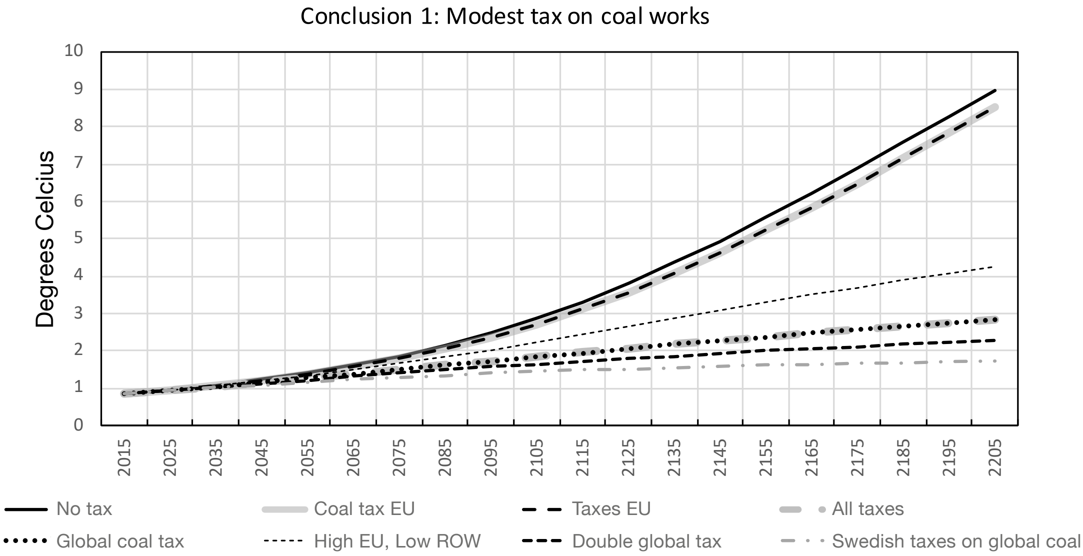
In previous work (Golosov et al., 2014) we constructed an IAM based on the fundamental contributions by Nordhaus (Nordhaus, 1994). We used it in particular to provide a simple formula for the optimal price on emissions. Key factors that determine the optimal level are how sensitive the climate is to emissions, how long carbon stays in the atmosphere and how damaging climate change is for human welfare. As described above we unfortunately have quite limited knowledge of these factors. Another important factor in determining the optimal level of the tax is how much we discount the welfare of future generations. Here, the ambiguity is due to the fact that we all can have different opinions on how to do this discounting.

In more recent work (Hassler et al., 2018 and 2020), we have used the model to address more positive questions. In those papers, three conclusions are drawn.

First, already a modest global price on emissions is effective in curbing climate change. Already an emission price of around 20 dollar per ton of CO_2 has strong effects on emissions and is in the main calibration sufficient to keep the temperature under 2 degrees during this century. Since a liter of gasoline produces around 2.3 kg of CO_2 an emission price of 20 dollar per ton amounts to only 4.6 euro cents per liter of gasoline. In figure 1, we show the effect on global warming over time for different emission prices. The main case is the 20 dollar price. Note, however, that in all simulations the price grows over time in at the same rate as global GDP. In Golosov at al. (2014), we show that this is optimal.

The lion's share of the effect on emissions in the model does not come from reductions in oil consumption but from coal. In sharp contrast to conventional oil, the market price of coal is close to the cost of extraction and the long-run elasticity of supply is high. Thus, even a small tax on emissions can make a lot of coal based energy unprofitable. This is fortunate, because also in contrast to conventional oil and gas, coal reserves are huge and most of it must stay in ground for any reasonable climate target to be met. Conventional oil instead, exists in limited supply and the model result clearly indicates that it is likely that it is socially optimal to use it also when the climate externalities are taken into account. I will return to this issue below.

Figure 1. Global warming for different emission prices.



