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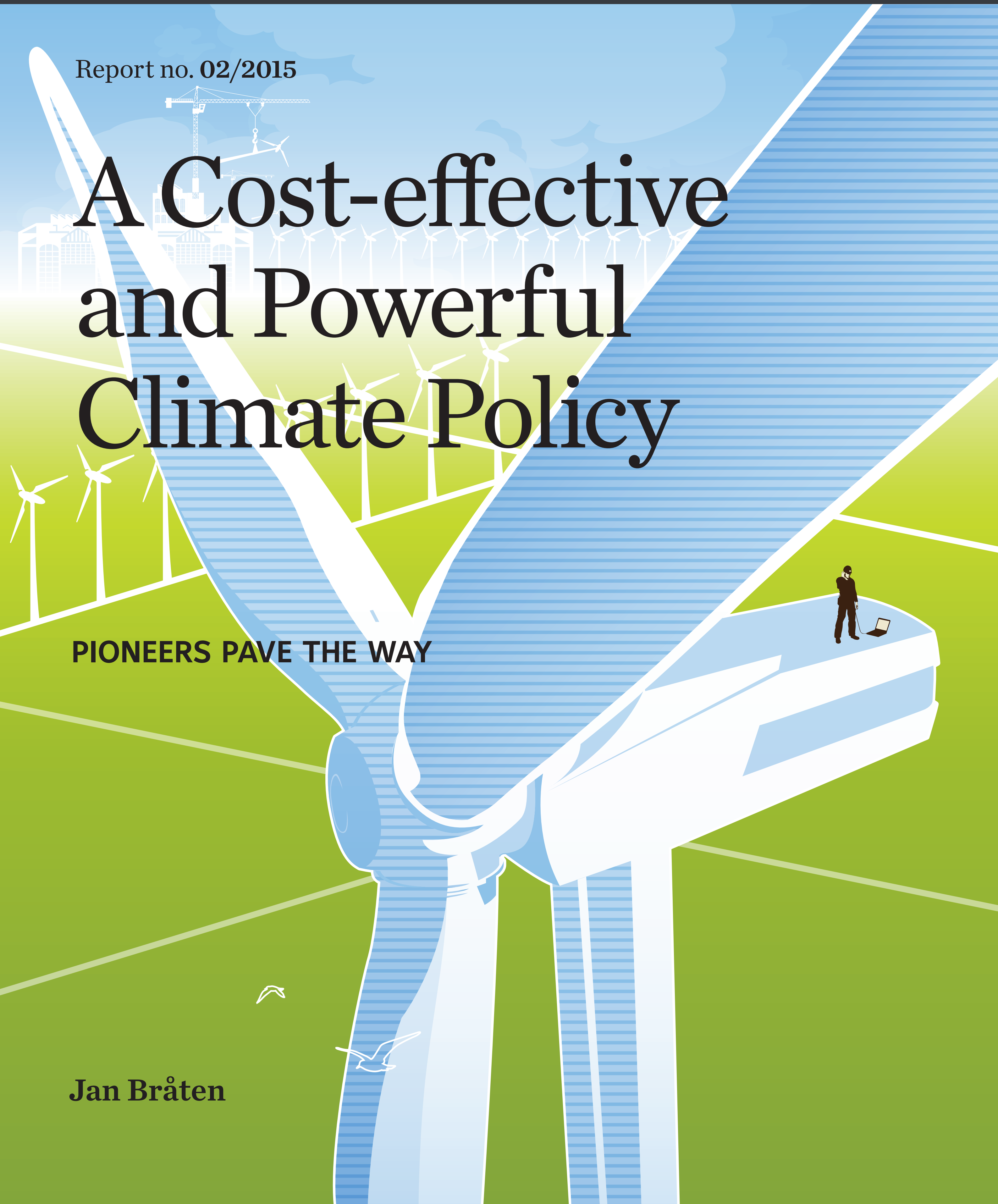
A Cost-effective and Powerful Climate Policy

PIONEERS PAVE THE WAY



Jan Bråten

A report on how increased emphasis on the development of technology and societal learning will make global climate policy cheaper and more powerful and about which policy instruments we need in order to stimulate such developments

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NORWEGIAN CLIMATE FOUNDATION

The Norwegian Climate Foundation is a non-profit organization founded in 2010 that aims to encourage enforced climate action, fast implementation of renewable energy and other climate-friendly technologies.
NCF is based in Bergen and backed by a number of strong academic institutions and businesses as well as local and regional authorities.
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FOREWORD

This report describes how we can promote a cost-effective and powerful climate policy by adopting a more holistic, long-term view of how societies, policy and technology develop.

We must view climate policy as a *process of long-term learning and restructuring,* rather than a series of stand-alone measures in a static world. Through broad learning processes, climate policies and practical measures that are decided on at a certain point in time can affect the long-term evolution of technology and costs, institutions and attitudes.

To a large degree, economists have been allowed to define what cost-effective climate policy is. Unfortunately, quite a few economists have done so based on assumptions that are inadequate in a global, long-term perspective. And that is exactly what the climate challenge is: global, and very long-term.

As an economist, I find it thought-provoking that many of the positive things that have happened in the arena of climate policy (such as the development of wind power and solar panels) have happened in spite of economists' advice rather than because of it. Developments have largely been driven by technologists, enthusiasts and visionary politicians. In the public debate, economists often seemed like critics, frequently referring to measures lacking cost-effectiveness. In some cases, such criticism might have been justified, but in many others, critics have had too narrow a perspective. Economics can offer important contributions to a powerful climate policy, but must take into account how technology, policy, organisation and attitudes will develop over time. Without this understanding, economic analyses have limited value.

I hope this report will encourage a general debate on the nature of a cost-effective and powerful climate policy. My goal is not to provide detailed instructions with specific measures. My goal is to highlight the need for more holistic, long-term thinking.

In order to promote broad debate across disciplines, I have tried to express things as simply as possible, but no simpler. I have used footnotes to provide relevant additional information and supplementary explanations of economic terms. The specific examples in this text are primarily used to illuminate and support my general points: Opinions of specific technological opportunities will change over time, but learning processes in order to meet the climate challenge will be important throughout.

As a reader, you deserve to know something about my background: Before I became an economist, I studied philosophy, sociology and mathematics at the University of Oslo, worked as a high school teacher for a few years, and as a programmer for a couple of years. In 1994 I graduated in economics (cand.oecon). My thesis was a game theory analysis of global climate and energy policy. In the same year, I started as a consultant at ECON Analyse, where I became a partner after a few years. Most of my work involved energy issues, which are often related to the climate challenge. Since 2005, I have worked at Statnett (the Norwegian TSO), where I am chief economist. Here, I have been dealing with questions related to economic efficiency, the energy system of the future and how we can develop a robust and decarbonised energy system. I am also a member of the board at EnergiX, The Research Council of Norway's energy research programme. This report expresses my personal opinion.

I would like to thank the following persons with backgrounds in economics, technology and other relevant disciplines for discussions and suggestions that have improved this report: Christian Grorud, Berit Tennbakk, Per Ove Eikeland, Torjus Folsland Bolkesjø, Asbjørn Torvanger, Tore Snekkvik, Anne Jorun Aas, Ane Torvanger Brunvoll, Per Espen Stoknes, Elin Lerum Boasson, Martha Marie Øberg, Anje Stiers, Maria Sandsmark, Ove Wolfgang, Anders Bjartnes, Kitty Byng, Marius Holm, Anders Kringstad, Lene Elizabeth Hodge, Arild Skedsmo, Inge Stenkløv and Marianne Sjølund.

Some might call this a long report. Given the importance of the topic and the many issues that could have been discussed, it is short.

Happy reading!

Oslo, 10th February 2015
Jan Bråten

NORWEGIAN CLIMATE FOUNDATION

The Norwegian Climate Foundation is very happy to be able to contribute to the discussion of climate policy by publishing and distributing this report. Jan Bråten has produced a major, important report which we believe will drive the discussion of climate policy many steps forward.

Oslo, 10th February 2015

Anders Bjartnes
Director
Norwegian Climate Foundation

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KEY MESSAGES

From a global perspective, it is cost-effective that some countries pave the way and develop new climate-friendly technologies and better climate policy solutions. Other countries can take inspiration, learn from the pioneers, and hence benefit from the cost reductions they create. Those who lead the way make it easier for others to follow.

In the year 2100, the world economy may be eight times larger than it is today. At the same time, greenhouse gas emissions will have to be close to zero. According to the European Commission's Energy Roadmap 2050, the power sector should have close to zero emissions as early as 2050. These goals require serious action. Substantial improvement in technology and increased knowledge of suitable measures and regulation are crucial if we are to succeed.

The price of solar panels has dropped by 99% in 35 years. This is because of focused research and the fact that extensive growth in the use of solar panels has stimulated innovation throughout the value chain and given rise to significant economies of scale. Several other technologies have also seen dramatic drops in price through increased deployment. In order to reach our climate goals, we need many such success stories.

Those who develop new solutions, only reap a limited share of the global benefits they create. For this reason, too little knowledge will be developed unless active steps are taken. Carbon pricing (a quota price or tax) alone will not solve this problem, as it does not favour measures that stimulate the necessary developments in technology. We need targeted measures in order to accelerate the development of new solutions. A high carbon price is important to stimulate emission cuts, but it clearly has its limitations.

The energy sector is responsible for two third of global emissions. In order to bring energy emissions down to zero, we need many new technologies, integration between power, transportation and heating, effective regulations and efficient energy markets.

More ambitious technology development can be promoted through countries banding together. Such alliances become more potent when their members also have some national benefit from the development. Alliances can increase the rate of learning and deliver more and better tools for cutting emissions. This is necessary in order to reach our climate goals.

We must view climate policy as a long-term process of restructuring and as a learning process in which what we do now, increases our own and others' ability to cut emissions in the future. Our learning concerns technology, laws and regulations, and attitudes.

SUMMARY

THE CLIMATE PROBLEM IS ALL-ENCOMPASSING, AND EMISSIONS MUST BE CLOSE TO ZERO BY 2100

The climate problem requires changes in every country and across almost all sectors. For us to have a realistic chance at limiting global warming to 2°C, emissions must be cut by around 60% between 2014 and 2050, and towards the end of this century, greenhouse gas emissions need to be close to zero. At the same time, the global population is expected to grow by more than 40% towards the year 2100, and world production of goods and services may increase eightfold (given annual economic growth of 2.5%). Today's economy is built on the use of fossil energy, which is also the biggest source of global warming. Future growth and prosperity need to be built on different energy solutions altogether.

In the European Commission's Energy Roadmap 2050, the power sector has almost zero emissions in 2050. In order to reach such goals, pervasive restructuring of energy production and consumption is required. There is also a need for changes within transport, in parts of agriculture and manufacturing, and in how we plan and build the society of tomorrow. To efficiently promote changes such as these, we need new and better technologies, new ways of organising institutions and sectors, and not least, new ways of thinking.

POLLUTERS MUST PAY – AND THOSE WHO DEVELOP BETTER CLIMATE SOLUTIONS MUST BE REWARDED

There is widespread support for the principle that polluters should pay for the cost they impose on society. This is often highlighted as the cost-effective solution, and the thinking behind it is as follows:

> *By letting all polluters pay an equally high tax (or quota price), the result is emission cuts wherever cutting emissions is cheaper than paying the tax. If the tax is for instance €25 per tonne, all emission cuts that cost less than €25 per tonne will be implemented. This is cost-effective, since emissions are cut where it is cheapest.*

The climate problem is a pollution problem. Therefore, it is tempting to conclude that the cost-effective solution is an equally high tax or quota price (hereafter referred to as a carbon price) for all greenhouse gas emissions, and that other measures are to be avoided. This would be wrong, however. Carbon pricing is important, but not sufficient to promote technology development and other knowledge development at the necessary pace. Carbon pricing also has other limitations.

