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Energy and Climate

Richard S. J. Tol[a,b,c,d,e,f]

[a]Department of Economics, University of Sussex, Brighton, UK
[b]Institute for Environmental Studies, Vrije Universiteit, Amsterdam
[c]Department of Spatial Economics, Vrije Universiteit, Amsterdam
[d]Tinbergen Institute, Amsterdam
[e]CESifo, Munich
[f]Payne Institute for Earth Resources, Colorado School of Mines, Golden, Colorado

r.tol@sussex.ac.uk

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Richard S.J. Tol[a,b,c,d,e,f,*]

[a] *Department of Economics, University of Sussex, Falmer, United Kingdom*
[b] *Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands*
[c] *Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands*
[d] *Tinbergen Institute, Amsterdam, The Netherlands*
[e] *CESifo, Munich, Germany*
[f] *Payne Institute for Earth Resources, Colorado School of Mines, Golden, CO, USA*

Abstract

Carbon dioxide emissions have grown less fast than the economy because of improvements in energy efficiency. Switching to less carbon-intensive fuels and climate policy have played a minor role. Scenarios of future emissions are optimistic about economic growth and energy efficiency, and the higher scenarios assume resurgent coal use at odds with current trends. Climate policy is cheap for moderate targets and smart implementation. Costs are much higher for more realistic policies and for more stringent targets. The negative emissions required by the Paris Agreement would need large subsidies. Greenhouse gas emission reduction is a global public good that is hard to provide. Key players in the climate debate benefit from the rents created by inefficient policies, from causing confusion, and from mixing climate with other matters.

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1. Introduction

Energy market and energy policy are intricately linked with climate change and climate policy. Carbon dioxide is the main anthropogenic greenhouse gas causing climate change, and the burning of fossil fuel is the main source of carbon dioxide emissions. Fossil fuels are carbohydrates. Combustion breaks the chemical bond between the carbon and the hydrogen. Both are oxidized, to CO_2 and H_2O, respectively. More energy is released when new bonds are formed than when the old bonds are broken. Net energy is released. That is, CO_2 emissions are intrinsic to this process. You cannot get energy out of fossil fuel without forming CO_2. Unlike sulphur or particulates, which are externalities as well as nuisances to energy conversion, carbon dioxide is not a nuisance; it is a pure externality. You cannot

*Jubilee Building, BN1 9SL, UK
Email address: `r.tol@sussex.ac.uk` (Richard S.J. Tol)
URL: `https://research.vu.nl/en/persons/rsj-tol` (Richard S.J. Tol)

solve, or even substantially reduce the climate problem without deeply affecting the energy sector, and you cannot understand climate change and policy without knowledge of energy markets and policies.

In this chapter, I do three things in a mixture of tutorial, review, commentary and analysis. In Section 2, I discuss past trends in carbon dioxide emissions and scenarios of future emissions, placing these in the context of fuel resources and reserves. Section 3 treats technical options to reduce emissions, and the costs of deploying these options in the first- and second-best. Section 4 surveys some of the issues around climate policy.[1] Section 5 concludes.

2. Trends and scenarios

2.1. Trends in carbon dioxide emissions

The *Kaya Identity* is a useful tool to understand trends in emissions (Kaya, 1997). If applied to carbon dioxide from fossil fuel combustion, it looks as follows:

$$M = P \frac{Y}{P} \frac{E}{Y} \frac{M}{E} \tag{1}$$

where M denotes emissions, P population, Y Gross Domestic Product, and E primary energy use. Thus the Kaya Identity has that emissions equal the number of people times per capita income times energy intensity (energy use per unit of economic activity) times carbon intensity (emissions per unit of energy use). This is an identity. On the right-hand side of Equation (1), P cancels P, Y Y and E E so that $M = M$.

Although an identity, it is useful, and perhaps more so if expressed in proportional growth rates. Take logs on both side of Equation (1) and the first partial derivative to time. Then

$$\frac{\partial \ln M}{\partial t} = \frac{\partial \ln P}{\partial t} + \frac{\partial \ln \frac{Y}{P}}{\partial t} + \frac{\partial \ln \frac{E}{Y}}{\partial t} + \frac{\partial \ln \frac{M}{E}}{\partial t} \tag{2}$$

As

$$\frac{\partial \ln X}{\partial t} = \frac{1}{X} \frac{\partial X}{\partial t} = \frac{\dot{X}}{X} \tag{3}$$

the growth rate of emissions equals the growth rate of the population plus the growth rate of per capita income plus the growth rate of energy intensity plus the growth rate of carbon intensity.

Fossil fuels come in a number of varieties. Peat emits most CO_2 per unit of energy (99-117 tCO_2/TJ), followed by coal (98-109 tCO_2/TJ), oil (73-77 tCO_2/TJ), and natural gas (56-58 tCO_2/TJ).

Figure 1 shows global carbon dioxide emissions between 1971 and 2014.[2] CO_2 emissions rose by 2.0% per year. Why? The Kaya Identity allows us to interpret past trends. Population growth was 1.5% per year over the same period. Emissions per capita thus rose by 0.5%

[1] I do not discuss the impact of climate change on energy use. See Auffhammer and Mansur (2014) for an excellent review.

[2] Data from the World Bank.

per year. Per capita income rose by 1.8% per year, again slower than the emissions growth rate. Total income thus rose by 3.3% per year, considerably faster than emissions. This is primarily because the energy intensity of production fell by 1.4% per year. The carbon intensity of the energy system rose, by 0.1% per year. In other words, population and income growth drove emissions up, with a bit of help from a switch to more carbon-intensive fuels. This was partly offset by improvements in energy efficiency.

There was little climate policy for most of the period shown in Figure 1. Bell (2015) study the impact of the EU ETS on emissions, Murray and Maniloff (2015) RGGI, and Aichele and Felbermayr (2012) and Aichele and Felbermayr (2013) the Kyoto Protocol. They find modest emission reductions, not surprisingly as carbon prices have been low and coverage incomplete.

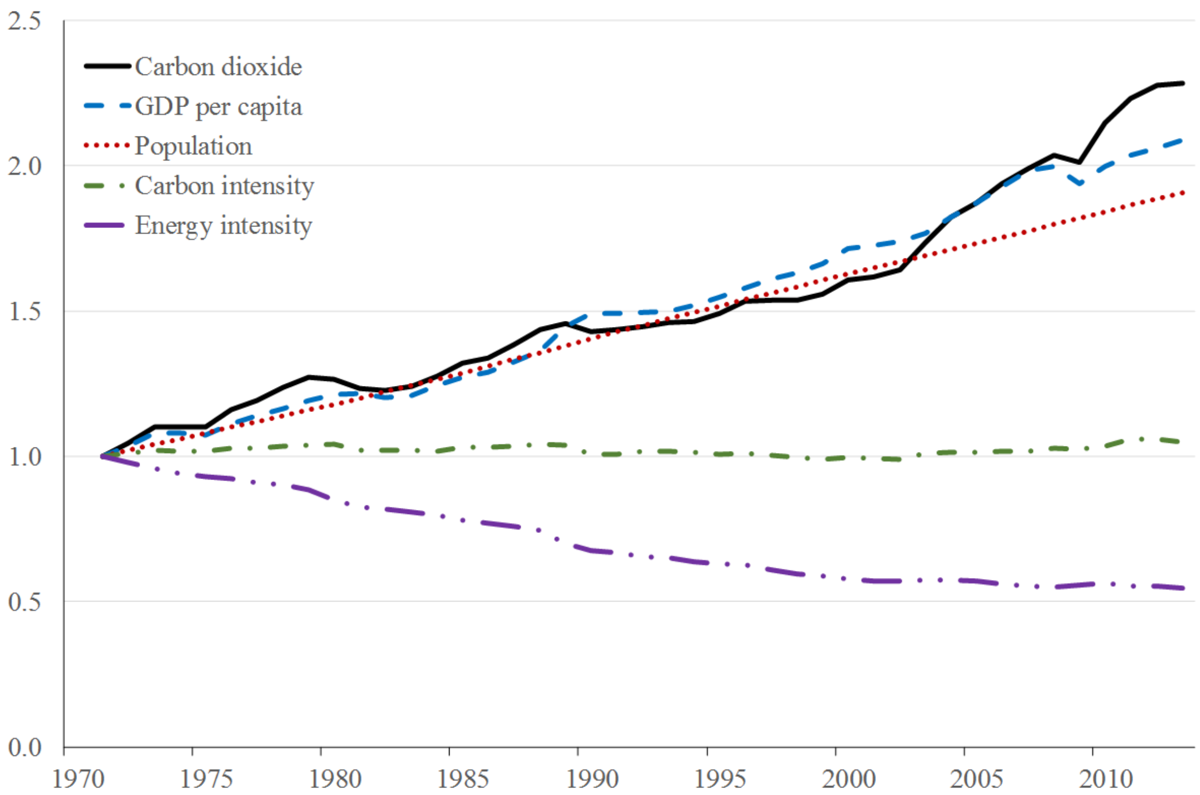


Figure 1: Global carbon dioxide emissions and its constituents.

2.2. Scenarios of future emissions

The Kaya Identity shows that, in order to project emissions into the future, we need to build scenarios of population growth, economic activity, energy use, and energy supply. Although our understanding of the processes of long-term development has considerably improved in recent decades, it does not permit any confidence in forecasts over a century or longer. Therefore, scenarios are built instead. Scenarios are not (conditional) predictions. Scenarios are not-implausible, internally consistent storylines of how the future might unfold.

Emission scenarios must include the number of people, but may also have their age structure—because that drives decisions on consumption and saving and hence economic growth and because people of different ages use energy differently (Dalton et al., 2008)—their education—because that drives labour productivity and hence growth and because people with different skills use energy differently (Gebreegziabher et al., 2012, Buechs and Schnepf, 2013) —and urbanization—because that drives travel and transport and hence energy use (Sadorsky, 2013). Emission scenarios must include per capita income, but may also have the structure of the economy—because certain sectors use more energy per unit value added than others (Hoekstra and Van Den Bergh, 2002)—and expenditure patterns—because air conditioning and long-distance holidays use a lot of energy (Reiss and White, 2005). Emission scenarios must include the energy intensity of economic production, and may include a range of primary and final energy sources and carriers—because emissions are more easily reduced in electrified transport than in liquid-fuel-based transport (Clarke et al., 2014). Emission scenarios must include the carbon intensity of the energy sector, and thus details of the supply of and demand for a range of different energy sources, their transformation and conversion, and transport of energy carriers.

There are two types of scenarios for climate change. In one, there is no climate policy. These are typically referred to as business-as-usual scenarios, although this is a bit of a misnomer as there has been climate policy in an increasing number of countries. In the other type of scenario, there is climate policy.

Figure 2 shows a key example of business-as-usual scenarios: the Shared Socioeconomic Pathways (SSPs) (van Vuuren et al., 2011, Riahi et al., 2017). Values are for the world as whole. The scenarios are broken down according to the Kaya Identity. The scenarios start in the year 2010. For comparison, the observed values for 1970-2010 are shown too. These scenarios were implemented with six alternative models. Figure 2 shows the mean plus or minus twice the standard deviation across these models.

There are five scenarios for each variable. However, two pairs of the population scenarios are really close together, while the income scenarios are more evenly spaced. The SSPs thus implicitly assume that population growth is independent of per capita income, an assumption at odds with everything we know about fertility and mortality (Galor and Weil, 1999, Herzer et al., 2012). All scenarios of per capita income show exponential growth, and most very rapid growth, even though some parts of the world have enjoyed little growth in the past. In the most pessimistic scenario, per capita income will roughly double. In 2100, the world average will be similar to the average income in Portugal in 2015. In the most optimistic scenario, per capita income will rise 14-fold. The world average in 2100 will be well above the 2015 average in Luxembourg. It is hard to imagine such richesse, but then again people in 1940 would not be able to imagine 2020 either. All scenarios show a steady improvement of energy efficiency, often at a rate that exceeds the experience of the last 40 years. Most scenarios show a steady fall in carbon intensity, even though recent history showed both decreases and increases. Although peculiar, the SSP scenarios form the basis of much research on climate change, its impacts, and policies to reduce greenhouse gas emissions.