An important qualification needs to be made here, however. For a modest tax to be effective, it has to be global. If, for example, China is allowed to continue using unpriced coal it becomes practically impossible to reach any climate goals. Even if the rest of the world implements a tax 20 times higher than the 20 dollar per ton discussed above it cannot compensate for the high emissions of China. Similar results accrue if fast growing regions like India or Africa are left out of an agreement on carbon pricing.

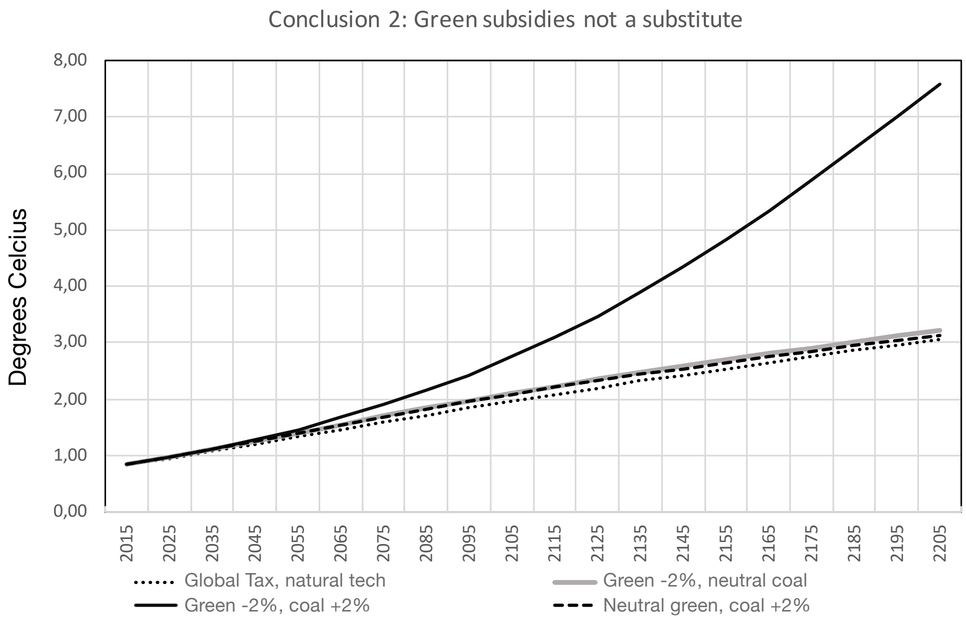
The second conclusion we draw is that subsidies to the development of cheap green energy is not likely to be an effective substitute for carbon pricing. In Figure 2, we show the consequences of a few experiments. The first is to subsidize technological improvements of green energy so that its price falls by 2% per year. At the same one manages to make the price of coal increase by 2% per year, either by a tax or by stopping technological advances in the coal industry. The consequence of this experiment is represented by the green line in Figure 2. As we see, global warming is very similar to the case of a moderate global tax represented by the dashed red curve (being the same as blue curve in figure 1). The second experiment is to only make green energy cheaper. This is represented by the thin black curve. As we see, this does not help the climate at all.

The reason for the result that cheaper green energy is unable to limit climate change is that the aggregate substitutability between different sources of energy is fairly low. Based on empirical surveys we set the elasticity of substitution to 0.95. This implies that cheaper green energy leads to more use of it, but it does not reduce the consumption of fossil based energy. So far, this is what we have seen globally. The use of green energy increases fast, but does not seem to drive out the use of fossil energy unless it is taxed.

There are many reasons for the, perhaps surprising, finding that the elasticity is not higher. One is that that green energy in the form of wind and sun, in contrast to fossil based energy, is non-controllable. This implies that the larger the share of wind and sun in the energy mix, the more negative becomes the correlation between price and production. The price is low when the sun shines and the wind blows. Therefore, a higher share of wind and sun reduces its profitability relative to controllable alternatives. Clearly, technical development in storage and demand flexibility may lead to higher substitutability. The hope that this will be sufficient for cheap green energy to drive out fossil energy without taxes seems fragile.