High carbon prices give consumers and industry an incentive to reduce emissions when that is cheaper than paying the carbon price. It also makes goods and services that involve high emissions more expensive. Higher prices encourage customers to look for more climate-friendly alternatives. If markets are sufficiently confident that carbon prices will stay high in the future, carbon prices may also be an important instrument in long-term change. But carbon pricing *will not* encourage development of new technologies to a desired (optimal) degree. This is because companies and countries that develop new solutions, only reap a small share of the benefit offered by their solutions.

DEVELOPERS OF KNOWLEDGE ONLY REAP SOME OF THE GLOBAL BENEFIT

Patent protection is an important driver for innovation, by giving developers the sole right to earn money on their solutions for a limited period (usually 20 years). Several types of learning cannot be patented effectively, but even when a new idea can be patented, much of its value (benefit) will still go to others. There are two reasons for this:

- **During the patent period**, the patent holder must give buyers a (significant) share of the benefit in order to make them buy the product (consumer surplus).

- **After the patent period**, anyone will be allowed to use the solution freely, without paying its developer. Since the climate problem will last for more than a century, good solutions could provide global benefits for many decades after the expiration of a patent. When it takes a long time to achieve widespread use of a product, most of its global benefit may in fact be realised after the expiration of the patent.

A lot of learning cannot be patented. This applies to informal learning and many general ideas. There is also value associated with discovering that certain solutions *do not* work. Others can learn from these mistakes, avoid making them and be inspired to search for better solutions. Knowledge of possibilities and impossibilities also provides valuable information to all those planning long-term investments, even if they do not plan to use the (potential) solutions themselves.

Since the climate problem is global and here to stay, and since in the long-term, we need radical changes that will bring emissions down to zero, technology development and other types of learning will play a crucial role in our ability to reach these goals. We need policies and a set of measures, that encourage the necessary developments in knowledge, and that drive the costs of new solutions way down.

LEARNING CURVES: DEPLOYMENT LOWERS COSTS

Long-term, publically-financed research and programmes that encourage innovation, are very important when it comes to developing new solutions, but they frequently prove insufficient. In order to accelerate the development of new technologies and bring costs down to a competitive level, it is often necessary to stimulate greater deployment/production. Learning curves describe the drop in price that many products see as they become more widespread. The drop in price is driven by two factors:

- *Learning through deployment and operation.* Development and widespread use of new technologies, such as wind turbines, provide practical experience and therefore stimulate innovation. Furthermore, private companies often require a high rate of return on investments (e.g. 10%) and have little desire to invest in innovation which may find a market in the distant future. But when governments create a market for a new product, e.g. by providing funding the deployment of wind and solar power, innovation comes more easily. The industry is far more willing to go for a new idea when the road to realisation is short. *Extensive deployment encourages innovation in every link of the value chain.*

- *Economies of scale.* When investors have sufficient confidence in future sales, they are willing to invest in better and more specialised manufacturing equipment. Larger volumes also make it possible to exploit manufacturing facilities better. An example: In the event of extensive development of offshore wind power in an area such as the North Sea, investment could be made in special boats and cranes for installation of turbines, and the result would be better utilisation of boats and maintenance equipment. When a product, for instance a hydrogen car, is made in larger quantities, the costs of development can be spread among more units, and the logistics of delivering manufacturing materials and the finished product can be more efficient. When Tesla builds its gigantic battery factory, it is expected to bring battery costs down by at least 30%. The advantages of greater production can be seen throughout the value chain.

The cost of solar panels has dropped by 99% in 35 years, and the cost of wind power on land has fallen by 90% in 32 years. For LED lights, costs dropped by 85% from 2008 to 2012. During the same period, the cost of electric car batteries was halved, and there is solid hope that increased production and technology development may bring costs down to a quarter of 2012 prices by 2022. This would make electric cars cheaper than petrol cars. Such price drops are of *crucial importance to climate policy,* because they make more countries do more to reduce emissions. In those gratifying cases where climate-friendly solutions turn out cheaper than old, polluting alternatives, and any institutional barriers are removed, emission reductions will start to happen on their own.

CARBON PRICING IS INSUFFICIENT FOR PROMOTING IMMATURE TECHNOLOGIES

A carbon price that is the same for all emissions will not distinguish between climate measures that could lead to large price drops in the future (through learning and economies of scale) and climate measures that offer no such effect. Since the cost reductions in question could be very large, this distinction is important.

The fact that development and deployment today contribute to lower costs in the future, must be taken into account when deciding what is cost-effective.

In order to stimulate learning effects and price drops through large scale manufacturing, we need designated and predictable funding for development and advancement of new solutions – in good interaction with research.

The development and deployment of solar panels, and the price drop that followed, could not have been brought about by a carbon price designed for all climate measures, or by a general funding that was equal for all renewable energy sources. To start with, immature technologies will typically have very high costs, and these costs will vary from one technology to another. In order to get development underway, funding needs to be adjusted to the cost level of each technology, and it should be reduced as the technology becomes cheaper. Today, offshore wind power costs around €0.15 – €0.18 per kWh. If this technology is to be developed further, the developers must be ensured income at this level.

When the goal is to develop specific technologies or solutions, instruments that directly target this goal will prove most effective. Instruments must be predictable and ensure the necessary profitability for investors.

MORE LIMITATIONS OF CARBON PRICING

One challenge of carbon pricing is that (private) companies often require *high rates of return on investments*. A high required rate of return means the companies place little emphasis on carbon prices in the distant future when considering emission-reducing measures. If there is also high *uncertainty* regarding future carbon prices, investors will be even less willing to stake their money on long-term emission-reducing measures. This applies to regular investments as well as investments in research and development (R&D).

Barriers that limit profitable energy efficiency must also be overcome using targeted measures.

A carbon price that only applies to some countries, could make industries with high emissions move to countries without carbon prices. This is called carbon leakage, and it might at worst lead to increased global emissions. When there is a need for a product (e.g. aluminium) in the future, policy instruments should be combined ("carrot and stick") so that the industry is encouraged to stay, *cut emissions where possible and develop more climate-friendly manufacturing technology. The latter is particularly important, as more climate-friendly technology may later help reduce emissions throughout the relevant industry in all countries.*

WE NEED TO DEVELOP AN ENERGY SYSTEM THAT IS ROBUST, EMISSION-FREE AND AFFORDABLE

The energy sector represents approx. two thirds of global greenhouse gas emissions. It is possible to reduce the emissions in the energy sector significantly towards 2050. If nothing is done, however, emissions will see a steep increase as a result of large economic growth globally. It is therefore very important to succeed in radical emission reductions in the energy sector. Building coal power plants and other infrastructure that entail high CO_2 emissions for many decades must be avoided, and it is important that we start developing solutions that can decarbonize our energy system completely.

Electricity will be a more important energy carrier in the future because we use electricity for more and more purposes, and because electricity will be put to use in new areas to reduce CO_2 emissions throughout the energy sector. It is easier to bring down emissions from power generation than from many other types of energy use. In parallel with declining emissions in the power sector, electricity can increasingly be used for transportation and heating. The heating and transport sector can get rid of its CO_2 emissions by using emission-free power and biomass/biofuels.

Traditionally, fossil power generation has ensured the necessary balance between consumption and generation. Now, fossil power will gradually be replaced by emission-free power, which is much harder to regulate, and which often varies depending on the weather. There will be hours when solar and wind facilities generate almost no power, and there will be times when they generate much more power than current consumption requires. *The challenge is to develop an emission-free power system that provides enough power in every situation. Ideally, we should also utilise the large surpluses that will occur at certain times.*

In order to bring emissions down to zero and also ensure supply in all situations, we need to develop new types of emission-free power that can cover consumption when the wind and sun have little to contribute. We will need new flexibility in generation and consumption, including technologies for storing energy. A stronger transmission grid must be built connecting areas and countries to alleviate local imbalances, and flexible heating solutions and intelligent control systems must be developed. The interaction of all these parts must be coordinated by suitable market solutions and regulations that exploit the benefits of trade between countries. *This is a process of restructuring and learning where we know the general direction, but many of the solutions will have to be developed along the way.*

Energy consumption is significant in the transport and heating sector. Heating (including the industrial use of heat) represents half of the energy end use in Europe. Using much more electricity in these two sectors will contribute to phasing out fossil fuels, better utilisation of renewable power and a more robust energy system:

Transportation. Vehicles with electric motors can be run on electricity from batteries or electricity generated from hydrogen in a fuel cell. Hydrogen can be made from electricity. The charging of batteries and the production of hydrogen could mainly take place during periods when the power system has plenty of capacity. Both batteries in electric cars (and elsewhere) and hydrogen solutions can give power back to the grid, when power becomes very scarce and prices are high. If the use of batteries and/or hydrogen becomes widespread, this contribution to flexibility could make a big difference.

Heating. In heating plants (e.g. district heating and smaller facilities), many countries use a lot of fossil energy. This could be replaced by electricity (in electric boilers) during periods with a surplus of renewable power (low prices) and by biomass or biofuel in other situations. Heat pumps will usually be in operation when there is a need for heat, but they may be turned off for a few hours if there is a scarcity of power (high prices). With a heat storage system (e.g. a large water tank), flexibility can be further increased.

Electrification of the transport and heating sector is an example of how we need to think in new ways and view investments in the various sectors in a larger context.

Various solutions and technologies will compete in contributing to an economical and secure supply. The usefulness of each technology will depend on which other solutions are developed and how much they cost. Making fundamental changes to the energy system leads to great uncertainty. In order to limit this uncertainty, it is important that authorities promote research, development and advancement of new, future-oriented solutions, to give us the clearest possible picture of the potential in different areas and the best possible platform for making long-term investment decisions.

Emissions in the power sector can be brought down a lot by replacing coal with gas, and by developing wind and solar power. But in order to reach our goal of zero emissions, we will have to develop many new zero emission solutions. Since it often takes several decades to develop new solutions and bring costs down, it is important that efforts in this area are intensified now.

SOCIETAL LEARNING PROCESSES ARE IMPORTANT

A cost-effective and powerful climate policy requires development of laws and regulations, institutions, markets and attitudes. *This involves learning processes that take time.* An example of this is the deregulation of power markets in Europe. England and Wales deregulated their power market as early as 1989 and Norway followed in 1990. Other countries followed throughout the '90s. A well-functioning European power market is important in promoting efficient use of resources and security of supply. It will be even more important in the future, when more variable power generation increases the need for trade. For this reason, the EU has for many years been aiming to establish an efficient, common market for power in Europe, but has still not quite reached this goal. *Developing suitable rules and organisations is difficult and can take a long time, in particular when several countries are involved.*

Attitudes often change in interaction with changes to laws, institutions and policy. Prior to reforms, the public is often sceptical, even though the reforms offer great benefits when viewed as a whole. An example of this is the absence of congestion charges in most cities. The value of less time wasted in heavy traffic could in itself make congestion charges highly beneficial to society. In addition, the local environment would improve, CO2 emissions would decline and there would be better opportunities to develop public transport options on roads. Economists largely agree that congestion charges are a good solution for cities, but even so, few cities have actually introduced them. Often, reforms receive more support after implementation. In Stockholm, for instance, the population voted in favour of keeping congestion charges after a trial period.

Successful reforms in one place can make it easier to gain support for comparable reforms elsewhere. This is both because we can learn from what others have done and can be confident of good results, and because it is easier to argue for a model that has been proven to work in practice. Success breeds success. Those who lead the way contribute to increased cost-effectiveness globally.

ALLIANCES OF MOTIVATED COUNTRIES CAN DRIVE TECHNOLOGY DEVELOPMENT FORWARD

A number of countries may have significant self-interest in developing solutions that also result in lower CO_2 emissions. For countries with big net imports of oil and gas, development of renewable energy and increased energy efficiency could encourage developments within industry and technology on a domestic level, lead to lower import bills, increase employment and reduce the risk of supply issues. In areas with serious pollution problems, the transition to emission-free power generation and electrification of transport could offer significant environmental rewards.