The availability of fossil fuels is a crucial part of any scenario of future carbon dioxide

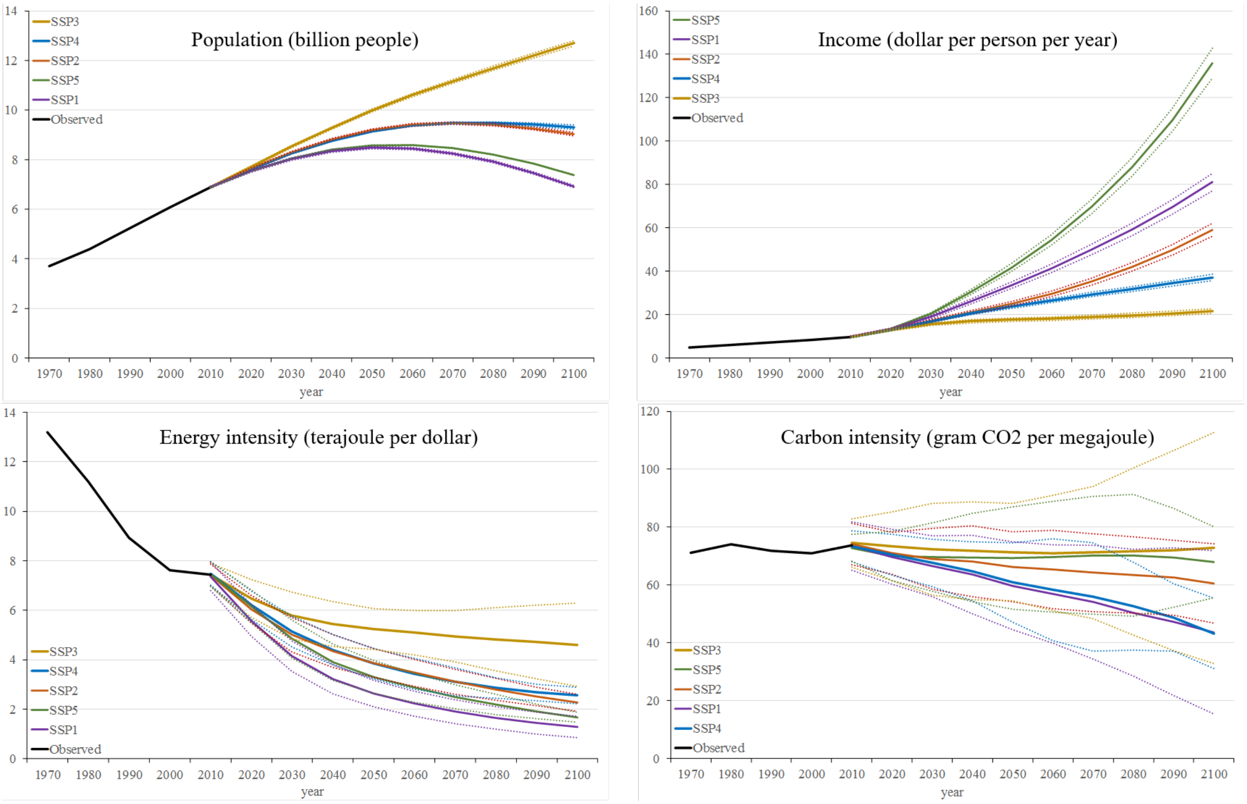
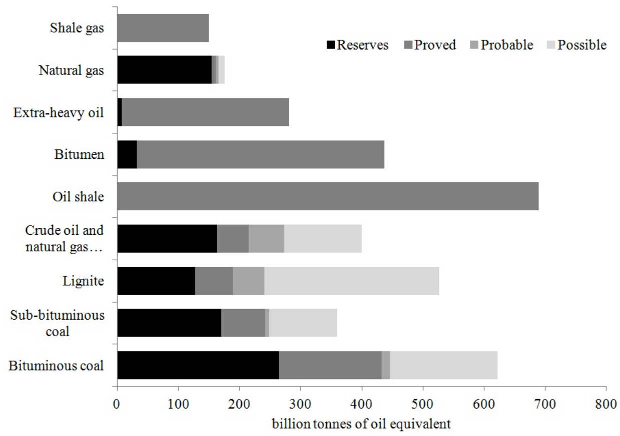


Figure 2: The SSP scenarios for the world broken down according to the Kaya Identity.

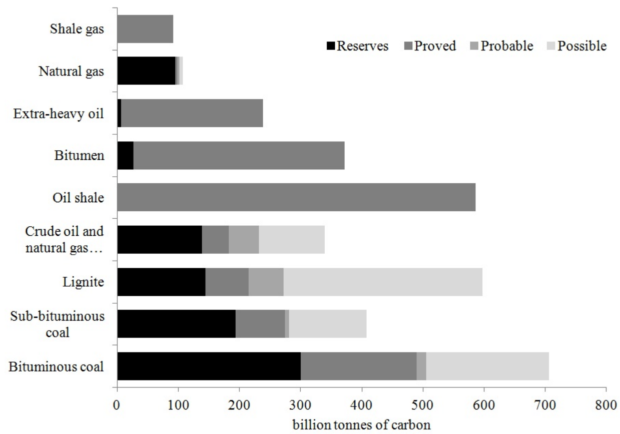
emissions. Figure 3 shows estimates of the reserves and resources of fossil fuels by type (WEC, 2010). The estimates are from 2010, when the shale gas revolution was tentatively reaching beyond the USA and the shale oil revolution was in its infancy. Reserves can be profitably exploited with current technology at current prices and costs. Resources are known or suspected to be there, and may become commercial in the future. Figure 3 reveals that conventional oil and gas reserves are relatively small: 317 billion tonnes of oil equivalent. In 2009, total primary energy use was 11.6 GTOE. There is therefore enough conventional oil and gas to cover energy demand for another 27 years. Figure 3 also reveals, however, that there are plenty of other types of fossil fuels, including coal and (what used to be) unconventional liquids and gases.

The second panel of Figure 3 shows the carbon dioxide emissions that would result if these fossil fuels were burned. For comparison, global 2008 emissions were 30 billion tonnes of CO_2. We can keep up current emissions for 100 years or more. The third panel shows the impact on the atmospheric concentration, should all available fossil fuels be burned at once. Conventional oil and gas can contribute only about 100 ppm. Other fossil fuels, reserves and resources, are worth another 1500 ppm.

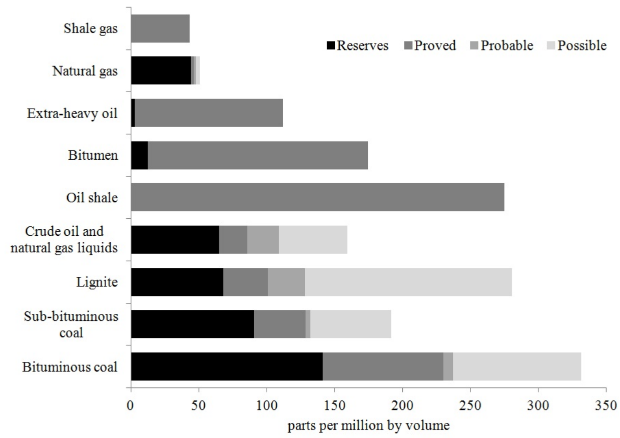
This implies that the climate problem is not driven by conventional oil and gas, but rather by what will replace conventional oil and gas when they run out. The future energy sector will therefore be very different. Different companies and countries will dominate.



Energy



Emissions



Concentrations

Figure 3: Fossil fuel reserves and resources as estimated for 2010 (top panel), their carbon content (middle panel), and implied carbon dioxide concentrations (bottom panel).

Table 1: Cumulative emissions projected over the 21st century in levels and as a share of gaseous+liquid and all fossil fuel reserves and proved resources.

Scenario	Level	Reserves		+ Resources	
	GtC	oil+gas	+coal	oil+gas	+coal
SSP1	1,002	375%	111%	64%	39%
SSP2	1,466	549%	162%	93%	58%
SSP3	1,758	621%	183%	106%	65%
SSP4	1,141	427%	126%	73%	45%
SSP5	2,056	770%	227%	131%	81%
6.0 Wm^{-2}	1,171	438%	129%	75%	46%
4.5 Wm^{-2}	820	307%	91%	52%	32%
3.4 Wm^{-2}	594	223%	66%	38%	23%
2.6 Wm^{-2}	373	139%	41%	24%	15%

Emissions are carbon dioxide emissions from fossil fuel combustion, cumulative over the period 2005-2100. Baseline scenarios are denoted by SSP*, policy scenarios by *Wm^{-1}. Results are averaged over models and, for the policy scenarios, baseline scenarios.

Technologies will be different too, and trillions of dollars will be invested in new equipment and infrastructure.

Table 1 further elaborates this. It compares cumulative emissions over the 21st century according to the five SSP scenarios to reserves and proven resources. In all scenarios, emissions exceed maximum emissions from gas and oil reserves, and from gas, oil and coal reserves. Two scenario exceeds gas, oil and oil reserves plus proven resources of gas and oil. No scenario exceeds gas, oil and coal reserves plus proven resources. As the scenarios project 80 years into the future, turning proven resources into reserves should be feasible.

Feasible is not the same as realistic. Coal is primarily used for power generation, where non-fossil alternatives are (close to) competitive. Ritchie and Dowlatabadi (2017) point out that the majority of coal reserves are low grade. For all that coal to be burned, we need to assume that heat transport will be electrified and power generation coal-based, or that liquified or gasified coal will be cheaper than biofuel.

3. Emission reduction

3.1. Options for emission reduction

The Kaya Identity allows us to assess how emissions can be cut. We would need to reduce population or income, or improve energy or carbon efficiency.

Fewer people is the first option (Bongaarts and O'Neill, 2018). Some murderous regimes in Africa and the Middle East actively seek to reduce the population of their countries. Few democratic countries would seek to emulate this in the name of climate policy. Indeed, population policy is controversial in most democracies. China, however, has often put forward its one-child policy as one of its major contributions to climate policy—although that policy dates back to a time when climate change was hardly recognized as a problem, and has recently been relaxed.

Slower economic growth is the second option (Kallis, 2011). The collapse of the former Soviet Union and its aftermath has shown that reducing the level of per capita income is an effective way of cutting greenhouse gas emissions (Bashmakov, 1994). The Great Recession further demonstrated the power of economic growth over emissions growth: The fall in carbon dioxide emissions in Europe is primarily due to its lacklustre economic performance (Bel and Joseph, 2015). However, promoting slower economic growth is not recommended to a politician seeking re-election.

That leaves us with just two of the four terms in the Kaya Identity.

Energy efficiency improvements have kept the rise of carbon dioxide emissions in check. This is shown in Figure 1 for recent times, but has been true for much longer (Nordhaus, 1996, Fouquet, 2008). Energy efficiency is likely to further improve in the future regardless of climate policy. This is because energy is a cost. A gadget that is the identical to its competitor but uses less energy is more appealing to customers. Companies therefore invest in improving the energy efficiency of their products.

Energy efficiency improvement does not necessarily imply reduced energy use (Schwarz and Taylor, 1995). For instance, the fuel efficiency of the US car fleet was roughly constant between 1980 and 2010. This is a remarkable feat of engineering as, over the same period, the size and weight of cars increased considerably.[3] The gains in fuel efficiency were used not to reduce energy use, but rather to increase comfort.

There is also the *rebound effect*, first formulated by Jevons (1865). Better energy efficiency means lower energy costs means higher energy use. Improving the insulation of homes, for instance, means that it is cheaper to heat the house. This often leads to higher indoor temperature at the expense of reduced energy use. Better fuel efficiency means it is cheaper to drive a long distance. This leads to longer drives. Estimates of the size of the rebound effect vary widely. This is no surprise as energy is used for so many different things in so many different ways. Typical estimates have that the rebound effect is 10-20% (Greening et al., 2000, Sorrell et al., 2009). That is, increased energy demand offsets one-tenth to one-fifth of the initial reduction in energy use.

Besides technical change, behavioural change can also reduce emissions (Kahn, 2007, Allcott, 2011). Engineers reckon that some 30% of energy used serves no purpose.[4] It is, however, easier to identify energy waste than to reduce it. People may boil a kettle full of water to make a single cup of tea. People may leave the light on in the bathroom. Most would agree they should not, but do it anyway. Government awareness campaigns are not particularly effective, and social pressure can be unpleasant.