The third and final conclusion addresses the huge uncertainty described above. A traditional calculation of the optimal tax requires that a probability distribution is assigned to uncertain parameters like the response of the climate to accu-

Figure 2. Global warming for different price paths of green and fossil energy.



mulated carbon emissions. Natural science cannot provide reliably such distributions since the uncertainty comes from the fact that different models yield different results and no one knows which is the right model.

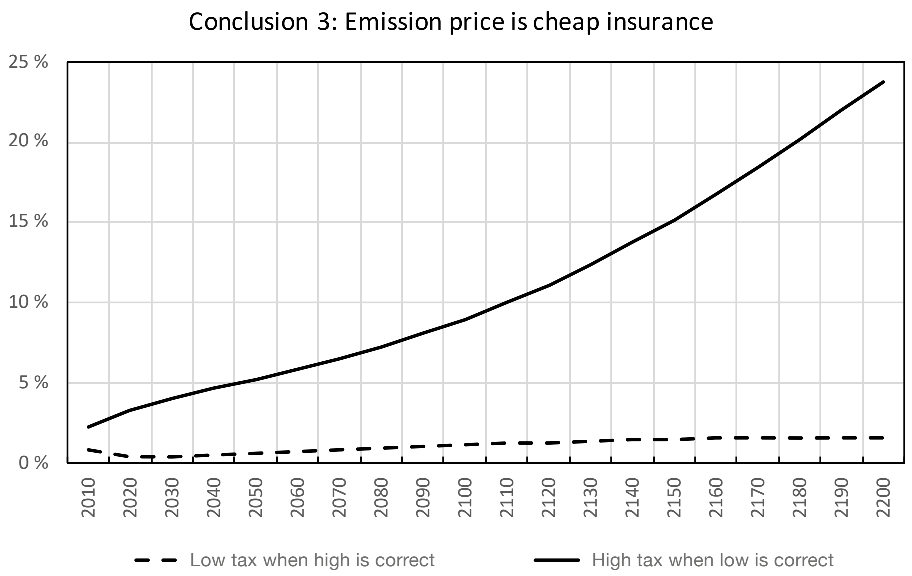
However, we argue that IAM's can provide valuable information also in a situation of such Knightian uncertainty. To illustrate this we note that given the large uncertainty, any chosen policy will ex-post turn out to be sub-optimal with probability one. But, all policy mistakes are not equally costly and the model can be used to evaluate this. A good policy recommendation in a situation of large uncertainty is to choose a policy that is robust, i.e., it is producing outcomes that are relatively insensitive to the things one is uncertain about.

Our simple application of this idea is to calculate the consequences of two policy mistakes. The first is to hope for the best and set a low carbon price that is optimal if the climate sensitivities to emission are low and climate damages are small. The policy mistake is realized ex post, when it turns out that climate sensitivities are high and climate damages large so that a high carbon price should have been chosen. The second policy mistake is the complete opposite. A high carbon price is chosen but ex-post it is realized that this was unnecessary since the climate sensitivity and climate damages are small.

To operationalize these ideas, we set the low climate sensitivity to the value at the lower end of the interval given by the climate panel IPCC.[4] Similarly, we set the high climate sensitivity to the value at the high end. Furthermore, we use a survey (Nordhaus and Moffat, 2017) of studies on global climate damages to get a similar range of the likely degree of damage sensitivity to climate change (see Hassler et al., 2018 for details). We use the end-values in this interval to generate a high and low economic sensitivity. In the best of cases, the climate sensitivity is low and the economic damage sensitivity is also low. If this turned out to be right, the optimal tax is low, according to our calculations only 6.9 USD per ton carbon (1.9 USD per ton CO_2). In the opposite case, high climate sensitivity and high economic damage sensitivity, the optimal tax becomes 264 USD per ton carbon (72 USD per ton CO_2). The first policy mistake is now to set the tax to 6.9 USD per ton carbon, while parameters are such that 264 USD is optimal. The second is to set it to 264 USD per ton carbon, while the right tax is 6.9.