When several countries have a strong self-interest in developing new solutions and also have large industrial and research capacity, effective alliances can be formed. Together, these countries can obtain the desired developments in technology and industrialisation.

By coordinating efforts and sharing expenses, countries could be motivated to do more than they otherwise would have done to develop new climate solutions. This makes emission reductions cheaper.

When the cost of emission cuts goes down, it becomes easier to bring other countries on board with ambitious emission reductions.

1. INTRODUCTION: COST-EFFECTIVENESS – IMPORTANT AND DIFFICULT

WE NEED A BROAD, LONG-TERM PERSPECTIVE ON CLIMATE POLICY

This report has been written to show that we need to think in a broader and more long-term perspective regarding climate policy measures. A broader perspective helps us to see more opportunities and find better solutions. The most important message of this report is that we need to view climate policy and climate measures as part of a global process of learning and restructuring. This learning process includes development of technology, institutional frameworks, policy instruments and public attitudes to measures and policy instruments. From one day to the next, society changes little and may seem static. But when we look back 20-30 years from our modern society, we discover that technology, the way things are organised, and attitudes have all changed considerably.

EVERYONE IS FOR COST-EFFECTIVENESS

In order to limit global warming to 2°C, big changes are required within industry, transport and agriculture, as well as complete restructuring of the energy sector. All countries must at some stage become part of this restructuring. We need an intelligent strategy to keep costs down. Low costs are important to save money, and have the additional benefit of making it easier to get every country on board with restructuring. Hence, low costs increase feasibility.

Cost-effectiveness is about avoiding waste of resources and unnecessarily expensive solutions. It is difficult to be against cost-effectiveness. This is why it carries a lot of weight when experts highlight some measures or solutions as more cost-effective than others. And since analyses of cost-effectiveness are part of economics, we economists have, to a large degree, been entrusted with the authority to define what is cost-effective.

A cost-effective policy will bring us to a given policy goal with as low societal costs as possible. Cost-effectiveness is therefore defined for a given goal or set of goals. If the goal is defined differently, other measures may become cost-effective. A clear description of the goal is therefore important for a sensible discussion of cost-effectiveness. As you will see in this report, conclusions about cost-effectiveness can be entirely wrong if analyses are built on assumptions that are too narrow or simply wrong.

In many cases, the discussion of cost-effective climate policy is characterised by a narrow interpretation of the goal, e.g. that national emissions must be brought down to a given level by a specific year. Is the goal really this narrow, or should we also be taking into account more long-term effects, and how a given measure may affect emissions in other countries?

Since the climate challenge is global and very long-term, there should in general be a broad, long-term approach to assessing the cost-effectiveness of climate policy and climate measures. It may be useful to use the term *dynamic, global cost-effectiveness* with regard to analyses that have a global perspective and take into account that in the long-term, measures can affect developments in price and technology and contribute to development of other useful knowledge.

If one employs a narrow approach to cost-effectiveness, one should state what is not taking into account for the sake of the clarity.

IS THE ECONOMISTS' ANSWER CARBON PRICING ALONE?

I use the terms carbon pricing and carbon price to mean a tax or a quota price linked to emissions of CO_2 and other greenhouse gases. [1]

In the public debate regarding choice of instruments in climate policy, for example in connection with the EU's emission targets for 2030, the impression may sometimes be given that the economists' answer is *carbon pricing and carbon pricing alone*. Some economists may also, unfortunately, have given the impression that not much should be done before a global climate agreement and a global carbon price have been established.

Many economists have, in my opinion, placed *too much* emphasis on the idea of carbon pricing solving most problems, including the need for technology development. Correspondingly, not enough emphasis has been placed on the limitations and challenges inherent in using carbon pricing as an instrument. Thus, the need for additional instruments is underestimated. Emphasis on carbon pricing alone could unnecessarily delay important processes of restructuring and learning. That could delay climate policy and make it more expensive.

In economic theory, a market imperfection is something that means the market does not make economically efficient use of resources.[2] There are *two important, general* market imperfections that need to be corrected in order to ensure cost-effective treatment of the climate challenge[3]:

The most talked-about, fundamental market imperfection is that greenhouse gas emissions cause global warming. In most cases, countries, consumers and businesses pay little or nothing for the damage caused by their emissions, and therefore do not have sufficient incentives to change their behaviour. A high carbon price now and a high expected carbon price in the future would be a strong driver for change. Read more about this in Chapter 3.

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1 For greenhouse gases other than CO2, the greenhouse effect of the gas is converted to a CO2 equivalent. The most correct weighting of various greenhouse gases will not be further discussed here.

2 An important form of market imperfection is linked to so-called external effects, or externalities. In economic theory, external effects are when human activity impacts other citizens' or countries' well-being while this effect is not reflected by market prices. If a business pollutes and e.g. damages the health of the local population, this is referred to as a negative externality. If an activity has positive ripple effects that businesses do not receive payment for, this is a positive externality. In a market economy, economic efficiency is promoted by letting activities that create negative externalities pay for the costs (tax equal to marginal damage from emissions) and by subsidising activities that result in positive externalities. This means market players take societal considerations (externalities) into account when making decisions.

3 In addition to the two general market imperfections I discuss here, there are a number of market imperfections linked to different markets. For instance, efficient energy use may be hampered by a lack of information or because the person who can increase energy efficiency in a building does not stand to gain anything from it. Some market imperfections are touched on in this report, but it does not aim to provide a complete overview of everything that should be corrected in various submarkets. The need for correction will also vary somewhat from country to country, depending on how the relevant sectors are organised.

The second market imperfection is related to the fact that knowledge is to a large degree a *public good*.[4] The climate problem will be a lot easier to deal with if we develop new and better technologies and more knowledge of how societies can cut their emissions most easily and cheaply. The challenge is that those who develop this knowledge only receive a small share of the benefits. Thus, *not enough knowledge is developed, bearing in mind what would be optimal*. This also applies to countries that finance the development of a new technology, when the whole world will be able to use the solutions after a time. The challenge of knowledge being a public good cannot be dealt with effectively through the use of carbon pricing alone.

Slower and more limited development of climate technology and other relevant knowledge will make climate policy more expensive and give us fewer tools to help cut emissions. It will also make it more difficult to get every country to agree to emission cuts. Since developments in technology and knowledge often take many years, and sometimes decades, this market imperfection is relatively insignificant with regard to emission reductions over the next few years, but it may be all-important in a long-term perspective. And the climate challenge is very long-term.

The viewpoints above are based on traditional economic theory. A number of economists have also pointed out that we need more than just carbon pricing. This applies to e.g. the Stern Review[5] and several reports from the IEA[6] and the OECD[7]. Even so, statements may still be heard that the most cost-effective solution would be if the EU only had goals for

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4 A pure public good is characterised by two things: 1) One consumer's use of good does not limit other consumers' ability to do the same. Increased use does not equal increased cost. 2) It is not possible to divide the good up and sell it to each individual consumer. If the commodity is available to one person, it is also available to others. There are few products that are purely public goods in each and every context, but a number of products fit the bill to a large degree. Information satisfies the first criterion, but some types of information do not satisfy the second criterion. It is for instance possible to patent many technical solutions and some other information can also be sold, e.g. through exclusive agreements that preclude further distribution of the information. When patent periods expire, the knowledge in the patents becomes a public good. Since the climate challenge is so long-term, use after the patent period may represent a significant share of the benefit of an invention. Some of the benefit will also fall to others during the patent period (read more about this in Chapter 5.2).

5 The Stern Review (Stern Review, 2007) highlights e.g. the following points in its Executive Summary: "Policy to reduce emissions should be based on three essential elements: carbon pricing, technology policy, and removal of barriers to behavioural change." "Policies are required to support the development of a range of low-carbon and high-efficiency technologies on an urgent timescale." Part 1 of the Stern Review, Chapter 2.7, says: "The second task of mitigation policy is to promote research, development and deployment. However, the inevitable absence of total credibility for GHG pricing policy decades into the future may inhibit investment in emission reduction, particularly the development of new technologies. Action on climate change requires urgency, and there are generally obstacles, due to inadequate property rights, preventing investors reaping the full return to new ideas. Specifically, there are spillovers in learning (another externality), associated with the development and adoption of new low-emission technologies that can affect how much emissions are reduced. Thus the economics of mitigating climate change involves understanding the processes of innovation."

6 In the report "Managing interactions between carbon pricing and existing energy policies", OECD/IEA 2013, Christina Hood writes in the Executive Summary: "A carbon price is generally considered necessary for enabling least-cost emission reductions, and should be a cornerstone element of a climate-energy policy package. However, it alone is not usually sufficient. The costs to society as a whole of decarbonisation over the short and long-term can be reduced by implementing a package of policies including energy efficiency, technology development and deployment, and support to overcome underlying infrastructure or financing barriers." (Hood 2013)

7 OECD Environmental Outlook to 2050, Climate Change Chapter (OECD, 2011) highlights e.g. the following points under Key messages:
- "Foster innovation and support new clean technologies."..."Perfecting these technologies will require a clear price on carbon, targeted government-funded R&D, and policies to reduce the financial risks of investing in new low-carbon technologies and to boost their deployment."
- "Complement carbon pricing with well-designed regulations. Carbon pricing and support for innovation may not be enough to ensure all energy-efficiency options are adopted or accessible..."

greenhouse gas emissions and that the quota market should be used as the only instrument in climate policy.

The financial crisis since 2008 has rendered the EU quota market almost ineffective, and demonstrated that future quota prices are shrouded in great uncertainty. A quota market in which players do not have enough faith, and in which prices vary a lot over time, can mean periodic stops in or a slowing down of important restructuring processes. That will delay the restructuring to a low-emission society and increase the cost. Carbon pricing can and should play an important role in stimulating short-term emission cuts and long-term change. But then the carbon price needs to be much higher than it currently is in Europe, and the market must have confidence that it will stay high (and preferably increase) in the future.

PATH DEPENDENCY – HOW CAN WE STEER DEVELOPMENTS IN THE DIRECTION WE WANT?

Path dependency is a metaphor for how events or initiatives at one point in time can have great significance for the developments that follow. When someone paves the way and evens out the path, it becomes easier for others to follow. It is easier to go where others have gone before. *This metaphor illustrates both challenges and opportunities in climate policy*.

The keyboard used with today's computers (QWERTY) was in its time created to take into account the mechanical limitations of typewriters. This keyboard has become so established that it is still in use, even though it is not optimal based on today's technology. Path dependency plays an important role in many parts of society. As we will see in Chapter 5, costs, consumer preferences, public regulations and public attitudes to various regulations are all significantly influenced by what has happened before.

- *Costs*. When manufacture of a new (immature) product increases, costs often go down due to technology development and other learning, and due to economies of scale. Lower costs mean more sales, which lead to further cost reductions.[8]

- *Preferences.* Getting used to something often leads to us preferring certain solutions over others. Many Italians want pasta every day because they are used to it, many older Norwegians want potatoes every day, etc. We are often resistant to change, but in many cases, we like changes once we get used to them.

- *Institutions and policy.* Attitudes to what is a sensible organisation of society, and what types of laws, regulations, taxes and fees we accept, are also influenced by what we are used to.

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8 Economics textbooks usually describe costs that rise with increasing production (rising supply curve). In the short-term, there may be rising costs because different facilities have different costs. Increased demand may require more expensive facilities to start producing. In the long-term, costs may rise if production is dependent on limited natural resources. If increasing oil production requires the use of fields that are less easy to access, costs will rise, assuming unchanged technology. For many industry products, however, we have seen a dramatic reduction in costs as a result of learning and the benefits of large scale (industrial) production. Mass production is much cheaper than tailor-made products.