Energy is also wasted because of misaligned incentives. A university lecturer is responsible for turning off teaching equipment at the end of class, but the money thus saved will disappear into the overall budget of the college. A landlord is responsible for building main-

[3] See EPA.

[4] This should be taken with a grain of salt. Experts also reckon that 30% of food is wasted, 30% of mobile data, and 30% of health spending.

tenance and retrofit, but the tenant often pays the energy bills. The costs of wall insulation cannot usually be recouped from increased rents, because running costs are not typically known to prospective renters (Fuerst and McAllister, 2011, Im et al., 2017).[5] If the rental market is tight, landlords have little reason to invest in maintenance. Solving these *principal-agent* problems—the principal pays the bills, the agent makes the decisions—make for nice exercises in industrial organisation, but reality is more resistant (Laffont and Martimort, 2009).

Lower energy demand is another form of behavioural change. People can put on a sweater and turn down the thermostat. They can move closer to work and cycle instead of drive. They can shower less. They can go for a staycation rather than a holiday in the Kingdom of Far Far Away. Only a small minority is prepared to make these changes for a better climate.

The carbon intensity of the energy sector is the fourth component of the Kaya Identity. The carbon intensity is improved by switching from high-carbon energy sources to low- or no-carbon energy. In recent years, power generation in the USA has switched from coal to gas and carbon dioxide emissions fell as a result.[6] This was done because the shale gas revolution brought abundant and cheap natural gas. In Europe, the opposite has happened.[7] With a population wary of fracking, cheap American coal has replaced natural gas and emissions have gone up. Japan and Germany have taken it a step further, replacing carbon-free nuclear power by gas, coal and even lignite.

There are several carbon-free energy sources. Hydropower and nuclear power are proven technologies (WEC, 2016d,f). Both are controversial. Hydropower needs a reservoir, displacing people and valuable agricultural land. With nuclear power, people worry about nuclear waste and safety—problems of the past, if you ask me, but the resulting escalation of costs is a concern—and about proliferation of nuclear material and knowledge for military application. Because of this, there is limited scope for a large expansion on nuclear and hydropower.

Besides hydropower, there are many other renewables sources of energy. Some renewables are confined to small niches, such as geothermal energy and tidal power (WEC, 2016c,e). Other renewables are more widely applicable (WEC, 2016h,g). Wind power is a key part of the carbon dioxide emission reduction strategy in many countries. Onshore wind power is 25-50% more expensive than coal- and gas-fired electricity—although approaching grid parity[8] in some areas. Offshore wind is more expensive still (IRENA, 2018). There has been some progress in reducing the costs, particularly through scale and material choice, but as wind is an established technology, breakthroughs are not expected. Cost savings come from scale economies. Besides the costs, wind power is intermittent and unpredictable. Backup generators are needed to prevent blackouts. On top of that, there is opposition to the visual intrusion of wind turbines, and turbines kill bats and birds.

[5] If the landlord covers the energy bill, energy use increase (Levinson and Niemann, 2004).

[6] See EIA.

[7] See EuroStat.

[8] A source of electricity is at grid parity if it can compete with other electricity supplies without government support.

Solar power is another key part of many a emission reduction policy. Apart from niche applications, solar power is expensive still, but costs have fallen faster and are likely to continue to fall rapidly (IRENA, 2018). This is because photovoltaic power piggybacks on technological progress in materials science and semiconductors. Intermittency is less than with wind, but photovoltaics do not work in the dark. Solar panels contain nasty chemicals and should be carefully disposed at the end of their life time. Concentrated solar power, where sunlight is used to heat a material like water or salt, does have the momentum to be a reliable and dispatchable energy source, and it is at or near grid parity in sunny places with cheap land.

Biomass is the most widely used renewable source of energy, but primarily in its traditional forms—wood, dried dung (WEC, 2016a). Unlike wind and solar power, bioenergy can be used to substitute the liquid fuels that propel most vehicles, ships and aircraft. The first generation of modern biofuels are expensive, and the materials used are often edible. Bioenergy use thus drives up the price of food (Ciaian and Kancs, 2011, Lotze-Campen et al., 2014). There is much research into second and third generation process, but little commercial application. Second generation bioenergy would use the same materials, thus directly competing with food production, but with improved processing. Fossil fuels are plant material nicely dried, compacted and converted by Mother Nature over millions of years. Biomass energy is recent plant material that needs to be gathered, dried, compacted and converted by people and their machines. As this is relatively new, progress can be expected in bringing down the costs. Third generation bioenergy uses different or modified source material. Over the last 10,000 years, we have optimized plants for food, but we have never much bothered with optimizing plants for energy. Rapid progress can therefore be expected, particularly now that genetic engineering is routine. However, although there regularly is exciting news from the lab, there has yet to be successful commercialisation (Guo et al., 2015, Enamala et al., 2018, Widjaya et al., 2018).

The Kaya Identity is about the structural causes of emissions and structural solutions. There is also an end-of-pipe solution: Carbon capture and storage (CCS). In CCS, carbon dioxide is separated before, during, or after burning. It is then captured and transported to be stored in a safe place (WEC, 2016b). Carbon capture requires capital and energy. In a conventional power plant, the investment cost of a power plant with capture is substantially higher than that of a similar plant without, and a large share of the energy output of the plant will be devoted to carbon capture (Davison, 2007, Rubin et al., 2007). The costs of carbon capture can be brought down with a radical redesign of power plants, for example the Allam Cycle (Allam et al., 2014), but that is as yet untested at scale. Transport of CO_2 is costly too. According to some estimates, if we want to capture all carbon dioxide from power generation, the transport network would be several times bigger than the network for oil and gas. The main issues with storage are permanence and safety. There is little point in storing carbon dioxide if it leaks out again. Sudden releases of carbon dioxide would endanger animal and human life.

3.2. The costs of emission reduction

Emission reduction costs money (Weyant, 1993, Clarke et al., 2014). There are various ways to look at this. Without climate policy, greenhouse gas emissions are free. With climate policy, emissions are not. Alternatively, climate policy imposes a new constraint on a maximization problem. If the constraint bites—that is, if emissions are lower than they otherwise would have been—the objective function must fall. Put yet another way, climate policy forces people and companies to use different technologies and different fuels than they would have without climate policy. Without climate policy, these technologies and fuels are available, but people choose not to use them, or not to the same extent. Climate policy gets people and companies to invest more in energy savings than they would of their own volition, and gets them to switch to more expensive energy sources.

It is difficult to estimate the costs of climate policy. Most climate policy analysis is done *ex ante*, comparing two hypothetical situations, with and without the policy. Ex post analysis compares observed history to a counterfactual. Cost estimates are only as good as the models used. Not all models are equally good, partly because there is little existing climate policy to calibrate models to, and partly because little attention is paid to model calibration (Tol, 2014).

Most studies agree that a complete decarbonization of the economy can be achieved at a reasonable cost if policies are smart, comprehensive and gradual. Models disagree, however, on how much emission reduction would cost. This is illustrated in Figure 4: emission reduction costs vary by an order of magnitude or more.[9]

There are various reasons for this. Modellers make different assumptions about what options are available to reduce greenhouse gas emissions, and at what cost. Obviously, if a model omits an option—say, hydrogen fuel-cells for private transport—or assumes that its costs are high, then that model will find that emission reduction is more expensive. Vice versa, if a model assumes that an option exists—say, unlimited capacity for carbon storage—or puts its costs at a lower level than what is commonly believed, then that model will find that emission reduction is less expensive.

The rate of technological change is a key determinant of future emission reduction costs (Clarke et al., 2008). The difference in the costs between carbon-neutral energy (solar, wind, nuclear) and carbon-emitting energy (coal, oil, gas), for instance, is a key assumption: emission reduction would be cheap if solar is only slightly more expensive than coal. That cost difference is reasonably well known for the present and past, but has to be assumed for the future. If technology advances faster in carbon-neutral energy than in carbon-emitting energy—say, solar is getting cheaper faster than coal—abatement cost are lower. Different models make different assumptions about the rates of technological progress.

Some models assume that progress in carbon-saving technologies accelerates in response to climate policy. Other models do not have such a response. The latter models thus has slower technological progress in energy efficiency and renewables, and higher costs of emission reduction. Some models assume that there is no opportunity cost to accelerating

[9] The results are from the SSP database. These results are an update of a subsample of the results shown in Clarke et al. (2014). The older, larger sample shows an even greater variation of results.

technological progress in energy; others do include an opportunity cost. Perhaps there are highly educated taxi-drivers, who would make a real contribution to the next generation of solar cells if only there were government support. But perhaps hiring clever people to work on solar power means that they will not work in materials science. These alternative assumptions further explain the wide range in cost estimates (Lans Bovenberg and Smulders, 1995, Goulder and Schneider, 1999, Goulder and Mathai, 2000, Smulders and de Nooij, 2003).

If a model assumes high price elasticities, high substitution elasticities, and rapid depreciation of capital, its cost estimates will be lower than of a model with low price elasticities, low substitution elasticities, and slow turnover of the capital stock. The latter model assumes that the world of energy use is set in its carbon-intensive ways, which makes it hard and expensive to change course.

Finally, some models assume that, in the scenario without climate policy, greenhouse gas emissions will not grow very fast. Consequently, emission targets (which are typically formulated as absolute targets) are within easy reach. Other models assume rapidly rising emissions, so that a large effort is needed to meet emissions targets.

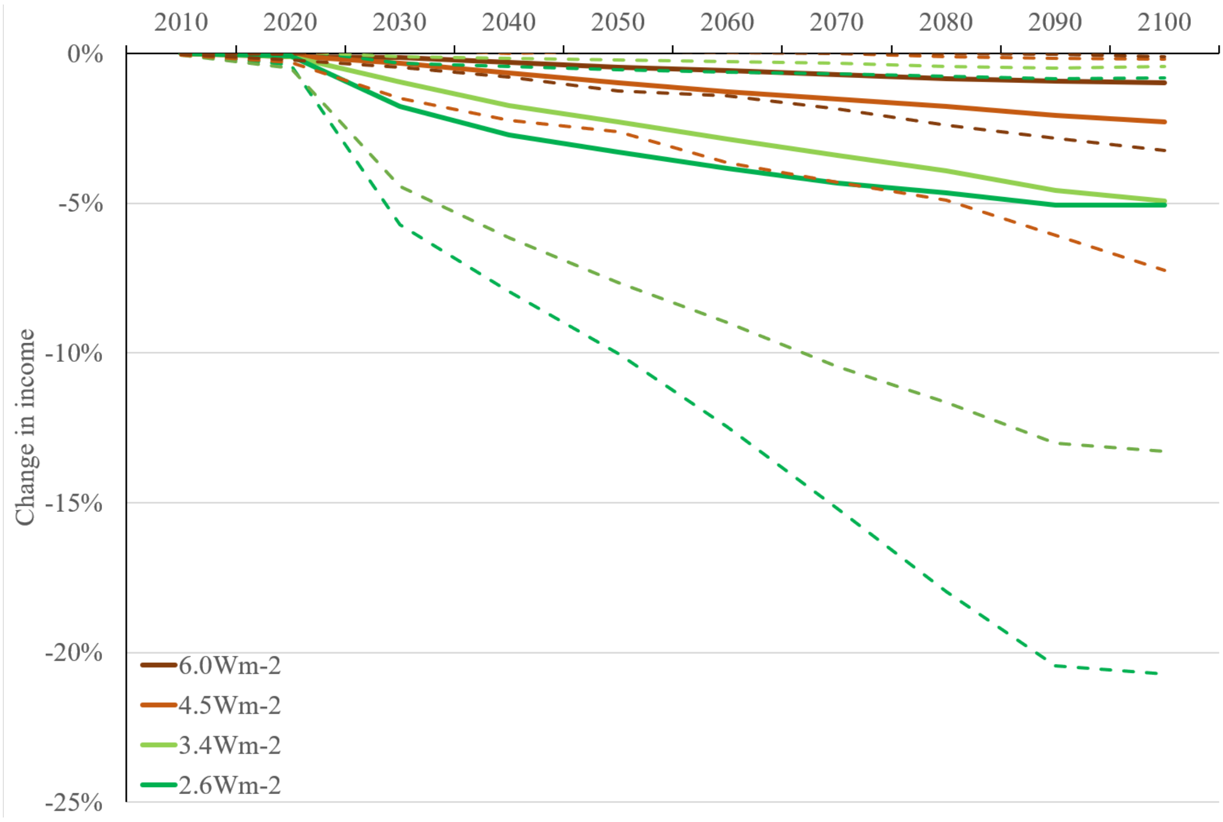


Figure 4: Total cost of emission reduction for the model average (solid line) and the most optimistic/pessimistic model (dashed lines) for four alternative atmospheric stabilization targets.