[4] *We use another measure of climate sensitivity than the one discussed above, namely the increase in the global mean temperature associated with a doubling of the atmospheric CO_2-concentration. IPCC's likely range for this value is 1.5 to 4.5 degrees C. See Hassler et al. (2018) for details.*

Figure 3. Costs in terms of lost consumption for two types of policy mistakes



What we find is that these two types of policy mistakes have very different costs. The first, setting a low carbon price while a high turned out to have been right has much larger negative consequences than the opposite. Figure 3 depicts the cost of the two policy mistakes over time measured as a share of aggregate global consumption. As we see the costs are very different.

Note also that this is the cost of the policy mistake. In addition, welfare is of course much lower if the sensitivities are high for a given policy. The conclusion is therefore that an ambitious climate policy is a good insurance. It does not cost much if it turns out you don't need it but it is very good to have if you do. It should be noted, however, that the argument relies on using a global carbon price as the climate policy. One can certainly think of climate policies that achieve the aim of climate neutrality in very expensive ways. In this case, the precautionary argument for the policy does not fly.

Timing of fossil fuel phase-out

In the longer run, say during this century, all fossil fuels needs to be phased out. In this section I will discuss the question which order fuels should be phased out and how we should over time allocate a given amount of emissions across different fuels. A way to analyze this question is to think about what would happen to the use of different fuels if a tax that corrects the emission externality were to be introduced. Fuels that remain profitable when the correct tax is introduced are by construction socially valuable to use. Their private values are larger than the damages they incur. The opposite is true for fuels that cannot bear the correct tax without becoming unprofitable.

As discussed above, the level of the optimal tax on carbon emissions depends on highly uncertain parameters and is therefore very hard to pin down. However, the analysis does not require a precise value of the tax. Coal for heat and electricity production is unprofitable also under very modest taxes. The current price of emissions allowances in the EU-ETS, around 25 euros per ton of CO_2 equivalent to approximately 6 euro cent per liter gasoline, makes coal unprofitable. Even in the US, the coal industry is unprofitable. Since 2011, the Dow Jones U.S. Coal index is down 99%. Despite the supposedly coal-friendly policies of Donald Trump, the index fell by 70% during 2019 and another 70% this year.

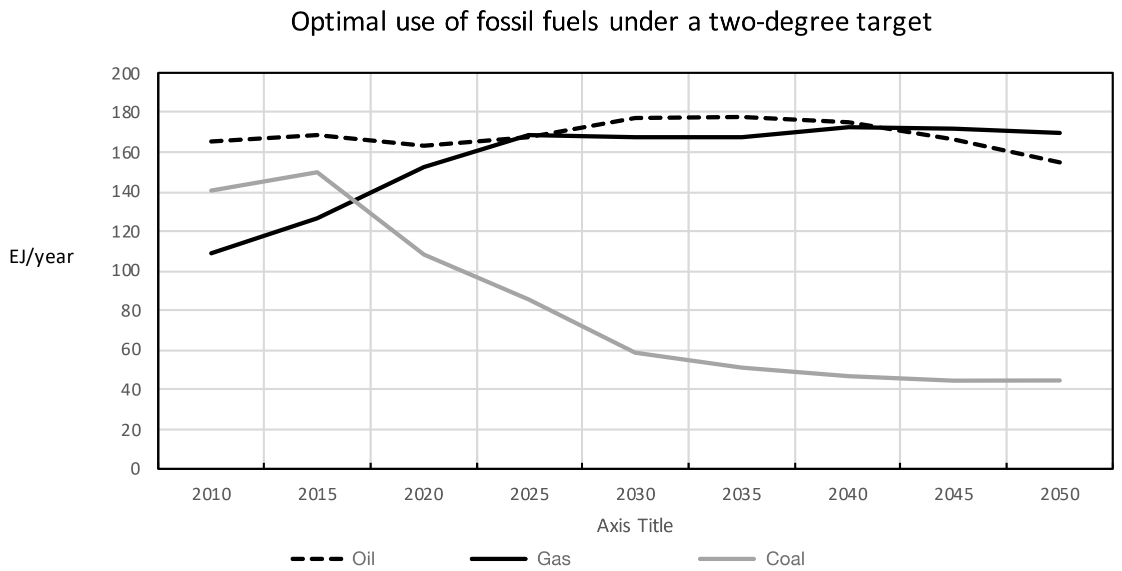
Conventional oil and gas are different. Even the high taxation of fossil fuels for transportation in Western Europe is clearly not making the sale of diesel and gasoline unprofitable. It certainly affects consumption and spurs the development of alternative green technologies. However, it is likely that conventional oil production will be profitable also with a carbon tax in line with the Swedish applied globally.[5]