Much economic thinking, and especially most introductions to economics, take costs and preferences for granted, and assume that the markets themselves will figure out the solutions that are most optimal from society's point of view (assuming corrections for external effects). With path dependency, it is not as obvious that markets will find the best solutions. Markets sometimes need a push to get on the desired development track. Someone has to blaze a useful trail, so that more and more people will follow it as a matter of course.

A river follows the terrain, but in the long-term it will also shape the terrain. Natural events or human intervention can lead the river into a different course, so that it shapes the terrain in a new way. In economics, such changes happen much faster than in the interaction between a river and the landscape. Through active policy, much can be accomplished to steer long-term developments in the direction we would like.

This report therefore has an optimistic message: By thinking beyond the narrowest economic models, and by viewing the development of climate policy as a long-term learning process, we can achieve more.

2. THE CLIMATE CHALLENGE IS HERE TO STAY AND AFFECTS ALL SECTORS

The climate problem affects almost all sectors in all countries, and is a permanent challenge which humanity has to face. Many greenhouse gases remain in the atmosphere for a long time; CO_2 has a lifetime of more than a hundred years. Current emissions will therefore contribute to global warming for several generations to come.

However, we do not know how much warming is caused by a given increase in greenhouse gases. The IPCC estimates the warming that results from a doubling of greenhouse gases in the atmosphere (climate sensitivity) to be in the range of 1.5°C – 4.5°C.[9] Uncertainty regarding how much the temperature will rise and how serious the consequences of a given temperature increase would be, added to the large inertia in the climate system, is an argument for a strong climate effort now. When it takes a long time to brake and the road is unfamiliar, you drive slowly.

It is important to start developing solutions now that will enable us to carry out far-ranging emission reductions later. This applies especially to technology that requires a long time to develop, and which may be crucial in dealing with the climate challenge. By starting to develop solutions for deep emission cuts early, we will reduce the costs of future climate policy and there will be a better chance of executing quick, comprehensive emission reductions later on. Especially if the climate problem turns out to be more serious than is currently expected, it is important to have developed the tools to make the necessary cuts. In addition, it is of course important that we cut emissions today where possible, and that we avoid investments that commit us to large emissions in the future.

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9 An important reason for the uncertainty is the interaction between increased evaporation and cloud formation. Global warming leads to increased evaporation. This means more water vapour (H2O) in the atmosphere since hotter air can hold more water. Increased evaporation also means more cloud formation and more precipitation. Vapour in the atmosphere increases global warming, while lower-lying clouds, conversely, decrease global warming. The interaction between these effects is uncertain. In addition, there are a number of other feedback mechanisms which make things uncertain. Increased warming results in for instance less snow cover on the ground and less ice cover on the sea in Arctic areas. This increases global warming, since snow and ice reflect more light back to space than open sea and bare land (the albedo effect). Global warming also leads to increased emissions of methane and CO2 from areas that have had permafrost, and from the seabed. These and other self-reinforcing effects contribute to the uncertainty regarding how much temperatures will actually increase.

Despite steadily increasing concentrations of greenhouse gases in the atmosphere, global warming appears to have slowed down the last 10-15 years. Some have taken this as a sign that climate sensitivity is lower than was previously assumed. However, several research reports have been published that can together explain the slower measured rate of warming of the atmosphere on the surface of the earth. Firstly, it has been pointed out that a significant temperature increase at the poles is not reflected by most statistics. Other explanatory factors are that variation in the activity of the sun (solar cycles) for a while has meant less warming, and that wind conditions and ocean currents have led to more heat being absorbed by the ocean for a time. For a short overview of the subject, see e.g. the article "Global warming Who pressed the pause button?" in The Economist (2014a). Here, the new research results are summarised thus: "The slowdown in rising temperatures over the past 15 years goes from being unexplained to overexplained".

Thinking far ahead, emissions of greenhouse gases must likely be reduced by at least 90% from the current level. Emissions may need to be reduced to zero or even to ”negative” figures towards the end of this century, if we are to have at least a 50% chance of keeping the temperature increase below 2°C.[10] This will require radical changes in the energy sector and in a number of other areas.

Currently, approximately 80% of global energy needs are covered by fossil fuels. Nearly all of this will at some stage need to be replaced by emission-free energy or solutions where CO_2 emissions are captured and stored (CCS), for instance in old gas fields. Increasing energy efficiency will be a great help in reducing emissions, but even with a determined focus on increasing energy efficiency, the total energy consumption is expected to rise for many years to come, not the least because many poorer countries currently do not have energy for many important comforts of modern life. For this reason, comprehensive alternatives *must* be developed. Most sectors of society will be affected by the need for energy restructuring.

Changes in the use of land, especially cutting down rainforests for agriculture, mean significant greenhouse gas emissions; the same is true of many types of food production (e.g. methane from domestic animals and wet rice cultivation) and damaging disposal of food waste (methane). Many industrial processes also result in direct greenhouse gas emissions, in addition to the emissions associated with their energy consumption. This applies to e.g. cement, aluminium, iron and steel.

Figure 2.1 shows how emissions must be cut dramatically at the same time as the world’s population is growing and economic activity is growing even faster. The figure shows the development relative to the level in 2014 (defined as 100).

In the figure, the world’s population increases to 9.2 billion in 2050, and rises to 10.3 billion in 2100.[11]

In the figure, *global economic growth* starts at 3% per year in 2014 and slows down gradually, reaching 2% growth per year in 2100. These growth figures are lower than historical growth and reflect assumptions that economic growth will gradually slow down somewhat. Based on the assumed rate of growth, global production (GWP) in 2050 will be as high as 2.7 times what it is today, and in the year 2100, production will be approximately *8 times what it is today*.

Both economic growth and increased population contribute – other things being equal – to higher emissions. At the same time, global emissions must be cut by approx. 60% by 2050[12], and to a level approaching zero by the year 2100. Cutting emissions of greenhouse gases to such an extent while population and prosperity will grow considerably, is clearly quite a challenge.

10 Most of the scenarios in the latest IPCC report include more technologies that will give negative emissions in the last half of this century, especially carbon capture and storage (CCS) in connection with biomass.

11 My illustration of potential population growth is marginally higher than the UN’s median alternative from 2010. See for instance Wikipedia (2014a). A recent analysis based on the UN’s population data (Yale Environment 360, 2014) indicates that population growth in Africa will be greater than previously assumed and that a better median estimate for the population in 2100 may be approx. 11 billion, i.e. somewhat higher than the curve I show here.

12 In 2014, the IPCC stated a range of 40-70% necessary cuts from 2010 to 2050. With an assumed growth from 2010 to 2014 of at least 2% per year, 60% cuts from 2014 to 2050 will be close to the middle of the range stated by the IPCC.

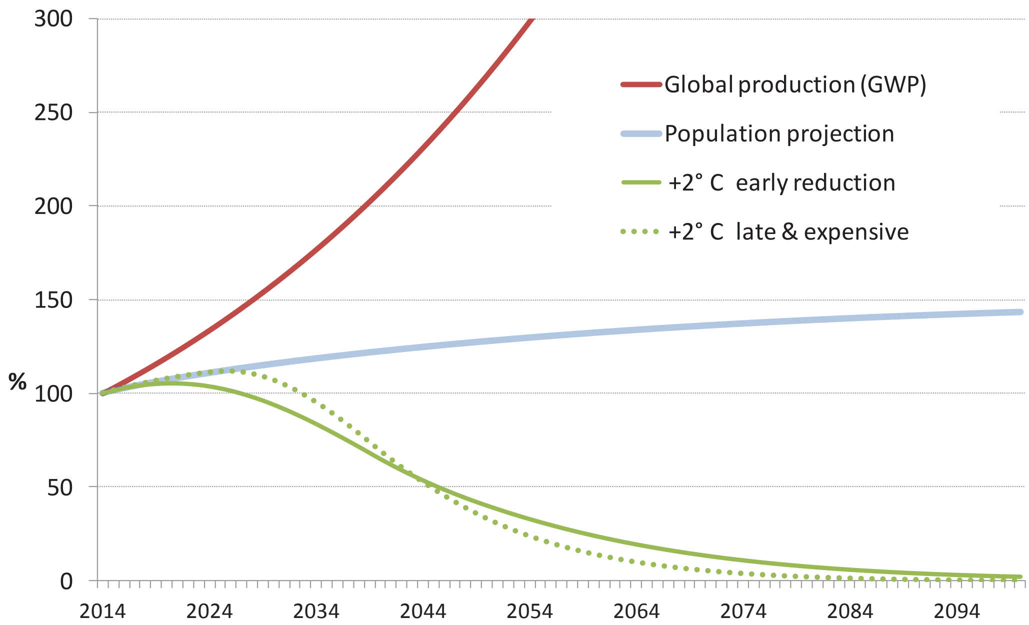


Figure 2.1 Possible development paths from 2014 for total world production, population and emissions of greenhouse gases compatible with the two-degree goal (2014 is 100%)

In the figure, the *growth* of greenhouse gas emissions slows down from 2014. In the solid case *+2°C early reduction*, the annual emissions reach their highest point in 2020, while in the case *+2°C late and expensive*, they reach their highest point in 2025. (The emission lines have been made to illustrate the principles.)

Ideally, emission reductions should have started earlier, using cheap emission cuts, but in many cases this has been difficult politically. It may not be realistic to stop global growth in emissions before 2020.

Since the dotted line assumes starting emission reductions later, more wide-ranging, expensive reductions will have to be carried out later. Starting reductions later means higher risk and could be much more costly if the climate challenge proves bigger than was first thought.

The emissions in 2050 are given here as 42% and 34%, respectively, of the level in 2014. Reductions must continue after 2050, and towards the end of the century, total emissions of greenhouse gases must be very low. The emissions of CO_2 must in practice be brought down towards zero, since it is very difficult to cut emissions of some other greenhouse gases.

The gradual reduction in emissions shown in the figure reflects, among other things, that it takes time to reduce emissions because infrastructure, such as buildings, transport systems, power stations and factories must be replaced by facilities that allow for zero emissions, or very low emissions. It is cheapest to make such changes gradually as and when facilities need to be replaced due to age, and, in any case, it would be impossible to replace everything at once. In order to reduce emissions at an acceptable rate, it is important that investment decisions that will affect emissions far into the future are compatible with the falling emissions curve. Investments that require high emission levels for many years must be avoided. The building of new coal power plants is an example of investments that can inhibit, delay and add expenses to a later reduction in emissions.

Figure 2.1 clearly shows that the climate challenge will not be resolved by 2050. It will be necessary to cut emissions significantly after 2050. This will take place in a world where more and more people can afford a lifestyle that requires energy and which may generate large emissions of greenhouse gases.

In theory, emissions can be cut a great deal using current technology, but in order to gain widespread support for radical cuts in emissions, there will likely be a need for great technological advances in addition to increasing public acceptance for changes in areas where there are no good, emission-free alternatives. Many of the technological solutions used to cut emissions now and in the coming years, for instance solar panels and wind turbines have been developed in the last 30 to 40 years. These technologies have still not been perfected.

The long perspective on the climate challenge and the need for such comprehensive cuts in emissions mean that technology development and broad societal learning can and should play an important role in the restructuring processes. New solutions that can contribute to emissions cuts far into the future in a growing world economy could have great significance for our capability to handle the climate challenge.

I will revisit this in Chapter 5.

TWO EXAMPLES OF THE CHALLENGES

The cement industry currently stands for approximately five percent of global CO2 emissions. Half of this is associated with the production process itself, and the remainder is mainly related to the use of fossil fuels as an energy source. If the fossil energy was replaced by emission-free energy, emissions could almost be halved. But if production grows by four percent a year (growth will primarily take place outside the OECD countries), it will more than quadruple by 2050. Then, total emissions from cement production would be more than double what they are today, even though energy use in the sector would be completely emission-free. Emissions from cement production would then account for a quarter of the total emissions we can allow ourselves in 2050, bearing in mind the two-degree goal.