The concentration target is the key policy variation in Figure 4. The more stringent the target, the higher the cost—and costs rise very rapidly from the more lenient to the more ambitious targets.

Participation of poorer countries in climate policy is another variation in policy scenarios (Clarke et al., 2009). This has a large impact on the estimated cost of emission reduction. If poorer countries are initially exempt from emission reduction, a fraction of emission is excluded from abatement, the rest will have to be reduced more to meet the same target. As emission reduction costs are more than linear in emission reduction effort, this necessarily drives up the total costs. Furthermore, many of the cheaper emission reduction options can be found in poorer countries, partly because these economies tend to rely on older, less efficient technology, and partly because money buys more in poorer countries.

Wigley et al. (1996) and Manne and Richels (2004) provide insight into the allocation of emission reduction effort over time, contrasting emission trajectories that start with radical emission cuts to ones that begin with modest abatement that accelerates over time. Cost savings vary between 10% and 60% depending on the model.

There are four reasons why money is saved if emission reduction targets are lenient at first while becoming more stringent over time. Greenhouse gas emissions are to a large degree determined by things that change only slowly, such as machinery and buildings, technology blueprints, and location choice. Emission reduction requires changes in behaviour and technology, but behaviour and technology are constrained by durable consumption goods and invested capital. A carbon tax does not reduce the emissions of those households and companies that continue to use the same cars, live and work in the same place and in the same building, and operate the same machinery. In those cases, a carbon tax simply imposes a penalty on investment decisions made in earlier, pre-climate-policy times. In other words, rapid emission reduction implies capital destruction, particularly rapid emission reduction that was unexpected when investment decisions were made. This is a deadweight loss to the economy. This deadweight loss falls over time as capital turns over, so that the carbon tax can increase without inducing excessive costs.

Technological change is another reason why emission reduction is expensive in the short term but cheaper in the medium to long term. Carbon-neutral energy is still immature technology. Although fossil fuel technology continues to progress, it is well developed and all the easy improvements have been made. Although there has been rapid progress in oil and gas exploitation, this has been about unlocking relatively expensive reserves, such as shale oil and gas. In contrast, we can still expect major technological breakthroughs with solar power and bioenergy. Furthermore, the easily accessible sources of fossil fuels are getting exhausted. So, over time, we expect the costs of fossil fuels to rise and the costs of renewables to fall. As the costs of emission reduction are driven by the difference in costs between fossil and renewable energy, abatement costs should fall over time.

Third, emission reduction costs in the future are discounted. The discount rate makes that costs incurred in the future are less important than costs incurred today. Postponing emission reduction reduces the net present value of the costs.

Fourth, emissions are degraded in the atmosphere. Climate policy targets typically refer to the long term, say the year 2100. Emissions in 2090 are more important to concentrations in 2100 than emissions in 2020. Put differently, later emission reduction is more effective than earlier emission reduction. Atmospheric degradation thus functions as a discount rate, so that it is better to reduce emissions later.

Figure 5 complements Figure 4. It shows results for the same set of models and the same set of scenarios, but now for the marginal abatement costs. This is best thought of as the carbon tax imposed on all greenhouse gas emissions from all economic activities in all countries. Per policy scenario, the models again disagree by an order of magnitude or more. The initial carbon tax required for meeting the least stringent target is modest, but this escalates with increased stringency.

The most stringent target—2.6 Wm^{-2}, roughly equivalent to keeping global warming at 2.0°C above pre-industrial, as agreed in Paris 2015—requires a \$14/tCO_2 carbon tax in 2020 (according to the average model). This is similar to the current carbon price in the EU and California, but the models assume that this carbon price applies to all greenhouse gas emissions from all sectors and in all countries. The carbon tax rises to \$90/tCO_2 in 2030 and to \$2,057/tCO_2 in 2100. The most pessimistic model has a global carbon tax of \$41/tCO_2 in 2020, rising to \$361/tCO_2 in 2030 and \$8,321/tCO_2 in 2100.

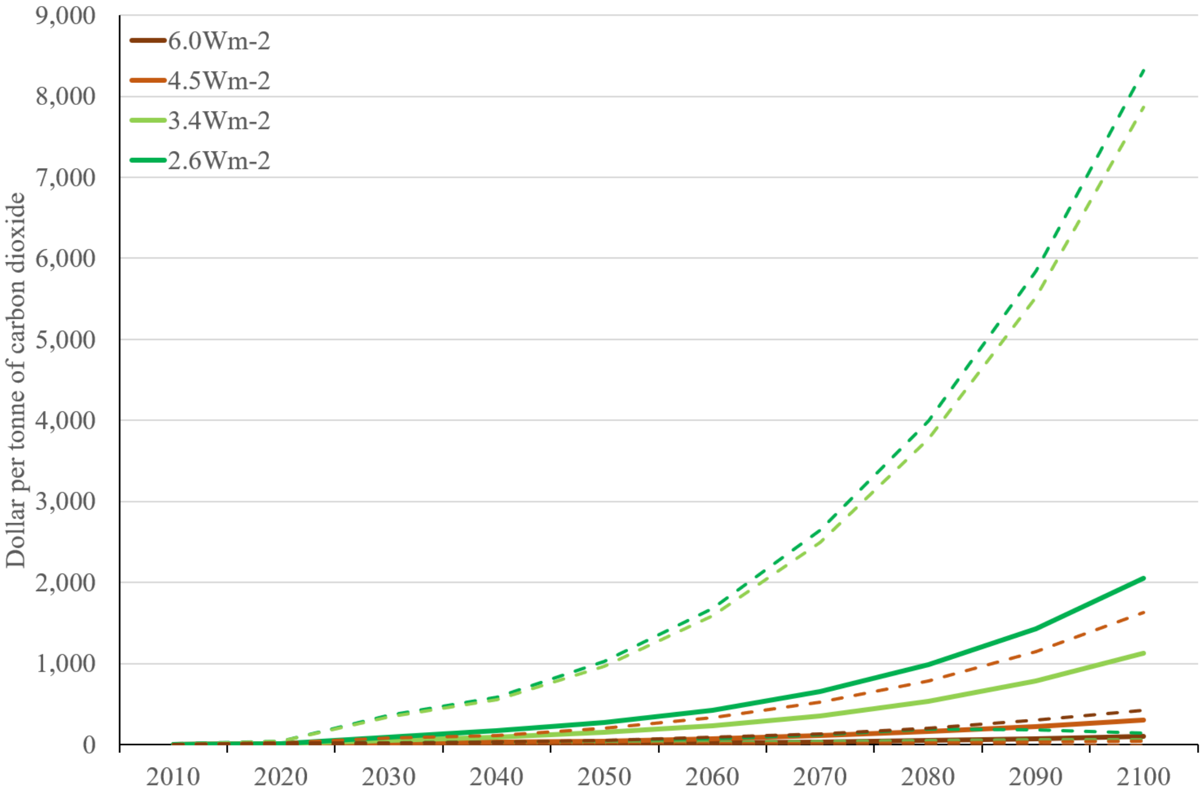


Figure 5: Carbon tax for the model average (solid line) and the most optimistic/pessimistic model (dashed lines) for four alternative atmospheric stabilization targets.

Clarke et al. (2009) found that the 2°C target is infeasible for physical, technical, economic or political reasons, a result echoed by the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) (Barker et al., 2007). Tavoni and Tol (2010) note that the aggregate results in the IPCC suffer from sample selection bias: Only the models in which emission reduction is cheap, report costs for the most stringent policy targets. As the more stringent targets are more relevant for policy, there is attrition bias too. Some models were used in both AR4 and AR5 (Clarke et al., 2014). In AR4, these models reported on average a carbon tax of \$13.83/tCO_2 needed in the near-term to meet a 550 ppm CO_2eq target by 2100, with a standard error of 1.70. The models that were used in AR4 but not in AR5 reported an average carbon tax of \$27.57/tCO_2 with a standard error of 2.24. The difference in means is close to significant ($p = 0.06$).

There is a political demand for the analysis of ambitious climate targets, initially focused on the 2.0°C target and more recently 1.5°C. Modellers have met that demand by expanding options for negative emissions. This includes negative carbon energy—biomass with carbon capture and storage (Wise et al., 2009)—and direct air capture—artificial photosynthesis or some other chemical process to remove carbon dioxide from the atmosphere (House et al., 2011).

Figure 6 shows just how much emissions will need to be cut in order to meet the more ambitious targets. In one scenarios, emissions will peak in 2050, in another in 2030. In the two remaining scenarios, emissions will peak in 2020. In the same two scenarios, emissions will be net negative by 2100. In 2010, carbon dioxide emissions were about 36 billion tonnes a year. Averaged across models, for the most ambitious policy target, in 2100, carbon dioxide emissions are a *negative* 10 billion tonnes per year.

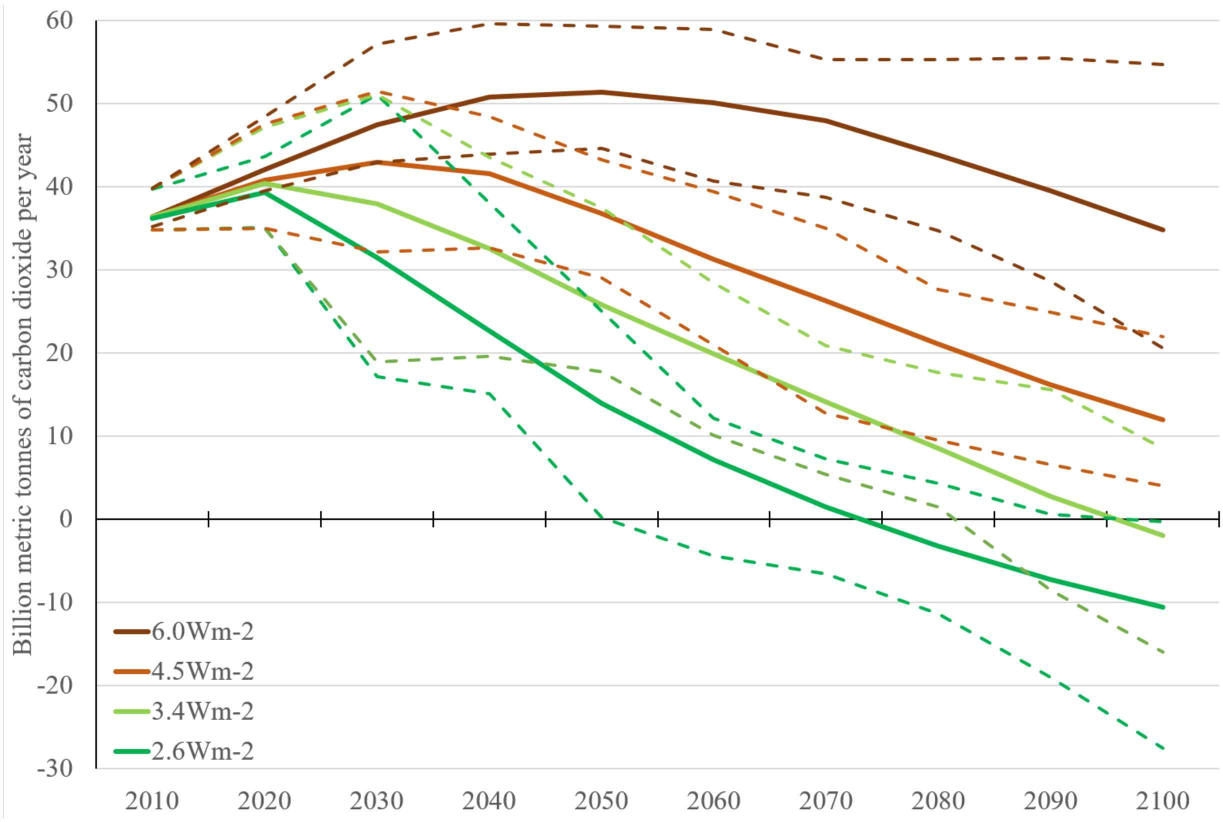


Figure 6: Carbon dioxide emission trajectories to stabilize the climate for the model average (solid line) and the most optimistic/pessimistic model (dashed lines) at four alternative levels of radiative forcing.