Unconventional sources of oil and gas (e.g., from fracking, arctic reserves and tar-sand) are more sensitive to taxation. It is likely that a tax like the Swedish, and perhaps also lower rates, would make them unprofitable and take away the incentives to develop new techniques for using currently unprofitable sources of fossil fuel.

The conclusion from this somewhat informal analysis is that coal is the fossil fuel that should be phased out first and that most of the remaining reserves of it should stay in ground. Conventional oil and gas should be used, probably until we run out of it.[6] Unconventional reserves should stay in ground and new technologies for using them should not be developed.

My simple analysis can be done more elaborately. An example is McGlade and Ekins (2015). They calculate the optimal differential phase-out of coal, gas and oil under an emission budget that (with some probability) keeps global warming below 2 degrees C. The result of their analysis is depicted in figure 4.

Figure 4. Optimal phase-out of oil, natural gas and coal.



Conclusion and policy advice

Let me end the discussion by drawing some conclusions relevant for policy makers based on the research done by me and my colleagues, as well as many others.

1. A global agreement on a (minimum) price on fossil carbon emission is necessary. In fact it is also likely to be sufficient to curb climate change. So far, international negotiations have focused on country-specific quotas. The issue of an

[5] As a back-of-envelope calculation, we can note that a barrel of oil contains around 115 kg of carbon, producing 420 kg of CO_2 when burnt. The Swedish carbon tax of around 100 euros per ton CO_2 implies a tax in the order of 40 euros per barrel. This is sizeable, but in the same order of magnitude as the cost advantage of conventional oil over more unconventional sources.

[6] Who should use the conventional oil and gas is another question. On equity grounds, one could argue that we in the west should leave the oil for consumers in China, India and Africa.

agreement on a price has not seriously been at the negotiation table. Clearly, coming to such an agreement is not easy, but other ways are not likely to be easier.

How the price is implemented, with a tax or tradable emission allowances is not important to agree on. Neither is what is done with the revenue from the system. Our emission trading system EU-ETS is after the latest reforms in 2018 a show case. It shows that also a large region of quite heterogeneous countries can come to an agreement on an effective climate policy based on a price of emissions.

2. Coal is the main climate issue, neither oil nor gas. Unless we manage to convince the Chinese to phase out their coal dependence and make sure India and Africa don't follow the same coal intensive development path, we cannot solve the climate problem.

3. National climate policies must be designed with a global perspective in mind. Many well-intended national climate policies only move emissions to other countries. Such polices are fruitless and risk taking the focus away from the global issue. Certainly, rich countries like Sweden and Finland can affect others by being front-runners. A clever and cost-effective transition to climate neutrality that can be used in other countries is likely to be spur more followers than a costly one.

4. Subsidies to green technology may be a valuable complement to pricing of emission by facilitating the change, but it is not a substitute. Subsidies to technologies that can be used in other countries to de-carbonize are valuable. However, subsidies should not be used for technologies that are not scalable and only helpful for reaching national emission targets.

5. Limiting climate change to say, 2-2.5 degrees Celsius does not have to be expensive and should likely not lead to large global damages although regional climate damages can be devastating. Ill designed and uncoordinated climate policy may be excessively costly. □

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