Significant R&D efforts are being made to develop types of cement which generate fewer or no emissions in the production process, and it may also be possible for cement production to utilise CCS. In addition, alternative building materials might be an option for some purposes, e.g. increased use of wood in smaller buildings.

Air traffic's contribution to global warming is increased by the fact that emissions take place at a great height. The effect of the height factor is uncertain, but may be significant. In my sample calculation I assume that air traffic is currently responsible for 3% of global emissions of greenhouse gases. Significant growth in air traffic is expected in years to come. The International Air Transport Association (IATA) expects an annual growth of around 5% per year until 2050. This is equivalent to almost six times as much air traffic in 2050 as today. Without technical improvements, in 2050 air traffic will equal 17% of the global emissions in 2014. Based on a goal of 60% cuts by 2050, air traffic using today's technology will alone use 43% of the emissions budget for 2050. With a goal of ever lower global emissions after 2050 and continued annual air traffic growth of five percent, emissions from air traffic will exceed the total emissions budget around the year 2060.

Luckily, technical improvements are in the pipeline. Energy efficiency in aircrafts has improved significantly over the years, and new aeroplanes that are built today use much less fuel than older planes. Even better planes with lower energy consumption and emissions are being developed. Using biofuel produced in a sustainable way can also lower emissions drastically, but biofuel will not remove the effects of emissions taking place at height. And biofuel may become a scarce resource as fossil fuels must be replaced in many areas. Bearing in mind a six fold increase in the demand for air transport, there is obviously a need for major technological innovations, and probably also for measures to limit projected growth. This may take place through developing good transport alternatives for shorter distances, increasing prices or reducing the need for air travel in other ways. Technology improvements comprise more efficient engines, better design of the fuselage, lighter materials and routes that require less energy consumption.

These two examples come from important sectors where emissions may increase significantly. Without good technological solutions and the means to channel demand in the right direction, emissions from these two sectors alone could claim a large proportion of the emissions the world can allow itself in 2050.

3. CARBON PRICING IS IMPORTANT

Carbon pricing is important in order to move the whole economy in a climate-friendly direction. In order to fulfil such a role, the carbon price must be sufficiently high and the markets must assume that it will stay high – and even rise – in the future. In Chapter 3.1 I explain the idea behind carbon pricing and why this measure is important. In Chapter 3.2 I explain why we also need to use other measures. This is discussed in greater detail in Chapters 5 and 6.

3.1 Carbon pricing stimulates change throughout the value chain

The good aspects of carbon pricing and environmental taxes are generally often explained thus: when polluters have to pay a tax (or a quota price), they are given an incentive to weigh the global community's desire to limit emissions against their own cost of reducing emissions. Rational companies and consumers will cut emissions as far as this is profitable, i.e. as long as the costs of reducing the emissions are lower than the cost of paying the tax. When all sectors have to pay the tax, a cost-effective reduction is achieved because emissions are cut where this is cheapest, across enterprises and sectors. (See Appendix 1 for a detailed explanation.) If the tax is priced to accurately reflect the damage per unit of the emissions, emissions will be reduced to an optimal degree. In a quota system, this is achieved by setting the sum of quotas equal to the acceptable level of emissions. The quota price in the market will then be high enough to bring emissions down to the desired level.

An important point is that a tax (or quota price) does not only affect emissions directly. Assuming efficient markets and no distorting government interventions, the cost of emissions will be included in the market prices of the products. Goods whose manufacturing entails pollution will therefore be more expensive, and the increase in price will reflect the emissions behind the manufacturing of the product. This gives consumers and companies at different stages of the value chain an incentive to switch to less polluting factors of production and products.

So, carbon pricing gives incentives both to reduce big and small emissions where they take place, and to switch to products that involve lower emissions. Both direct emission reductions and a switch to products with lower emissions will be important in achieving a powerful climate policy, since most sectors, and a vast number of factors of production and products, are subject to the emission of greenhouse gases. Sometimes, direct emission reductions in the production process are cheapest; at other times, it may be better to replace products that represent high emissions with less polluting alternatives. The pricing of emissions ensures markets make these choices in a cost-effective manner, assuming that other societal costs and benefits are also reflected in prices and taxes.

The fact that emission costs in connection with the production of a commodity are reflected in the price means that it is less important whether the buyer of the product pays for the emissions, or the industry which emits CO_2 when manufacturing the product, pays. Both parties have an incentive to do something about the problem, and in the end, it is the buyers who have to pay for the product's ultimate contribution to greenhouse gas emissions.[13]

The presentation above describes the core of economic theory of how to handle so-called externalities. This has been economists' standard solution for dealing with environmental issues. This theory is taught to economics students; it is elegant and easy to understand. For this reason, it is understandable that some insist that carbon pricing – and carbon pricing alone – is the ideal cost-effective solution to the climate problem. But as we shall see below and in the next chapters, things are more complicated.

3.2 Other external effects must also be included

When considering the cost of a climate measure, we must correct the business economic (commercial) costs for *all* market imperfections. Emissions from coal power that constitute a health hazard should for instance be paid for by coal power. A new study from MIT has found that the health benefits of a number of relevant climate measures in the US significantly outweigh the costs.[14] In light of this, climate measures become cheap and in some cases profitable, even disregarding the climate benefits. Imperfections in the market and a lack of pricing of other externalities mean that in some cases, climate measures may have "negative costs", i.e. these measures are economically profitable independent of the climate challenge.

Climate measures may also contribute to the learning process and to the development of technology, so that later climate measures will be cheaper or so that other benefits are achieved in future. For example, support for the development of solar cells may be profitable in a global, long-term perspective regardless of the need to slow down global warming. When present efforts mean lower costs for future climate measures and those who implement the measures only reap some of the benefits, we have a market failure. In this case present measures involve a *positive externality*. In order to make markets adapt in an economically efficient manner, activities that have positive externalities should be *subsidised*.

In Figure 3.1 below, I have illustrated how the total costs of different measures can be compared by taking into account positive and negative external effects.

13 In practice, markets do not work perfectly, and authorities in various countries sometimes intervene to limit cost transfer (cf. e.g. significant subsidies for fossil energy in some countries). The transfer of emission costs to the price may therefore be less perfect than described here. Still, it is reasonable to expect that this effect will be an important contribution to change.

14 See Health benefits offset costs of climate policies (Peterka, 2014), and Capturing the multiple benefits of energy efficiency (IEA, 2014)

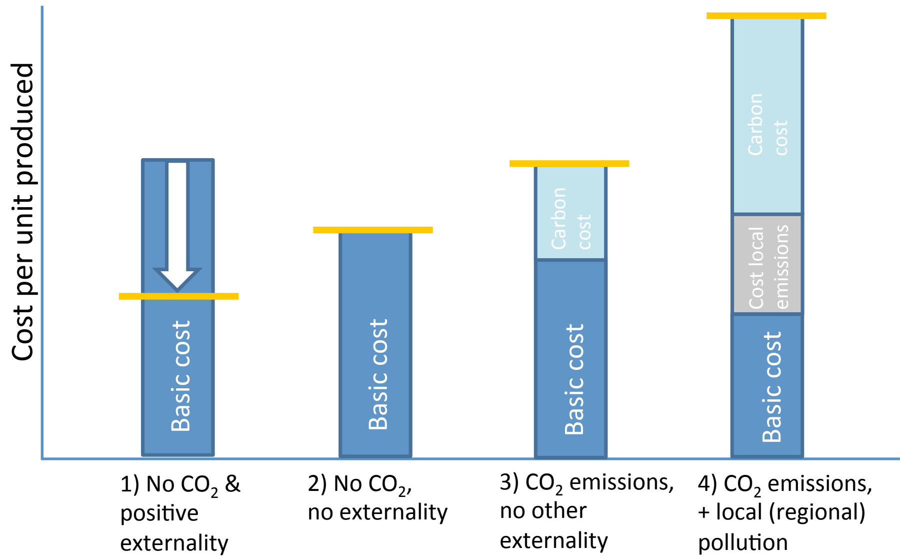


Figure 3.1 Private economic costs (basic costs) corrected for positive and negative external effects

The dark blue columns labelled *Basic cost* show regular commercial costs. By correcting for different positive and negative external effects, we arrive at an economic cost represented by the yellow lines in the figure. Before the corrections, 4) (on the right) is the cheapest, then 3), then 2), while 1) is the most expensive.

With the corrections, 1) is the cheapest because there is a significant positive external effect here (learning which provides future cost reductions). The positive external effect is reflected by the white arrow pointing down. When we include the cost of the CO_2 emissions, 3) is more expensive than 2). And finally, 4) is the most expensive because this solution entails both large CO_2 emissions and significant environmental disadvantages in other areas.

This figure could, for instance, illustrate different technologies for power generation. 1) Would be a zero emission technology where development contributes to a future price drop. 2) Would be a mature, emission-free technology where such learning opportunities can be disregarded (e.g. conventional hydro power or nuclear power). 3) Could be gas power (CCGT) which has relatively small local and regional environmental disadvantages compared with coal power. 4) Could be a coal power plant which results in significant damage to both the environment and health and much greater CO_2 emissions per kWh than a gas power plant.

Estimating the size of such positive and negative externalities is challenging, but that does not mean that they can be ignored.

All or most countries benefit from future costs of climate measures going down. However, if only the benefit to one's own country is considered when national climate policy is determined, less weight will be placed on the future cost reduction (cf. positive externality in the left column in Figure 3.1, arrow pointing down). One might then arrive at a different conclusion regarding what is most cost-effective.

4. THE ENERGY REVOLUTION HAS BEGUN

Energy policy and climate policy go hand in hand. The energy sector represents around two third of global emissions of greenhouse gases. Much of the growth in emissions in recent years has been in connection with energy use. Especially energy-related emissions *outside* the OECD have grown quickly, from 45% of total energy-related emissions in 2000, to 60% in 2012 (IEA, 2012). This growth is due to the fact that energy consumption is closely tied to economic growth, especially in developing countries. *Without extensive measures, growth in energy demand will mean a steep increase in global* CO_2 *emissions.*

It is simpler to cut emissions in the energy sector than in a number of other areas, such as some types of agriculture, certain industrial processes and aviation. Turning the growth in emissions in the energy sector to a decline is therefore a key part of climate policy. Two main types of measures are necessary in order to achieve this:

a) We must limit energy consumption through increased energy efficiency and prices that reflect the full cost of energy use, and

b) We must replace fossil energy sources with emission-free energy.

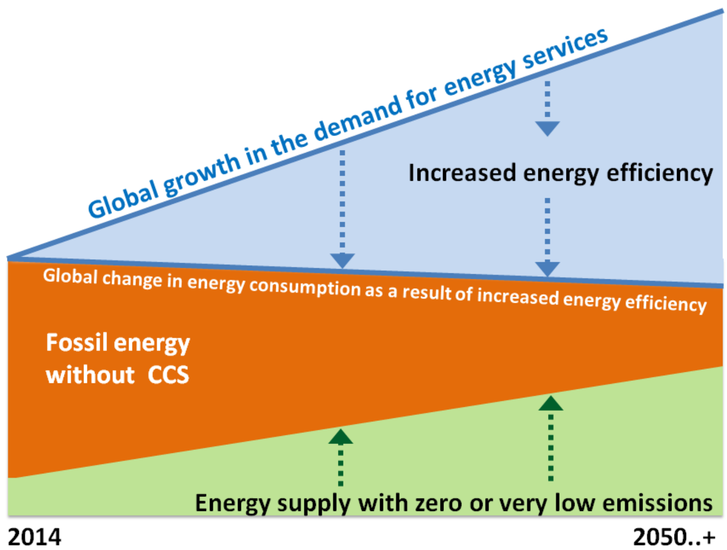


Figure 4.1 Illustration of challenges and opportunities: Increased energy efficiency limits consumption and emission-free energy replaces fossil energy (without CCS)

Figure 4.1 illustrates these two types of measures. Renewable energy will play a crucial role in delivering emission-free energy. But nuclear power and fossil power with CCS may also be important, especially in areas where there is limited access to renewable energy sources.