As they grow, energy crops remove carbon dioxide from the atmosphere. This requires and deserves a carbon subsidy. If we take the above 10 $GtCO_2$ and a carbon tax of \$2,000/tCO_2, the net carbon subsidy will thus be 20 trillion dollars per year, almost 4% of GDP. See Figure 7. This is the central estimate. In the worst case, this is almost 17%. Carbon subsidies may thus pose a very substantial burden on either the public finances or taxpayers. The central estimate is comparable to current spending on defense in the USA, the worst case to health care. Besides the cost, incidence is problematic too. Energy crops will be grown in monoculture on large farms, probably corporate farms, and certainly heavily mechanized farms. Processing will similarly be done by large firms. It is hard to imagine an electoral strategy that would sustain a stream of large subsidies to agri-energy multinationals, particularly if negative carbon energy is successful and the threat of climate change recedes.

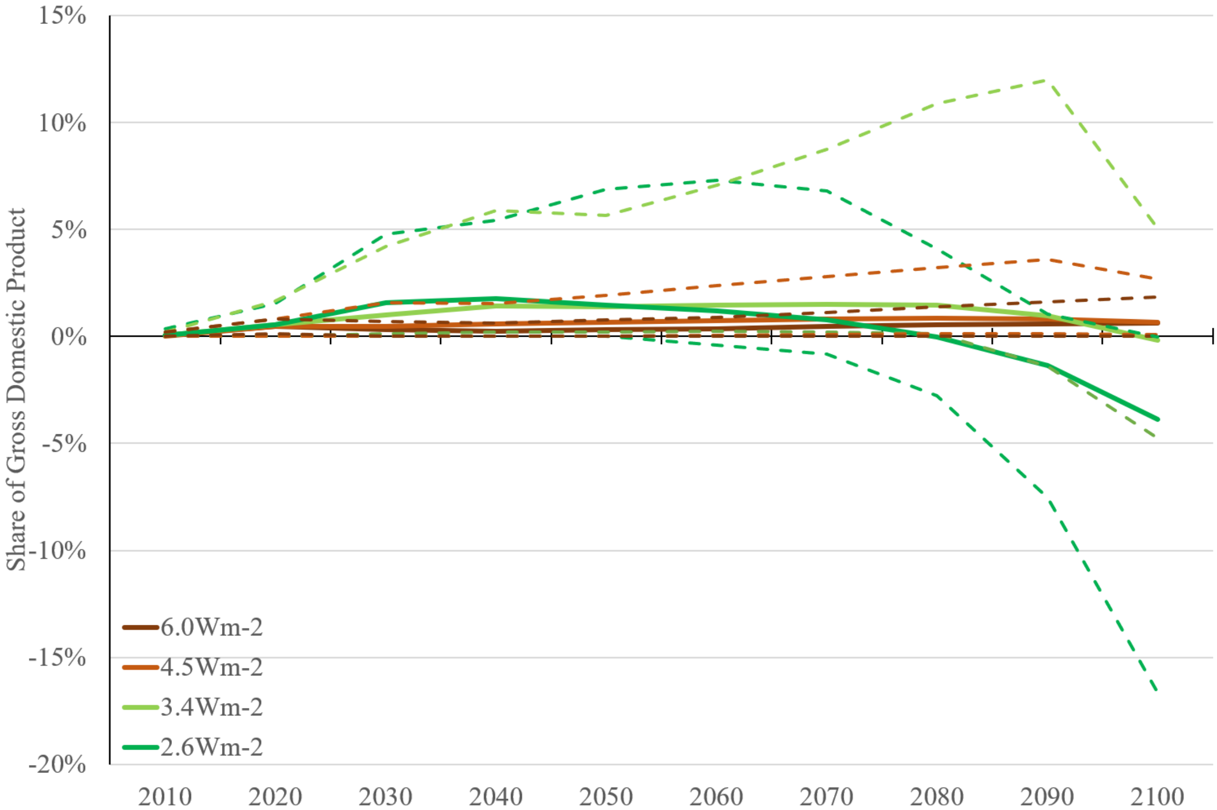


Figure 7: Carbon tax revenue for the model average (solid line) and the most optimistic/pessimistic model (dashed lines) for four alternative atmospheric stabilization targets.

3.3. Double dividends

There are claims that the costs of emission reduction are negative—that is, that it would be possible to save emissions and save money at the same time. Some of the claims are the result of bad accounting. Two common mistakes are the following. First, people confuse the technological change that is part of the no-policy scenario with the accelerated technological change in the policy scenario. The no-policy scenario indeed contains a large number of actions that are both commercially viable and reduce emissions. Energy efficiency improves over time, also in the absence of climate policy. Because these investments are commercially viable, they do not need policy support—and it is thus wrong to attribute them to climate policy.

Another common mistake is to underestimate the costs of investment—this is often referred to as the *energy paradox* (Jaffe and Stavins, 1994, Metcalf and Hassett, 1999, van Soest and Bulte, 2001, Greene, 2011, Allcott and Wozny, 2014). Most greenhouse gas emission reduction requires an upfront investment (e.g., wall insulation, solar panel) in return for lower energy costs later. The discount rate is thus crucial in determining whether this investment is worthwhile. Some analysts assume that households and companies can borrow money at the same rate of interest as the government can. In fact, private rates of interest tend to be higher than public ones. That makes investment less attractive. As another example, well-established technologies have acquired a reputation and a dense network of mechanics for installation, maintenance and repair. New technologies lack those, a cost that is easily overlooked.

That said, there may be genuine reasons why the costs of emission abatement may be different than suggested above—perhaps smaller or even negative. The models in these tables are either optimization models or equilibrium models. A market equilibrium is a Pareto optimum. If the no policy scenario is an optimum, any policy intervention bears a cost.

In reality, however, the no-climate-policy case is characterized by many market imperfections and policy distortions. Climate policy may overcome some of these, and this would reduce its costs.

A carbon tax is one way to implement climate policy. A carbon tax raises energy prices, the *carbon tax effect*. Like any tax, a carbon tax is distortionary. In an undistorted market, rational actors find a Pareto optimum. A tax changes the choices people make, and leads that market to an equilibrium with lower welfare. The welfare loss is a measure for the degree of distortion of the tax.

However, a carbon tax brings revenue too, and that revenue could be used to reduce other, more distortionary taxes (Bovenberg and van der Ploeg, 1994, Goulder, 1995, Bovenberg and Goulder, 1996, Bovenberg, 1999, Parry and Bento, 2000). Taxes are distortionary because they distort behaviour, moving people and companies away from the Pareto optimum, making them do things they would rather not. Taxes are more distortionary if they are higher, if price elasticities are higher (because behaviour is more responsive), and if the tax base is narrower (as fewer people are affected, by definition, then, for the same revenue, the behaviour of those people is further distorted). A carbon tax starts from a low level, price elasticities are low, and a carbon tax has a broad base. It is therefore not particularly distortionary (even though it is specifically designed to change behaviour). If the carbon tax revenue is used to reduce another tax, there may well be a benefit—and that benefit may more than offset the initial cost of abatement. This is known as the *revenue-recycling effect*.

Let us assume that the revenue of the carbon tax is used to reduce the labour tax. A labour tax drives a wedge between the marginal productivity of the worker—the willingness to pay of the employer for the employee's efforts—and the marginal value of leisure—the willingness to accept compensation for the employee for giving up leisure. A labour tax thus reduces welfare and employment. Reducing the labour tax using the revenues of the carbon tax then increases welfare and employment.

Energy is a necessary good, so carbon taxes tend to be regressive, hurting the poor more than the rich. A reduction in labour taxes only helps the poor who are (potentially) in the labour market and who earn more than the personal exemption. A reduction in value-added tax disproportionally benefits all on the lower end of the income distribution. There may be a triple dividend: lower emissions, faster economic growth, and less inequality (Mayeres and Proost, 2001, van Heerden et al., 2006).

There is third effect, however: The *tax-interaction effect*. A carbon tax increases the price of energy. As energy use is ubiquitous, all other prices increase too. The real wage falls—that is, the reward for labour falls. In other words, the revenue-recycling effect implies a smaller wedge between marginal productivity and marginal leisure but the tax-interaction effect leads to a large wedge. The carbon tax, through its effect on prices, increases the distortionarity of the labour tax. There are theoretical models in which the tax-interaction effect is necessarily larger, in absolute terms, than the revenue-recycling effect.

Applied models show mixed evidence (Bosquet, 2000). Results depend on the starting point. In Europe, labour taxes tend to be high and are thus a prime target for a beneficial reduction. In the USA, tax reform that stimulates savings and investment is more desirable. Results also depend on assumptions about market structure and elasticities. The revenue of a carbon tax may be used to reduce other taxes and this would bring benefits that at least partially offset the costs of emission reduction. If the tax reform is well-tailored to the specific circumstances of the fiscal system, then that benefit may be substantial. It is not the case that any use of the revenue is beneficial: It may be used to increase hand-outs to friends and allies of the government. It is also not the case that any tax reform is equally beneficial. The benefits that exist in theory are not necessarily realized in practice.

3.4. Suboptimal regulation

While there is a large literature on the double dividend, discussing whether regulatory and fiscal imperfections could be explored to reduce the costs of emission abatement, less attention has been paid to how imperfect climate policy might increase said costs.

Under ideal conditions, first-best regulation is straightforward: The costs of emission reduction should be equated, at the margin, for all sources of emissions (Baumol and Oates, 1971). Governments routinely violate this principle, with different implicit and even explicit carbon prices for different sectors and for differently sized companies within sectors. Although climate change is a single externality, emitters are often subject to multiple regulations on their greenhouse gas emissions (Boehringer et al., 2008, Boehringer and Rosendahl, 2010). Regulations often aimed at a poor proxy for emissions rather than at emissions directly (Proost and Van Dender, 2001), and instrument choice may be suboptimal (Webster et al., 2010).

Conditions are not ideal. Optimal policy deviates from the principle of equal marginal costs to accommodate for market power (Baumol and Bradford, 1970), for multiple externalities (Ruebbelke, 2003, Parry and Small, 2005), and for prior tax distortions (Babiker et al., 2003). Such deviations are subtle and specific, and rarely observed in actual policy design.

All this makes that climate policy is far more expensive than what is assumed in models (Boehringer et al., 2009, Fowlie et al., 2018).

4. Climate policy

Greenhouse gas emissions can be reduced in a number of ways. More efficient energy use and a switch to alternative energy sources are the two main options. This is best stimulated by a carbon price. Incentive-based policy instruments are better suited for reducing emissions from diffuse and heterogeneous sources than rule-based instruments (Baumol and Oates, 1971). Taxes are more appropriate for stock pollutants than tradable permits (Weitzman, 1974, Pizer, 1999). A carbon tax, and only a carbon tax (Tinbergen, 1952), is therefore the cheapest way to reduce greenhouse gas emissions.

Net present abatement costs are lowest if all emissions from all sectors and all countries are taxed equally and if the carbon tax rises with roughly the interest rate (Lemoine and Rudik, 2017). Higher carbon taxes would lead to deeper emission cuts. Only a modest carbon tax is needed to keep atmospheric concentrations below a high target but the required tax rapidly increases with the stringency of the target.

4.1. The structure of the climate debate

The solution to climate change is simple: A carbon tax. I argue elsewhere that the optimal carbon tax is relatively small. A casual observer of climate policy and the media would have a different impression. Seven things stand in the way of simple solution.

First, there is a demand for an explanation of the world in terms of Sin and a Final Reckoning. The story of climate change is often a religious one (Hulme, 2008, Bruckner, 2014). Emissions (sin) lead to climate change (eternal doom); we must reduce our emissions (atone for our sins). This sentiment is widespread. It is often referred to as Millenarianism (Landes, 2011). It has led to an environmental movement (a priesthood) that thrives on preaching climate alarmism, often separated from its factual basis. In order to maximize their membership and income, environmental NGOs meet the demand for scaremongering and moral superiority (Bell, 2015), but the alt-green do little to win over the majority.