The transition from coal to gas in the power sector could mean important contributions to reducing emissions during the first 30 years. This is because gas power has around half the emissions of coal power, and gas is also easier to regulate up and down in line with changing needs as consumption and intermittent renewable power generation vary. In the long-term, however, emissions need to be reduced to such an extent that not even gas power can be used to any great degree without CCS (cf. Chapter 2 and Figure 2.1).

R&D and policies for implementing new energy solutions on a large scale have led to dramatic cost reductions. This is a result of concentrated efforts in a few countries and gives an indication of how important strong, ambitious, long-term technology policies might be. In Chapter 4.1 we will look at how the prices of solar cell panels (PV), wind power, batteries for electric cars and LED lights have fallen. In Chapter 4.2 I explain why it is important to continue the R&D efforts to push prices further down and develop a wider range of solutions. We need a broad set of technologies to build a sustainable global *energy system*, and costs should ideally be so low that all countries will prefer the sustainable solutions.

4.1 Ambitious technology development has given dramatic price drops

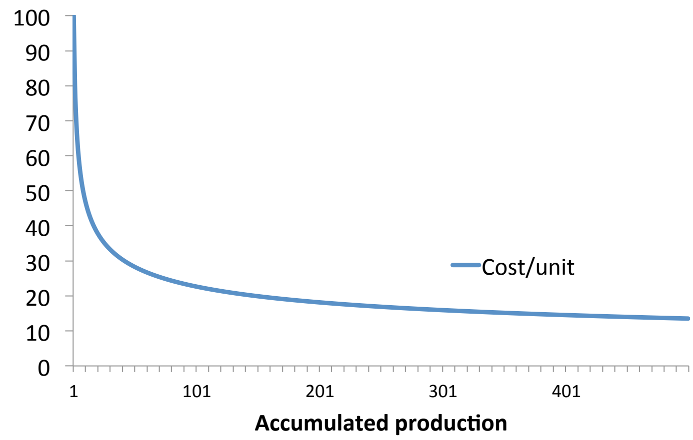


Figure 4.2 Price drop at 20% learning rate

It is a common observation that the price of a new technology drops significantly as production volume rises. This type of price drop is often illustrated by so-called *learning curves*. The associated *learning rate* is defined as a percentage reduction in unit costs through a doubling of accumulated production. In Figure 4.2, I show the price drop in a stylised case where the learning rate is 20% and the first manufactured unit costs 100.

A report entitled *Revolution Now,* U.S. Department of Energy (2013), summarises the price drop for four selected technologies: onshore wind power, solar cell panels, LED lights and larger batteries for electric vehicles (EV). Here are some of the main points from the report:

- In the 35 years until 2012, the price of roof top panels with solar cells fell by 99%, to 1% of their cost 35 years before. Reference is made to Mints (2012). It is estimated that the learning rate for manufacturing of solar cells has been approx. 20%. From 2008 to 2012, prices fell from $3.40/watt to $0.80/watt (76%). Some of this is due to overproduction and pricing pressure, but much can also be explained by technological advances and the benefits of larger-scale production. When the panel itself (the solar cells) becomes cheaper, other costs, such as adjustments, installation and permits, account for a larger percentage of the total cost. The report shows that these costs are approx. five times higher in the US than in Germany. Part of the explanation is that a much higher turnover in Germany has brought down installation costs. The report has a very optimistic view of the future where solar panels are concerned: *"Current trends indicate that solar energy has a very bright future."*

- For onshore wind power, costs have been reduced by approx. 90% from 1980 to 2012. Costs rose from 2001 to 2009 due to increased material costs (commodity prices) and construction in locations with less favourable wind conditions, but after 2009 costs have fallen significantly again. The price drop for wind power is partly due to increases in the size of turbines, but a number of other factors also play a part.

- For over ten years, the U.S. Department of Energy has been supporting research to improve LED technology, and the Department has also made considerable investments in production to reduce costs. At the same time, the light quality has improved significantly. In four years, from 2008 to 2012, the price of LED lights fell by 85%. (The EU's ban on incandescent lamps has also contributed to a much bigger market for LED and has therefore stimulated innovation and benefits from economies of scale, but Revolution Now focuses on the use of policy instruments and development in the US.) Current LED light use 85% less energy than conventional light bulbs. An article on the website Reneweconomy (Wright, 2014) reports research results which indicate that it could be possible to cut LED electricity consumption to one third of the current level for LED, i.e. resulting in a total energy saving of 95%.

- The cost of batteries for electric cars has dropped by more than 50% from 2008 to 2012, to a level below $500 per kWh storage capacity. One can envisage opportunities for further price drops: *"Some private sector analysts have said that there is a relatively clear technology path to $200/kWh for battery storage by 2020. The Department is working with industry, academia and our own labs towards an even more aggressive goal of $125/kWh by 2022. At that point, ownership costs for a 280-mile EV will be equal to a standard vehicle."* (280 Miles is equal to 450 km)

Many new technologies, both in and outside of the energy sector, have seen large price drops as they have become more common.

Floating offshore wind power is a technology in the early stages of the learning curve. After a few years during which Statoil has been testing one pilot turbine (Hywind) of 2.3 MW off the Norwegian coast, five turbines of 6 MW each are now to be built off the coast of Scotland. See Garus (2013). With this upscaling, Statoil expects the costs per MW of installed capacity to fall to one third of the costs of the pilot. Even so, a further significant price drop is necessary

U.S. DEPARTMENT OF ENERGY:

- *Solar panels: 99% price drop in 35 years*
- *LED lights: 85% price drop in 4 years*
- *Onshore wind power: 90% in 32 years*
- *Batteries for electric cars: > 50% price drop in 4 years*

in order for this technology to become competitive.

The increase in the cost for wind power from 2001 to 2009 illustrates that costs can rise even though the technology improves. This may be due to more expensive factors of production or that the best areas are already being used. Problems may also arise relating to quality and durability, and cause us to *acknowledge* that the actual costs are higher than was first thought. This last point illustrates that for technologies with high investment costs, low operating costs and long lifetimes, it could take many years before a clear picture of the actual cost level emerges. Wind turbines are often designed for a lifetime of 20 years, but many believe they will last longer than that. Maintenance costs will also be associated with uncertainty for new and untested technologies.

For a technology such as wind power, learning may mean lower investment costs per turbine (per MW capacity), improved selection of construction areas, better placement in the terrain, less impact on the environment, longer lifetimes, lower maintenance costs and optimisation of actual power generation. Brand new concepts are also being developed in order to harness energy from the wind. For an overview of the many improvements which have brought wind power to where it is today and some further perspectives, see for instance the article *Where Is The Real Innovation In Wind Energy?* from CleanTechnica (Barnard, 2014).

Both for the technologies discussed in Revolution Now and in a number of other areas, there are good opportunities to bring costs further down, perhaps significantly further down. Different technology leads are being pursued based on various materials, to improve performance and bring costs down.

4.2 The whole energy system needs restructuring

In some places, electricity from wind power and solar cells is now cheaper than electricity from new coal power (total costs), even aside from coal power's climate and environmental costs. (Parkinson, 2013.) This illustrates what fantastic successes the efforts invested into solar and wind power have created. But *fantastic* is in this context *insufficient*. If we are to succeed in limiting global warming to +2°C, these efforts must continue.

A key challenge may be described based on the difference between fossil power generation on the one hand and wind and solar power on the other: While fossil power generation can be regulated and adapted to consumption, power generation from solar and wind power is dependent on the weather and is therefore highly variable. Sometimes, hardly any power will be generated by solar panels and wind turbines in Europe. This *could* coincide with high energy consumption, e.g. during cold winter periods of little wind. This is a significant challenge which needs to be resolved, since at any given moment there must be as much power going into the grid as there is going out of it.

The overarching challenge is to develop an energy and power system that can offer both a minimum of CO_2 emissions and high security of supply. It is also important that this system is as cheap as possible, both to save money and to make it easier to gain global support for this type of climate measures.

Here in Chapter 4.2 we will examine this challenge more closely – and I will go into more detail on several of the issues in Appendix 2. A good understanding of the challenges is important when determining which climate strategy is cost-effective and powerful in the energy sector.

There are two reasons why I focus specifically on the power system below: i) electricity will become more important as emissions are reduced in the energy sector, and ii) a power system with high security of supply is crucial to a modern society. The EU Energy Roadmap 2050 requires the power sector in Europe to have close to zero CO_2 emissions in 2050. This in turn requires a power system radically different from the one we have today. The system must be developed so that new production technologies, storage systems for power, consumer flexibility and electricity grids *together* ensure robustness and sustainability at the lowest possible total cost. In order to succeed we need new technologies to be developed, major, long-term investments, good institutional frameworks and suitable markets to coordinate the development and operation of the entire system.

4.2.1 A DOUBLE CHALLENGE

Electricity plays an increasingly important role in society because we use electricity for an increasing number of services. This is related to the development of ICT, the electric motor's useful qualities for carrying out mechanical operations, growth in affluence and also climate policy. The requirements for security of supply become more stringent when more services are dependent on electricity.

The power system faces a double challenge: While requirements regarding security of supply will become more stringent in the years to come, climate policy entails that easily-controllable, stable fossil power generation must be replaced by emission-free power generation which in most cases is less flexible and in many cases varies depending on the weather. The most flexible renewable power technology is based on biomass (bioenergy), which can be regulated almost on a par with fossil power, and hydropower from reservoirs. Hydropower can be very flexible within the limitations set by the reservoir, water discharge restrictions and precipitation. Geothermal power plants can run at a set rate, but are so far only economically feasible in areas with particularly favourable geological conditions.

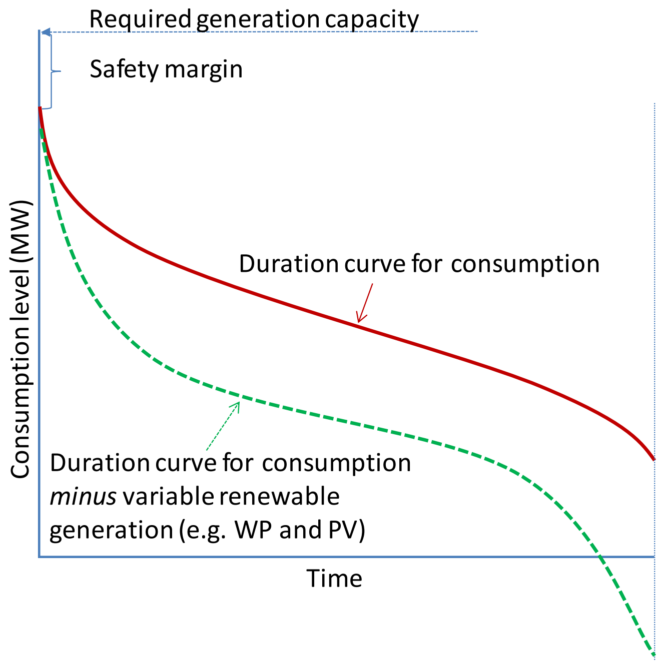
An entire power system can be based on fossil power, but it cannot be based on solar and wind power alone. Even though the progress regarding solar and wind power has been impressive and may continue, a number of additional solutions must be developed in order for the power system to work acceptably without fossil power.

Fossil fuels will for decades be part of the energy mix and contribute to flexibility in the power sector. But since it might take many years to develop good new emission-free solutions, it is important to start the process now (cf. how long it has taken to develop wind power and solar cells). The sooner good alternative solutions are developed, the sooner it will be possible to phase out the use of fossil energy. Furthermore, the need for new flexibility will increase in the coming decades as the percentage of renewable power rises and the percentage of fossil power declines.

4.2.2 THE CHALLENGE OF VARIABLE RENEWABLE POWER GENERATION

In general, wind power and solar power complement each other nicely in Europe. Wind power generates more power during the winter months when consumption is highest, and solar power generates power during the day and mostly during the summer months. Still, there are periods when the total generation from solar and wind power will be close to zero. Average generation per week and month also varies significantly, and a study detailed in Appendix 2 showed that *annual* total generation of solar and wind power for a large group of

Figure 4.3 Duration curve for consumption and duration curve for consumption minus variable renewable power



European countries varies by +/- 14%. The fact that there may be long periods of relatively low power generation from solar and wind power has implications for what kind of solutions can be used to cover consumption.

In Figure 4.3 I have drawn a typical duration curve for electricity consumption in an imaginary country (red line). Here, consumption for each hour in a representative year has been sorted according to the level of consumption, from highest consumption (left) to lowest consumption (right). Generation capacity that is somewhat higher than the highest consumption is required in order to serve this consumption profile.[15]

Total power consumption throughout the year (kWh) equals the area below the red duration curve for consumption. To start with, let us imagine that consumption is covered by

15 A safety margin is required to compensate for the fact that power plants may stop due to operating problems. There have for instance been cases of simultaneous loss of significant amounts of nuclear power in several countries (e.g. Sweden) in later years. In order to limit the risk of supply issues, it is desirable to have a total capacity somewhat higher than the maximum consumption. This safety margin ensures that the likelihood of supply problems is small. Since variable renewable power will sometimes produce a lot when consumption is at a peak, the new renewable power generation reduces the number of hours when there is a need for high capacity. Thus, renewable power will also somewhat reduce the likelihood of supply issues. Solar cells may for instance provide important contributions to security of supply in Europe during heat waves when conventional thermal power stations may have cooling issues. To simplify, I will overlook the need for a safety margin in the rest of the discussion.

fossil power. The country then develops its wind and solar power considerably. The production pattern of wind and solar power means that there will be periods when these energy sources contribute very little at the same time as consumption is at its peak, for instance during a cold winter evening with almost no wind. Such periods may not necessarily occur every year; the point is that they may happen occasionally. This is a challenge which must be solved since a modern society will not accept significant power cuts. The costs in the form of lost production and comfort are too high.

In order to gain a picture of the need for power generation other than solar and wind power, the duration curve for *consumption minus production of solar and wind power* can be drawn, as I have done, viz. the dotted green line in Figure 4.3. (One finds consumption minus solar and wind power for each hour throughout the year. Then these numbers are ranged from the highest to the lowest value in the green line.) As is clear from the figure, almost as much *capacity* is required as before the development to cover peaks in consumption, but the fossil power plants will produce less power throughout the year. The decline in fossil power generation is equal to the area between the two curves. In the far right of the figure, we can see that consumption minus wind and solar power generation is negative. Here, renewable energy generation is greater than consumption. Unless this excess power can be exported, stored for later use or another use can be found for it, it will be wasted. (I will come back to opportunities for using excess power.) In a situation where renewable power goes to waste, the marginal value of power generation is close to zero.

In this example, the *fixed* costs of fossil power generation do not decrease significantly, since almost as much fossil capacity is required after the development of solar and wind power. There are increased (fixed) costs associated with development of wind and solar power, while the *variable* costs of fossil power replaced by renewable power are saved. The variable costs saved are primarily fuel costs and costs of CO_2 emissions and other pollution. (Also, operation and maintenance costs may be reduced to some degree). Since almost the same capacity must be maintained in fossil power plants, this may on the whole be an expensive solution. Moreover, it will not reduce emissions enough in the long-term. *There is therefore a need for better solutions, both to bring emissions down towards zero and to limit total costs.* In the rest of this chapter, I will discuss this challenge and contributions to solving it, step by step.

The deficit problem and the surplus problem

The deficit problem is that even with extensive deployment of for example solar and wind power, there will still be periods when renewable generation is not sufficient to cover consumption. The challenge is to solve this problem without CO_2 emissions and without very high costs.

The surplus problem is that during some periods, renewable generation will be significantly higher than consumption. The power system can easily handle this situation by shutting down some power generation. Windmills, for example, can stand still even though there is wind. But from an economic point of view, it is obviously much better if this power can be used to create value. That would reduce the economic burden of having an emission-free power system and could also reduce emissions in other areas.

Solutions that store power or move consumption and generation from one period to another can contribute to solving both the deficit problem and the surplus problem.

4.2.3 DECLINING PROFITABILITY THROUGH DEVELOPMENT OF EACH TECHNOLOGY – AN OPTIMAL MIX

Power cannot be stored without significant cost, and consumption varies a lot over time – cf. the duration curve in Figure 4.3. This means it is cost-effective to use several technologies for power generation. Technologies with low variable costs and high fixed costs will provide low costs per kWh when their full capacity is utilised most of the year. On the other hand, technologies with relatively low fixed costs and high variable costs (e.g. gas turbines) are better suited to covering peaks in consumption. Gas turbines can also be regulated up and down at a relatively low cost.

The optimal composition of production capacity depends on the duration curve for consumption and on how high the fixed and variable costs are for each available technology.

The fact that power consumption varies and will be served by different power generation technologies with different variable costs, entails that the marginal cost of covering consumption (and the market price) varies significantly over the course of a 24-hour or 7-day period.[16] When consumption is high (and wind power generation is low), the power plants with the highest operating costs must be put to use, and market prices are therefore higher.

When wind power generation is high, not so many fossil power plants need to be started. It is then enough to start power plants with relatively low generation costs. Power prices are therefore generally lower during periods with high wind power production. This is called the merit order effect, and it becomes stronger the more wind power is expanded. If total wind power generation is greater than consumption plus opportunities for export, the (economically correct) price of power is close to zero.[17]

In power markets dominated by thermal power, power prices are often significantly higher during the day than during the night. This is because consumption is highest during the day. Solar power (both solar cells (PV) and concentrated solar power) can benefit from this, but it is worth noting that if a lot of solar power is developed, market prices will be pushed far down on very sunny days. There will be periods when the power prices are higher during the evening and night than during the day. Such prices will reflect the fact that the benefit of more solar power (PV) falls gradually as more solar capacity is introduced. If the power can be stored and used at other times, or if consumption can be increased during the periods in question, e.g. for charging electric cars, the drop in price will be less significant.

If solar power or wind power becomes cheaper, it will be cost-effective to increase capacity. If costs become low enough, it may become cost-effective to develop the capacity to a point where some generation is worthless. Profitability is given by the *total value of annual power*

16 An exception is the Norwegian/Nordic hydropower system. Here, prices vary little throughout the day and week, because the hydro reservoirs stores large amounts of energy. Hydropower plants with reservoirs move as much power generation as possible to periods with the highest prices. This limits short-term fluctuations in Nordic power prices.

17 Power prices may also drop to zero or become negative even though there is some fossil or nuclear power generation. This is because it costs a fair amount to shut down thermal power production and start it again later. For a short period, it may then be best to keep production going even though prices are at zero or negative. A lot of renewable power does not have costs like these associated with shutdown and startup, and economically, it would make sense to shut down this type of power generation if prices drop to zero or below. But when renewable power receives support for each kWh generated, irrespective of power prices, there is money to be made even though the market price is negative. In these situations, support helps create problems in the system. This is a weakness of many support schemes, and the rules should be changed so that plants do not receive money for generation during hours when prices are at zero or below.

generation minus *total costs*. All power generated does not necessarily have to generate revenue. But it is always better, if possible, to create value from all renewable energy.

4.2.4 HOW CAN WE CREATE A ROBUST, EFFICIENT POWER SYSTEM WITHOUT CO_2 EMISSIONS?

Below, I will describe three main types of measures that can help create a balance between consumption and generation in a power system with CO_2 emissions close to zero:

1. *Evening out random variations* in renewable power generation by developing different technologies (with different production patterns) and by connecting different areas

2. *Developing new flexibility* in power generation, consumption and storage of power and energy, to achieve a balance between consumption and production, and to utilise excess generation of renewable power as efficiently as possible

3. *Exploit existing flexibility better* by building stronger grids, so that flexibility in one area can contribute to balancing other areas. Stronger grids also make it possible to build more flexibility where this is cheapest

(1) Evening out random variations in unregulated (intermittent) power generation. By developing several types of renewable power generation (with different production patterns – cf. wind power and PV), we will achieve a more stable total power generation. Complementary renewable technologies could be geothermal power, new types of wind power, wave power, tidal power, power from ocean currents and osmotic power (salinity gradients). Nuclear power and fossil power with CCS will also contribute to less random variation in the total emission-free power generation. Biomass or biofuels used for combined generation of heat and power (CHP) will often generate most power when the weather is cold. This is an advantage in countries with cold climates, as power consumption is at a peak during cold periods.

A significant evening out of variable renewable power generation is also achieved by connecting areas that are far away from each other. The total power generation of many wind farms spread over a larger area varies less (in percentage) than the variation of any individual wind farm. Even so, all the countries surrounding the North Sea often get either a lot of wind or very little wind at the same time. If a larger area is examined, such as from northern Scandinavia to Southern Europe, the covariance in wind is less. Equally, the covariance in power generation from solar panels declines over a greater distance. Increased transmission capacity is a prerequisite for making use of this effect.

Some areas have especially good wind conditions, others have especially good solar conditions, and still others have potential for geothermal power or hydro power (with or without reservoirs). A strong grid connecting countries and regions makes it easier to make proper use of the different generation opportunities.

Some of the technologies I have mentioned above are in very early stages of development and it is obviously uncertain how many of them will succeed. Since these technologies are immature, it may be tempting to assume that they will not make significant contributions in the future. However, it is worth remembering that many had such a view of wind power and solar panels 20 years ago.

(2) New flexibility. Flexibility can increase a) in *power generation,* b) in *consumption* and c) in the form of increased opportunities to *store power and energy* from periods of surplus for periods of deficit. Storage may be located at power producers, consumers or in the grid, depending on what is most practicable for each technology.

In generation, new hydropower from reservoirs offers increased flexibility. It is also possible to build more pumped storage in Europe by using existing lakes as reservoirs. A pumped storage power plant pumps water up from a lower-lying reservoir to a reservoir at higher elevation when there is a surplus of power (low prices). The power is generated later, when power prices are higher. The energy loss associated with pumping and later power generation is around 20%. (Efficiency is approx. 80%.) A significant proportion of this potential is located in Norway, but other countries also have possibilities. New artificial reservoirs for pumped storage power can also be built, as has been done in some countries. This is of course much more expensive than using natural reservoirs.

Combined heat and power generation based on biomass/biofuel (CHP) can be made more flexible than it is currently by adding facilities for heat storage and making other modifications. It is then easier to operate the facilities based on the power system's needs and store the surplus heat for later. (For instance, one might generate power during the day and deliver heat around the clock.) It is also possible to make adjustments so that power and heat generation stops while power prices are very low (surplus), and instead *buy power* from the grid to cover the need for heating (with electric boilers).

Biogas can be used flexibly in a traditional gas power plant. Gas turbines may be able to cover occasional (but lengthy) peaks in consumption, possibly supported by some fossil gas if there is not enough biogas or gas from hydrogen (see below). It is much cheaper to store energy in the form of gas than in batteries.[18] Concentrated solar power accumulates heat in a core and can therefore also regulate power generation somewhat, especially to cover consumption throughout the evening.

Consumption may become more flexible. For smaller consumption units, the development of smart grids will be a key to realising flexibility. In some types of consumer flexibility, power consumption shifts to other times. In a market, such adaptation will normally be governed by *price differences between periods*. The same applies to moving power generation to other times, for instance for hydropower with reservoirs. Shifting power consumption and power generation can reduce both the surplus problem and the deficit problem.

In other cases, consumption is increased or reduced during one period without the opposite taking place in a later period. Companies can in some cases stop production temporarily because power prices are so high that manufacturing is no longer profitable, and households can choose to reduce their consumption when prices are very high. Another type of flexibility is switching between electricity and other energy carriers, e.g. for heating.