Second, climate policy is a godsend for politicians. Climate change is a problem that spans centuries. Substantial emission reduction requires decades and global cooperation. A politician can thus make grand promises about saving the world while shifting the burden of actually doing something (and so hurting constituents) to her successor and blaming some foreigner for current inaction. Climate change also provides an opportunity for politicians to distract attention (Kerry, 2009, Lagarde, 2013, 2015).

Third, climate policy allows bureaucrats to create new bureaucracies (Niskanen, 1971). Climate policy has been a political priority for about two decades. Emissions have hardly budged, but a vast number of civil servants and larger numbers of consultants and do-gooders have occupied themselves with creating a bureaucratic fiction that something is happening.

Fourth, besides expanded bureaucracies, climate policy can be used to create rents in the form of subsidies, grandparented emission permits, mandated markets and tax breaks. Climate policy thus serves the interests of rent seekers, as well as the interests of policy makers who use rent creation to reward allies (Pearce, 2006, Leahy and Tol, 2012, Brandt and Svendsen, 2014).

Fifth, climate policy requires government intervention at the global scale (Biermann et al., 2012). This antagonizes many, and feeds the fears of right-wing conspiracy theorists. This had led to a movement that attacks climate policy at any opportunity, and extends those attacks to the climate science that underpins that policy, and the scientists who conduct the research (Fisher et al., 2013). Alarmists have retaliated in kind, exaggerating wildly (Stern et al., 2007, Steffen et al., 2018) and playing nasty (Hauschild, 2011, Gleick, 2012). Political orientation is now a key predictor of attitudes towards climate science (McCright and Dunlap, 2011, Kahan, 2013, 2015, Krange et al., 2018). The result is polarization, which hampers reasoned discussion on climate policy (Hulme, 2009, Hoffman, 2011) and emission reduction (Steg, 2018).

Sixth, greenhouse gas emission reduction is a global public good (Barrett, 1990). The costs of emission abatement are borne by the country that reduces the emissions. The benefits of emission reduction are shared by all of humankind. It is thus individually rational to do very little, and hope that others will do a lot. As every country reasons the same way, nothing much happens. Providing public goods is difficult without a government (Bradford, 2008, Battaglini and Harstad, 2015). Any solution to the climate problem should start with acknowledging that we live in a world of many countries, the majority of which jealously guards their sovereignty. That means that climate policy should serve a domestic constituency. Opinion polls in democratic countries have consistently shown over a period of 25 years that a majority is in favour of greenhouse gas emission reduction, even if that means more expensive energy.

Unilateral climate policy is expensive, however. If a country raises its price of energy, but its trading partners do not, business will shift abroad. A country will be more ambitious if it is confident that its neighbours will adopt roughly the same climate policy. The United Nations Framework Convention on Climate Change (UNFCCC), reinforced in its Paris Agreement, foresees an annual meeting at which countries can indeed pledge their near-term abatement plans and review other countries progress against previous pledges. This is facilitated by internationally agreed standards on emissions monitoring and reporting. As the actions of trading partners matter most, regional trade organizations, such as the EU, NAFTA, MERCUSOR and ASEAN, should play a bigger role in this process. The costs of emission reduction vary greatly. It therefore makes sense if countries were allowed to reduce emissions by investing in abatement in other countries. The Kyoto Protocol of the UNFCCC establishes exactly this. Unlike the emissions targets of the Kyoto Protocol, its flexibility mechanisms did not expire.

Seventh, global climate policy has been used as a tactical argument by those who desire a world government for other reasons. Because climate change is such a prominent issue, champions of other worthy causes too have joined the bandwagon. The ultimate goal of climate policy—decarbonisation of the economy—is thus obscured, and the climate debate further complicated.

4.2. Misconceptions about climate policy

4.2.1. Employment

It is sometimes argued that switching to renewable energy would create jobs. Obviously, there is job displacement as renewables expand at the expense of fossil fuels. As the former are more labour-intensive than the latter, there would be net job creation, *all else equal*. Labour is expensive, so this is one of the reasons why renewables are more expensive than fossil fuels. Throughout history, productivity has increased, and wages with it, as capital and energy were used to complement labour. Needing more workers for the same output of energy—the very definition of an increase in the labour-intensity of energy supply—is thus a sign of *regress* rather than *progress*. Baumol's Cost Disease, a rise in wages without a concomitant rise in labour productivity (Baumol and Bowen, 1966), affects energy.

But *all else is not equal*. Only a small fraction of the labour force is employed in the energy sector. Changes in the labour-intensity of the energy sector therefore cannot have a substantial impact on overall employment. However, energy is used throughout the economy. More expensive energy has only a small, negative effect on employment in sectors other than energy, but this small proportional effect can, in absolute terms, outweigh the impact in the energy sector as it applies to so many more workers (Patuelli et al., 2005)—unless the revenue of a carbon tax or permit auctions is used to stimulate the economy or reduce the cost of labour (Bovenberg and Goulder, 1996).

4.2.2. Grand plans

Some have called for a Manhattan Programme, an Apollo Programme or a Marshall Programme for climate change (Yang and Oppenheimer, 2007, Layard et al., 2015, Courtney, 2016). The Manhatten Programme developed a new weapon of mass destruction. The Apollo Programme restored technological supremacy over an adversary. The Marshall Programme helped recovery from devastation.

The misnomers aside, calls for a major public investment programme are misguided. This is the wrong approach. The government should levy a carbon tax to incentivize private investment, and improve regulations to attract investment in natural monopolies such as transport networks and power grids. Greenhouse gas emission reduction does not require an expansion of the public sector.

Full decarbonisation of the economy will take a long time. The costs of doing so depend on technological change. If the costs of renewable energy will continue to fall rapidly, relative to the costs of fossil fuels, then emission reduction policies will be cheap—and may even become redundant as renewables outcompete fossil fuels on merit. This is generally accepted. But there is some confusion about the nature of this technological progress, and the role of public policy. Technological progress comes in three stages: invention (a new blueprint), innovation (taking the blueprint to its first sell), and diffusion (taking a product from its first sell to market saturation). The public sector is best placed to provide invention and the pre-competitive parts of innovation, but the private sector is better at competitive innovation and diffusion, with the government retreating to guaranteeing property rights and correcting externalities (Golosov et al., 2014). The bulk of the desired decarbonisation of the economy can be done with proven technologies (Pacala and Socolow, 2004), so the government should take a back seat in directly stimulating technological progress (Newell et al., 1999).

4.2.3. Divestment

Some have called for divestment from fossil energy, with some success.[10] The intent is clear: Fossil fuels will go out of business if starved of capital. Investors are free to choose their portfolio, of course, and while this approach should be commended for its bottom-up, grassroots spirit, it is unlikely to work.

Suppose that there are two types of investors, green and brown, where the former think that fossil fuels are bad and the latter do not care. If total green capital is relatively small, divestment would have a negligible effect on the market. Green investors, however, have denied themselves a profitable investment and an opportunity to diversify their investment portfolio. Green investors have thus made themselves worse off. They have also lost their vote as activist shareholders.

If total green capital is large enough to suppress the price of fossil capital when divesting, they create an opportunity for brown investors to purchase these assets at a discount as the price falls below the net present value of expected returns. Divestment makes green investors worse off, and enriches brown investors.

However, in this case, divestment raises the cost of fossil capital, so that investment falls and emissions are reduced. These effects are probably minor. The gas, oil and coal industry are dominated by state-owned or -controlled firms. The divestment campaign has had some effect in the Western Europe and North America, with some divestment from publicly owned companies. This does not really affect total investment.

The divestment movement is closely aligned with the "Keep it in the ground" campaign.[11] It is clear from Section 2.2 that climate policy implies keeping fossil fuel reserves in the ground. What matters most is stopping the development of new coal mines, and the exploitation of unconventional oil and gas. The campaign, however, is concentrated in western countries and focuses on conventional oil and gas. The reserves and resources to be left in the ground are concentrated in other parts of the world (Cust et al., 2017, Manley et al.).

5. Conclusion

Over the last 45 years, emissions of carbon dioxide have grown, but considerably less fast than the economy. This is because of improvements in energy efficiency, rather than

[10] See 350.

[11] See the Guardian.

switching to less carbon-intensive fuels. Climate policy played a minor role. Future projections of emissions are optimistic about economic growth and energy efficiency. The higher emission scenarios assume an increase in coal exploitation that is at Trumpian odds with current trends in relative fuel prices and resource assessments.

The costs of climate policy are minimal if targets are moderate and implementation is (close to) first-best. If carbon tax revenue is used in fiscal policy reform, the costs may even be benefits. However, costs rapidly escalate for suboptimal policies and for the stringent targets favoured by the Paris Agreement. Negative emissions would require subsidies, perhaps very large ones.

Actual climate policy and the debate about climate policy is beset by problems. Key players benefit from the rents created by inefficient policies, from creating confusion, and from mixing climate with other matters—and greenhouse gas emission reduction is a global public good that is hard to provide in the best of circumstances.

In sum, climate policy is likely to remain needlessly expensive and not very effective. Climate change will be curtailed by market forces that favour low-carbon gas and zero-carbon renewables.

References

R. Aichele and G. Felbermayr. Kyoto and the carbon footprint of nations. *Journal of Environmental Economics and Management*, 63(3):336–354, 2012. ISSN 0095-0696. doi: https://doi.org/10.1016/j.jeem.2011.10.005. URL http://www.sciencedirect.com/science/article/pii/S0095069611001422.

R. Aichele and G. Felbermayr. The effect of the kyoto protocol on carbon emissions. *Journal of Policy Analysis and Management*, 32(4):731–757, 2013. doi: 10.1002/pam.21720.

R. Allam, J. Fetvedt, B. Forrest, and D. Freed. The oxy-fuel, supercritical co2 allam cycle: New cycle developments to produce even lower-cost electricity from fossil fuels without atmospheric emissions. volume 3B, 2014. doi: 10.1115/GT2014-26952.

H. Allcott. Social norms and energy conservation. *Journal of Public Economics*, 95(9-10):1082–1095, 2011. doi: 10.1016/j.jpubeco.2011.03.003.

H. Allcott and N. Wozny. Gasoline prices, fuel economy, and the energy paradox. *Review of Economics and Statistics*, 96(5):779–795, 2014. doi: 10.1162/REST_a_00419.

M. Auffhammer and E. T. Mansur. Measuring climatic impacts on energy consumption: A review of the empirical literature. *Energy Economics*, 46:522 – 530, 2014. ISSN 0140-9883. doi: https://doi.org/10.1016/j.eneco.2014.04.017. URL http://www.sciencedirect.com/science/article/pii/S0140988314001017.

M. Babiker, G. Metcalf, and J. Reilly. Tax distortions and global climate policy. *Journal of Environmental Economics and Management*, 46(2):269–287, 2003. doi: 10.1016/S0095-0696(02)00039-6.

T. Barker, I. Bashmakov, A. Alharthi, M. Amann, L. Cifuentes, J. Drexhage, M. Duan, O. Edenhofer, B. P. Flannery, M. J. Grubb, M. Hoogwijk, F. I. Ibitoye, C. J. Jepma, W. A. Pizer, and K. Yamaji. *Mitigation from a Cross-Sectoral Perspective*, pages 619–690. Cambridge University Press, Cambridge, 2007.

S. Barrett. The problem of global environmental protection. *Oxford Review of Economic Policy*, 6(1):68–79, 1990.

I. Bashmakov. *Russia: Energy Related Greenhouse Gas Emissions - Present and Future*, pages 379–401. IIASA, Laxenburg, 1994. October 13-15.

M. Battaglini and B. Harstad. Participation and duration of environmental agreements. *Journal of Political Economy*, 124(1):160–204, 2015. ISSN 0022-3808. doi: 10.1086/684478. URL http://dx.doi.org/10.1086/684478.

W. Baumol and W. Bowen. *Performing Arts, The Economic Dilemma: a study of problems common to theater, opera, music, and dance.* Twentieth Century Fund, New York, 1966.

W. Baumol and D. Bradford. Optimal departures from marginal cost pricing. *American Economic Review*, 60(3):265–83, 1970.

W. J. Baumol and W. E. Oates. The use of standards and prices for the protection of the environment. *Scandinavian Journal of Economics*, 73(1):42–54, 1971.

G. Bel and S. Joseph. Emission abatement: Untangling the impacts of the eu ets and the economic crisis. *Energy Economics*, 49:531–539, 2015. ISSN 0140-9883. doi: http://dx.doi.org/10.1016/j.eneco.2015.03.014.

L. Bell. *Scared Witless: Prophets and Profits of Climate Doom*. Stairway Press, Las Vegas, 2015.

F. Biermann, K. Abbott, S. Andresen, K. Baeckstrand, S. Bernstein, M. M. Betsill, H. Bulkeley, B. Cashore, J. Clapp, C. Folke, A. Gupta, J. Gupta, P. M. Haas, A. Jordan, N. Kanie, T. Kluvankova-Oravska, L. Lebel, D. Liverman, J. Meadowcroft, R. B. Mitchell, P. Newell, S. Oberthr, L. Olsson, P. Pattberg, R. Sanchez-Rodriguez, H. Schroeder, A. Underdal, S. C. Vieira, C. Vogel, O. R. Young, A. Brock, and R. Zondervan. Navigating the anthropocene: Improving earth system governance. *Science*, 335(6074): 1306–1307, 2012.

C. Boehringer and K. Rosendahl. Green promotes the dirtiest: On the interaction between black and green quotas in energy markets. *Journal of Regulatory Economics*, 37(3):316–325, 2010. doi: 10.1007/s11149-010-9116-1.

C. Boehringer, H. Koschel, and U. Moslener. Efficiency losses from overlapping regulation of eu carbon emissions. *Journal of Regulatory Economics*, 33(3):299–317, 2008. doi: 10.1007/s11149-007-9054-8.

C. Boehringer, T. Rutherford, and R. Tol. The eu 20/20/2020 targets: An overview of the emf22 assessment. *Energy Economics*, 31(SUPPL. 2):S268–S273, 2009. doi: 10.1016/j.eneco.2009.10.010.

J. Bongaarts and B. C. O'Neill. Global warming policy: Is population left out in the cold? *Science*, 361(6403): 650–652, 2018. ISSN 0036-8075. doi: 10.1126/science.aat8680. URL http://science.sciencemag.org/content/361/6403/650.

B. Bosquet. Environmental tax reform: Does it work? a survey of the empirical evidence. *Ecological Economics*, 34(1):19–32, 2000. doi: 10.1016/S0921-8009(00)00173-7.

A. Bovenberg. Green tax reforms and the double dividend: An updated reader's guide. *International Tax and Public Finance*, 6(3):421–443, 1999. doi: 10.1023/A:1008715920337.

A. Bovenberg and F. van der Ploeg. Environmental policy, public finance and the labour market in a second-best world. *Journal of Public Economics*, 55(3):349–390, 1994. doi: 10.1016/0047-2727(93)01398-T.

A. L. Bovenberg and L. H. Goulder. Optimal environmental taxation in the presence of other taxes: General-equilibrium analyses. *American Economic Review*, 86(4):985–1000, 1996.

D. F. Bradford. *Improving on Kyoto: Greenhouse Gas Control as the Purchase of a Global Public Good*, pages 13–36. MIT Press, Cambridge, 2008.

U. Brandt and G. Svendsen. A blind eye to industry-level corruption? the risk of favouring domestic industries in the eu ets. *Energy and Environment*, 25(2):263–280, 2014.

P. Bruckner. *The Fanaticism of the Apocalypse: Save the Earth, Punish Human Beings*. Polity Press, Cambridge, 2014.

M. Buechs and S. Schnepf. Who emits most? associations between socio-economic factors and uk households' home energy, transport, indirect and total co2 emissions. *Ecological Economics*, 90:114–123, 2013. doi: 10.1016/j.ecolecon.2013.03.007.

P. Ciaian and D. Kancs. Interdependencies in the energy-bioenergy-food price systems: A cointegration analysis. *Resource and Energy Economics*, 33(1):326–348, 2011. doi: 10.1016/j.reseneeco.2010.07.004.

L. Clarke, J. Edmonds, V. Krey, R. Richels, S. Rose, and M. Tavoni. International climate policy architectures: Overview of the emf 22 international scenarios. *Energy Economics*, 31 (S2):S64–S81, 2009. URL http://www.sciencedirect.com/science/article/B6V7G-4XHVH34-2/2/67f06e207a515adba42f7455a99f648e.

L. Clarke, K. Jiang, K. Akimoto, M. H. Babiker, G. J. Blanford, K. A. Fisher-Vanden, J. C. Hourcade, V. Krey, E. Kriegler, A. Loeschel, D. W. McCollum, S. Paltsev, S. Rose, P. R. Shukla, M. Tavoni, D. van Vuuren, and B. Van Der Zwaan. *Assessing Transformation Pathways*. Cambridge University Press, Cambridge, 2014.

L. E. Clarke, J. P. Weyant, and J. Edmonds. On the sources of technological change: What do the models assume. *Energy Economics*, 30(2):409–424, 2008. URL http://www.sciencedirect.com/science/article/B6V7G-4KHC38M-1/2/5aa43ec2fcfe3adeb997f61e896aea43.

C. Courtney. Marshall-style plan needed on carbon, 2016. URL http://www.concordmonitor.com/Successful-CO2-phase-out-requires-Marshall-style-plan-6983021.

J. Cust, D. Manley, and G. Cecchinato. Unburnable wealth of nations. *Finance and Development*, (March): 46–49, 2017.

M. Dalton, B. O'Neill, A. Prskawetz, L. Jiang, and J. Pitkin. Population aging and future carbon emissions in the united states. *Energy Economics*, 30(2):642–675, 2008. doi: 10.1016/j.eneco.2006.07.002.

J. Davison. Performance and costs of power plants with capture and storage of co¡inf¿2¡/inf¿. *Energy*, 32 (7):1163–1176, 2007. doi: 10.1016/j.energy.2006.07.039.

M. Enamala, S. Enamala, M. Chavali, J. Donepudi, R. Yadavalli, B. Kolapalli, T. Aradhyula, J. Velpuri, and C. Kuppam. Production of biofuels from microalgae - a review on cultivation, harvesting, lipid extraction, and numerous applications of microalgae. *Renewable and Sustainable Energy Reviews*, 94:49–68, 2018. doi: 10.1016/j.rser.2018.05.012.

D. R. Fisher, J. Waggle, and P. Leifeld. Where does political polarization come from? locating polarization within the u.s. climate change debate. *American Behavioral Scientist*, 57(1):70–92, 2013.

R. Fouquet. *Heat, Power and Light – Revolutions in Energy Services*. Edward Elgar, Cheltenham, 2008.

M. Fowlie, M. Greenstone, and C. Wolfram. Do energy efficiency investments deliver? evidence from the weatherization assistance program*. *The Quarterly Journal of Economics*, 133(3):1597–1644, 2018. doi: 10.1093/qje/qjy005. URL http://dx.doi.org/10.1093/qje/qjy005.

F. Fuerst and P. McAllister. The impact of energy performance certificates on the rental and capital values of commercial property assets. *Energy Policy*, 39(10):6608–6614, 2011. doi: 10.1016/j.enpol.2011.08.005.

O. Galor and D. N. Weil. From malthusian stagnation to modern growth. *American Economic Review*, 89 (2):150–154, 1999.

Z. Gebreegziabher, A. Mekonnen, M. Kassie, and G. Khlin. Urban energy transition and technology adoption: The case of tigrai, northern ethiopia. *Energy Economics*, 34(2):410–418, 2012. doi: 10.1016/j.eneco.2011.07.017.

P. H. Gleick. The origin of the heartland documents, 20 Feb 2012 2012. URL http://www.huffingtonpost.com/peter-h-gleick/heartland-institute-documents_b_1289669.html.

M. Golosov, J. Hassler, P. Krusell, and A. Tsyvinski. Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88, 2014. doi: 10.3982/ECTA10217. URL https://onlinelibrary.wiley.com/doi/abs/10.3982/ECTA10217.

L. Goulder. Environmental taxation and the double dividend: A reader's guide. *International Tax and Public Finance*, 2(2):157–183, 1995. doi: 10.1007/BF00877495.

L. H. Goulder and K. Mathai. Optimal co 2 abatement in the presence of induced technological change. *Journal of Environmental Economics and Management*, 39:1–38, 2000.

L. H. Goulder and S. H. Schneider. Induced technological change and the attractiveness of co 2 abatement policies. *Resource and Energy Economics*, 21:211–253, 1999.

D. Greene. Uncertainty, loss aversion, and markets for energy efficiency. *Energy Economics*, 33(4):608–616, 2011. doi: 10.1016/j.eneco.2010.08.009.

L. Greening, D. Greene, and C. Difiglio. Energy efficiency and consumption - the rebound effect - a survey. *Energy Policy*, 28(6-7):389–401, 2000. doi: 10.1016/S0301-4215(00)00021-5.

M. Guo, W. Song, and J. Buhain. Bioenergy and biofuels: History, status, and perspective. *Renewable and Sustainable Energy Reviews*, 42:712–725, 2015. doi: 10.1016/j.rser.2014.10.013.

J. Hauschild. Verurteilter forscher: Eklat um klimaberater der bundesregierung. *Spiegel*, 1 Dec 2011 2011.

D. Herzer, H. Strulik, and S. Vollmer. The long-run determinants of fertility: One century of demographic change 1900-1999. *Journal of Economic Growth*, 17(4):357–385, 2012. doi: 10.1007/s10887-012-9085-6.

R. Hoekstra and J. Van Den Bergh. Structural decomposition analysis of physical flows in the economy. *Environmental and Resource Economics*, 23(3):357–378, 2002. doi: 10.1023/A:1021234216845.

A. J. Hoffman. Talking past each other? cultural framing of skeptical and convinced logics in the climate change debate. *Organization and Environment*, 24(1):3–33, 2011.

K. House, A. Baclig, M. Ranjan, E. Van Nierop, J. Wilcox, and H. Herzog. Economic and energetic analysis of capturing co¡inf¿2¡/inf¿from ambient air. *Proceedings of the National Academy of Sciences of the United States of America*, 108(51):20428–20433, 2011. doi: 10.1073/pnas.1012253108.

M. Hulme. The conquering of climate: Discourses of fear and their dissolution. *Geographical Journal*, 174 (1):5–16, 2008.

M. Hulme. *Why We Disagree about Climate Change: Understanding Controversy, Inaction and Opportunity.* Cambridge University Press, Cambridge, 2009.

J. Im, Y. Seo, K. Cetin, and J. Singh. Energy efficiency in u.s. residential rental housing: Adoption rates and impact on rent. *Applied Energy*, 205:1021–1033, 2017. doi: 10.1016/j.apenergy.2017.08.047.

IRENA. *Renewable Power Generation Costs in 2017.* International Renewable Energy Agency, Abu Dhabi, 2018.

A. Jaffe and R. Stavins. The energy paradox and the diffusion of conservation technology. *Resource and Energy Economics*, 16(2):91–122, 1994. doi: 10.1016/0928-7655(94)90001-9.

W. S. Jevons. *The Coal Question.* McMillan, London, 1865.

D. M. Kahan. Ideology, motivated reasoning, and cognitive reflection. *Judgment and Decision Making*, 8 (4):407–424, 2013.

D. M. Kahan. Climate-science communication and the measurement problem. *Political Psychology*, 36(S1): 1–43, 2015.

M. Kahn. Do greens drive hummers or hybrids? environmental ideology as a determinant of consumer choice. *Journal of Environmental Economics and Management*, 54(2):129–145, 2007. doi: 10.1016/j.jeem.2007.05.001.

G. Kallis. In defence of degrowth. *Ecological Economics*, 70(5):873–880, 2011. doi: 10.1016/j.ecolecon.2010.12.007.

Y. Kaya. *Environment, energy, and economy : strategies for sustainability.* United Nations University Press, Tokyo, 1997.

J. Kerry. Climate change is our greatest long-term security threat, 2009. URL https://thinkprogress.org/john-kerry-climate-change-is-our-greatest-long-term-security-threat-f9c12e7d098f#.fe9h1xtyc.

O. Krange, B. P. Kaltenborn, and M. Hultman. Cool dudes in norway: climate change denial among conservative norwegian men. *Environmental Sociology*, 0(0):1–11, 2018. doi: 10.1080/23251042.2018.1488516. URL https://doi.org/10.1080/23251042.2018.1488516.

J.-J. Laffont and D. Martimort. *The theory of incentives: The principal-agent model.* 2009.

C. Lagarde. Transcript of a press roundtable with imf managing director, 1 August 2013 2013. URL https://www.imf.org/external/np/tr/2013/tr080113a.htm.

C. Lagarde. Ten myths about climate change policy. *Finance and Investment*, (1 December):64–67, 2015.

R. Landes. *Heaven on Earth: The Varieties of the Millennial Experience.* Oxford University Press, Oxford, 2011.

A. Lans Bovenberg and S. Smulders. Environmental quality and pollution-augmenting technological change in a two-sector endogenous growth model. *Journal of Public Economics*, 57(3):369–391, 1995. doi: 10.1016/0047-2727(95)80002-Q.

R. Layard, G. O'Donnell, N. H. Stern, and A. Turner. The case for a global apollo programme to limit climate change, 2015. URL http://voxeu.org/article/apollo-programme-conquer-climate-change.

E. Leahy and R. S. J. Tol. Greener homes: An ex-post estimate of the cost of carbon dioxide emission reduction using administrative micro-data from the republic of ireland. *Environmental Economics and Policy Studies*, 14(3):219–239, 2012.

D. Lemoine and I. Rudik. Steering the climate system: Using inertia to lower the cost of policy. *American Economic Review*, 107(10):2947–57, October 2017. doi: 10.1257/aer.20150986. URL http://www.aeaweb.org/articles?id=10.1257/aer.20150986.

A. Levinson and S. Niemann. Energy use by apartment tenants when landlords pay for utilities. *Resource and Energy Economics*, 26(1):51–75, 2004. doi: 10.1016/S0928-7655(03)00047-2.

H. Lotze-Campen, M. von Lampe, P. Kyle, S. Fujimori, P. Havlik, H. van Meijl, T. Hasegawa, A. Popp, C. Schmitz, A. Tabeau, H. Valin, D. Willenbockel, and M. Wise. Impacts of increased bioenergy demand on global food markets: An agmip economic model intercomparison. *Agricultural Economics (United Kingdom)*, 45(1):103–116, 2014. doi: 10.1111/agec.12092.

D. Manley, J. Cust, and G. Cecchinato. Stranded nations? the climate policy implications for fossil fuel-rich developing countries. Technical report, Oxford Centre for the Analysis of Resource Rich Economies, University of Oxford, Oxford.

A. S. Manne and R. G. Richels. The impact of learning-by-doing on the timing and costs of co 2 abatement. *Energy Economics*, 26:603–619, 2004.

I. Mayeres and S. Proost. Marginal tax reform, externalities and income distribution. *Journal of Public Economics*, 79(2):343–363, 2001. doi: 10.1016/S0047-2727(99)00100-0.

A. M. McCright and R. E. Dunlap. Cool dudes: The denial of climate change among conservative white males in the united states. *Global Environmental Change*, 21(4):1163–1172, 2011.

G. Metcalf and K. Hassett. Measuring the energy savings from home improvement investments: Evidence from monthly billing data. *Review of Economics and Statistics*, 81(3):516–528, 1999. doi: 10.1162/003465399558274.

B. C. Murray and P. T. Maniloff. Why have greenhouse emissions in rggi states declined? an econometric attribution to economic, energy market, and policy factors. *Energy Economics*, 51:581 – 589, 2015. ISSN 0140-9883. doi: https://doi.org/10.1016/j.eneco.2015.07.013. URL http://www.sciencedirect.com/science/article/pii/S0140988315002273.

R. G. Newell, A. B. Jaffe, and R. N. Stavins. The induced innovation hypothesis and energy-saving technological change. *Quarterly Journal of Economics*, pages 941–975, 1999.

W. A. Niskanen. *Bureaucracy and Public Economics*. Edward Elgar, Cheltenham, 1971.

W. D. Nordhaus. *Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not*, pages 27–70. National Bureau for Economic Research, Chicago, 1996.

S. Pacala and R. Socolow. Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science*, 305(5686):968–972, 2004.

I. Parry and A. Bento. Tax deductions, environmental policy, and the 'double dividend' hypothesis. *Journal of Environmental Economics and Management*, 39(1):67–96, 2000. doi: 10.1006/jeem.1999.1093.

I. W. H. Parry and K. A. Small. Does britain or the united states have the right gasoline tax? *American Economic Review*, 95(4):1276–1289, 2005.

R. Patuelli, P. Nijkamp, and E. Pels. Environmental tax reform and the double dividend: A meta-analytical performance assessment. *Ecological Economics*, 55(4):564–583, 2005.

D. W. Pearce. The political economy of an energy tax: The united kingdom's climate change levy. *Energy Economics*, 28:149–158, 2006.

W. A. Pizer. The optimal choice of climate change policy in the presence of uncertainty. *Resource and Energy Economics*, 21:255–287, 1999.

S. Proost and K. Van Dender. The welfare impacts of alternative policies to address atmospheric pollution in urban road transport. *Regional Science and Urban Economics*, 31(4):383–411, 2001. doi: 10.1016/S0166-0462(00)00079-X.

P. Reiss and M. White. Household electricity demand, revisited. *Review of Economic Studies*, 72(3):853–883, 2005. doi: 10.1111/0034-6527.00354.

K. Riahi, D. P. van Vuuren, E. Kriegler, J. Edmonds, B. C. ONeill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J. C. Cuaresma, S. KC, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpender, L. A. D. Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J. C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, and M. Tavoni. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42:153 – 168, 2017. ISSN 0959-3780. doi: https://doi.org/10.1016/j.gloenvcha.2016.05.009. URL http://www.sciencedirect.com/science/article/pii/S0959378016300681.

J. Ritchie and H. Dowlatabadi. The 1000 gtc coal question: Are cases of vastly expanded future coal combustion still plausible? *Energy Economics*, 65:16–31, 2017. doi: 10.1016/j.eneco.2017.04.015.

E. Rubin, C. Chen, and A. Rao. Cost and performance of fossil fuel power plants with co¡inf¿2¡/inf¿capture and storage. *Energy Policy*, 35(9):4444–4454, 2007. doi: 10.1016/j.enpol.2007.03.009.

D. Ruebbelke. An analysis of differing abatement incentives. *Resource and Energy Economics*, 25(3):269–294, 2003. doi: 10.1016/S0928-7655(03)00032-0.

P. Sadorsky. Do urbanization and industrialization affect energy intensity in developing countries? *Energy Economics*, 37:52–59, 2013. doi: 10.1016/j.eneco.2013.01.009.

P. M. Schwarz and T. N. Taylor. Cold hands, warm hearth?: climate, net takeback, and household comfort. *Energy Journal*, 16(1):41–54, 1995. doi: 10.5547/ISSN0195-6574-EJ-Vol16-No1-3.

S. Smulders and M. de Nooij. The impact of the energy conservation on technology and economic growth. *Resource and Energy Economics*, 25(1):59–79, 2003. doi: 10.1016/S0928-7655(02)00017-9.

S. Sorrell, J. Dimitropoulos, and M. Sommerville. Empirical estimates of the direct rebound effect: A review. *Energy Policy*, 37(4):1356–1371, 2009. doi: 10.1016/j.enpol.2008.11.026.

W. Steffen, J. Rockström, K. Richardson, T. M. Lenton, C. Folke, D. Liverman, C. P. Summerhayes, A. D. Barnosky, S. E. Cornell, M. Crucifix, J. F. Donges, I. Fetzer, S. J. Lade, M. Scheffer, R. Winkelmann, and H. J. Schellnhuber. Trajectories of the earth system in the anthropocene. *Proceedings of the National Academy of Sciences*, 2018. ISSN 0027-8424. doi: 10.1073/pnas.1810141115. URL http://www.pnas.org/content/early/2018/08/07/1810141115.

L. Steg. Limiting climate change requires research on climate action. *Nature Climate Change*, 2018. ISSN 1758-6798. doi: 10.1038/s41558-018-0269-8. URL https://doi.org/10.1038/s41558-018-0269-8.

N. H. Stern, S. Peters, V. Bakhski, A. Bowen, C. Cameron, S. Catovsky, D. Crane, S. Cruickshank, S. Dietz, N. Edmondson, S.-L. Garbett, L. Hamid, G. Hoffman, D. Ingram, B. Jones, N. Patmore, H. Radcliffe, R. Sathiyarajah, M. Stock, C. Taylor, T. Vernon, H. Wanjie, and D. Zenghelis. *Stern Review: The Economics of Climate Change*. Cambridge University Press, Cambridge, 2007.

M. Tavoni and R. S. J. Tol. Counting only the hits? the risk of underestimating the costs of stringent climate policy: A letter. *Climatic Change*, 100(3):769–778, 2010.

J. Tinbergen. *On the Theory of Economic Policy*. North Holland, Amsterdam, 1952.

R. S. J. Tol. Ambiguity reduction by objective model selection, with an application to the costs of the eu 2030 climate targets. *Energies*, 7(11):6886–6896, 2014. ISSN 1996-1073. doi: 10.3390/en7116886. URL http://www.mdpi.com/1996-1073/7/11/6886.

J. H. van Heerden, R. Gerlagh, J. N. Blignaut, M. Horridge, S. Hess, R. Mabugu, and M. Mabugu. Searching for triple dividends in south africa: Fighting co2 pollution and poverty while promoting growth. *Energy Journal*, 27(2):113–141, 2006.

D. van Soest and E. Bulte. Does the energy-efficiency paradox exist? technological progress and uncertainty. *Environmental and Resource Economics*, 18(1):101–112, 2001. doi: 10.1023/A:1011112406964.

D. P. van Vuuren, 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. The representative concentration pathways: An overview. *Climatic Change*, 109(1):5–31, 2011.

M. Webster, I. Sue Wing, and L. Jakobovits. Second-best instruments for near-term climate policy: Intensity targets vs. the safety valve. *Journal of Environmental Economics and Management*, 59(3):250–259, 2010. doi: 10.1016/j.jeem.2010.01.002.

WEC. *Survey of Energy Resources*. World Energy Council, London, 2010.

WEC. *World Energy Resources—Bioenergy*. World Energy Council, London, 2016a.

WEC. *World Energy Resources—Carbon capture & storage*. World Energy Council, London, 2016b.

WEC. *World Energy Resources—Geothermal*. World Energy Council, London, 2016c.

WEC. *World Energy Resources—Hydropower*. World Energy Council, London, 2016d.

WEC. *World Energy Resources—Marine resources*. World Energy Council, London, 2016e.

WEC. *World Energy Resources—Uranium & Nuclear power*. World Energy Council, London, 2016f.

WEC. *World Energy Resources—Solar*. World Energy Council, London, 2016g.

WEC. *World Energy Resources—Wind*. World Energy Council, London, 2016h.

M. L. Weitzman. Prices vs. quantities. *Review of Economic Studies*, 41(4):477–491, 1974.

J. P. Weyant. Costs of reducing global carbon emissions. *Journal of Economic Perspectives*, 7(4):27–46, 1993.

E. Widjaya, G. Chen, L. Bowtell, and C. Hills. Gasification of non-woody biomass: A literature review. *Renewable and Sustainable Energy Reviews*, 89:184–193, 2018. doi: 10.1016/j.rser.2018.03.023.

T. M. L. Wigley, R. Richels, and J. A. Edmonds. Economic and environmental choices in the stabilization of atmospheric co2 concentrations. *Nature*, 379:240, 1996. doi: 10.1038/379240a0. URL http://dx.doi.org/10.1038/379240a0.

M. Wise, K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S. Smith, A. Janetos, and J. Edmonds. Implications of limiting co¡inf¿2¡/inf¿concentrations for land use and energy. *Science*, 324 (5931):1183–1186, 2009. doi: 10.1126/science.1168475.

C.-J. Yang and M. Oppenheimer. A manhattan project for climate change? *Climatic Change*, 80(3):199–204, 2007. ISSN 1573-1480. doi: 10.1007/s10584-006-9202-7.