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18 Seasonal storage of gas is employed in both Europe and a number of other markets to compensate for the fact that consumption of gas is higher during the winter than in summer, while gas production is more constant throughout the year. There are large storage facilities (e.g. in old gas fields) that can continue to be used in the future. Storage costs mean that gas prices are generally higher in winter than in summer. The cost of storing gas on a seasonal basis is relatively low.

Flexibility in power consumption can be increased significantly through electrification in the transport and heating sector. See more details on this below.

Storage of power and energy. I have already mentioned pumped storage power. Energy can also be stored in the form of compressed air, for example in old mines. This potential is limited and efficiency is 70-80%. Work is also taking place on a number of other concepts for storage of power and energy for different purposes, with different storage times, response times, capacity, etc.

Energy storage in heating systems may have great significance in the future and is described under the heading of integration of the power sector in the heating and transport sector.

Based on today's battery prices, the number of charge cycles that batteries can handle and the energy loss (more than 15% for several types, let than 5% for Li-ion) per charge cycle, it is still far from profitable to invest in batteries to buy electricity when power prices are low and sell it when prices are high. But several types of batteries have seen significant advances in the last few years and may become relevant in different contexts. As we saw in Chapter 4.1, the U.S. Department of Energy has set a goal of reducing the cost of Li-ion batteries to $125 per kWh storage capacity by 2022. And it may be simpler to reduce the cost of stationary batteries, since the same limitations with regard to weight and volume do not apply. The fact that many different technologies are being developed gives hope of new breakthroughs and a significant drop in costs. [19]

Batteries may have lower functionality after many years of use in electric cars and other functions with high performance standards. They may then get a second life as relatively cheap energy storage for the power system, since the requirements are not the same there.

Based on the U.S. Department of Energy's cost goal of $125 per kWh for 2022 (for Li-ion), a *potential* cost reduction down to *$25 per kWh* could be described as a revolution. But even at that price, storage on a larger scale and for longer periods will be expensive, and many other alternatives will be cheaper. A price tag of $25 per kWh means that a storage capacity of 1 TWh would cost *$25 billion*. (A storage capacity comparable to the total reservoir capacity in the Norwegian hydropower system would cost more than $2,000 billion.)

Many system challenges will be simpler to solve if the cost of batteries drops significantly or the quality improves. Even if batteries were to remain relatively expensive, profitability may become acceptable where batteries can cover several needs and especially if they can be used frequently. Batteries ensuring power supply in the event of grid problems, for instance in base stations for the mobile phone network, could likely also be used to support the power system where necessary. Profitability will also improve in instances where stationary batteries could reduce the need for grid investments.

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19 The summer of 2014 has seen three interesting news items regarding possible advances where batteries are concerned: (1) A Japanese company (Power Japan Plus) has announced the possibility of dual carbon batteries. Developers claim these will be cheaper than lithium-ion, be based on readily available, harmless, recyclable materials and can be charged 20 times faster than today's lithium-ion. (Borghino, 2014) (2) According to Ingram (2014a), Japanese scientists claim they have developed a battery that has seven times the energy density of today's lithium-ion batteries, and that will also be cheaper and safer. Such an improvement in energy density means that an electric car battery would take up less room than the petrol tank of an average car of the same size, and be able to cover the same distance. If this becomes possible, it will open up many new areas for battery use. (3) Tesla and Toshiba have together decided to build a factory that in a few years will double the world's capacity for manu-facture of lithium-ion batteries. Tesla has formerly stated that this development will bring costs down by 30%. It has been hinted that this is a conservative estimate, and independent observers have speculated that costs may come down to $100 per kWh as early as 2017. (Ingram, 2014b) It is hard to know when and whether all these improvements will arrive on the market. But each of them could have great significance, especially for use of electricity in the transport sector.

Batteries are undergoing very interesting technological developments that could result in many possibilities. However, it is important to remember that there are several other types of flexibility that may be cheaper in many situations, and that different sources of flexibility may offer different advantages. As we will see in 4.2.5, the heating sector will probably be able to deliver a high degree of both long-term and short-term flexibility.

(3) Better utilisation of existing and potential new flexibility. A stronger grid makes it possible to use flexibility in one area to deal with imbalances in other areas. A stronger grid also allows the development of more flexibility where this is cheapest, for instance in the Norwegian hydropower system.

In addition to the factors reviewed above, increasing energy efficiency in a way that reduces consumption in situations where there tends to be a scarcity of power could be very valuable to society, both financially and as a contribution to sustainable development. Different measures that increase energy efficiency will affect the *time profile* for consumption differently. In many countries, maximum consumption of electricity (and energy for heating) is linked to cold periods. Better insulation of buildings (lower heat loss) will then result in lower maximum consumption. A transition from heating using fossil energy or biofuel to using heat pumps could be very energy-efficient and advantageous when looking at the big picture, but it could also result in a higher maximum consumption of electricity. If heat pumps can be controlled in a clever way, so they stop when consumption is at its highest, the increase in maximum consumption can in many cases be constrained. I will return to this topic below.

4.2.5 INTEGRATING THE POWER, HEATING AND TRANSPORT SECTORS OFFERS MANY BENEFITS

It is often easier to reduce CO_2 emissions in power generation than in other energy use. By reducing emissions in the power sector and using ever-cleaner electricity in other sectors, emissions can be brought down. Electrification is a means to reducing CO_2 emissions throughout the energy sector.

Emissions from energy use are closely linked to the choice of transport types and engine types, heating solutions, design of buildings and towns, and to the choice of energy carriers and types of power generation. Such choices can commit a society to high emissions for many years. Cost-effective restructuring of the energy system means that new solutions should as far as possible be developed when there is a need for reinvestment or new investments in the system. When renovating or constructing new buildings, future-oriented energy solutions must be chosen. For example, when old fossil power plants are ready for closure, it is important that they are replaced by emission-free solutions.

To allow new solutions to be phased in at economically viable points in time, restructuring in the power sector must take place in parallel with restructuring in the sectors that increasingly use electricity. If restructuring in the heating and transportation sectors does not take place in parallel, the emission reductions will take much too long, or be unreasonably costly.

Below, we will examine how increased integration between the power supply and the transport and heating sector would make the energy and power system robust, offer good exploitation of resources and make it easier to reduce CO_2 emissions in all three sectors.

In the transport sector, *electric vehicles* may provide an important contribution to emission reductions. When batteries become good enough and cheap enough (cf. 4.1), electric cars will have a number of advantages over traditional cars. Electric cars use approximately a third of the energy required by a petrol car, electric motors are quiet and highly durable, and they do not cause local pollution. *Hydrogen*, which can be produced through electrolysis, may also have an important part to play in the transport sector. Hydrogen from a tank in the vehicle is used to produce electricity in a fuel cell. The electricity powers an electric motor, as in an electric car. Both battery and hydrogen solutions are enjoying significant technological progress, while the two technologies each have their strengths and weaknesses. Fuel cells have in recent years become more energy efficient, smaller, lighter and significantly cheaper. Hydrogen tanks have also become lighter and cheaper. Electric cars with batteries may become the best option for smaller vehicles, while hydrogen could be the preferred option for larger vehicles built for longer distances. And in some cases, the technologies may be integrated in the form of an electric car with a small fuel cell and a small hydrogen tank as a range extender. [20]

Increased use of electricity or hydrogen may also be applicable for public transport and freight. South Korea is testing solutions with electric buses, where the batteries are charged wirelessly at bus stops. Hydrogen is also relevant to public transport and heavier goods transport. In cities where pollution is an issue, transport solutions based on electricity and hydrogen will cut local pollution significantly. In Norway, an electric ferry is introduced.

In addition to solutions based on electricity and hydrogen, types of biofuels that do not compete with food resources, may also play an important part, for example within air transport, shipping and heavy transport. For bioenergy, much research is being conducted in the area of conversion processes (biochemical and thermochemical) for different purposes for use as biogas, bio-oil, etc. A driving force here is the focus on bio refining which could lead to more socially profitable value chains, because the use of biomass is being optimised for energy as well as for other purposes. Withdrawals of biomass must be sustainable, the whole cycle must be studied and withdrawals must be weighed against the value of binding carbon for longer in for example forests.

Bioenergy might have an important role to play in different parts of the energy system such as the transport sector or to provide flexibility in the heating sector. IEA analyses and EU policies also highlight the need for several energy systems that can work together.

Charging batteries for electric cars and production of hydrogen through electrolysis may to a significant degree work together with the power system and contribute to flexibility. Passenger cars are parked most of the time and therefore offer a certain amount of freedom with regard to when and how fast their batteries are charged. The night especially is often a suitable time for charging, both for the power system and for the car owners. Hydrogen provides even more flexibility, as hydrogen can be produced from electricity during periods of good access to power, and stored under pressure in large tanks. The vehicle owners then fill their car tanks with hydrogen as necessary, as we do now with petrol and diesel.

Batteries in electric cars and hydrogen solutions can also feed power back to the grid during periods of high demand. In Germany, maximum consumption of power on a cold winter's

20 Battery technologies and hydrogen solutions are currently racing each other. It is difficult to know what will end up as the best solutions in different areas. Tanks for storage of hydrogen can offer certain large-scale advantages, but if batteries can achieve a sufficiently high level of energy density and low cost, or can be charged very quickly (e.g. while driving), battery-based electric propulsion may be the best solution even for larger vehicles.

day is around 80 GW. In 25 years' time, it is likely that electric cars may be able to deliver 10 – 15 GW, possibly much more, during 6-8 critical hours.[21]

The flexibility which electric cars could provide would be relatively short-term. Charging can often be delayed for a short time, and some stored power may be given back to the grid, but owners of electric cars are unlikely to cut down on their driving, even if electricity prices were to become very high. Long-term flexibility is therefore very small. (Plug-in hybrids, however, may supply more long-term flexibility.)

For hydrogen, flexibility may be more long-term, due to larger energy stores in stationary hydrogen tanks. If larger value chains are developed where hydrogen is either used directly in the transport sector or converted to for example methane gas (power to gas) or liquid fuel, even greater flexibility could be achieved. The cycle from electricity to hydrogen and back results in a significant energy loss, and work is being done to reduce this loss, both through electrolysis (approx. 70% efficiency) and through generation of power in the fuel cell (typically 40-60% efficiency). (If one can make use of the waste heat from compression of hydrogen gas and power generation in the fuel cells, profitability will improve.) The technological and cost development of these solutions and developments in the energy system as a whole, will ultimately determine the significance of hydrogen and hydrogen based fuels in the transport sector.

The heating sector includes heating of buildings and heat for industrial processes. This sector is larger than many assume. In Europe half of the energy end use is for heating. In the Nordic countries, total heating consumption is equal to total power consumption (around 400 TWh) and in Germany, heating consumption is significantly higher than power consumption.

Currently, some biomass, some waste and a lot of fossil fuel are used for heating. Many industrialised countries have built district heating systems in cities and use waste heat from thermal power plants or other sources of heat in industrial processes that require heat or in district heating systems. In coal power plants, around 40% of the energy in the coal becomes power, while most of it becomes waste heat. Reasonably efficient gas power plants may have around 55% electric efficiency, the best ones are pushing 60%.

Due to the relatively low efficiency for power generation in the thermal plants, many are of the opinion that electricity should not be used for heating. They have held the view that fossil energy should be burned directly for heating. Burning gas for heating achieves approx. 90% efficiency. This might seem a better solution than producing electricity from gas with 55% efficiency and then using the electricity for heating. However, as the energy system is in the process of decarbonising and modernising, this logic fails for several reasons:

21 Assume that in 2040, Germany has 20 million electric cars with an average battery size of 60 kWh, that 60% of these cars are parked and connected to the grid at any given time, and the owners of the cars accept that the grid can take on average 10% (up to 6 kWh) of their battery capacity when necessary. (Probably not that often.) Based on the above assumptions, the electric cars could deliver 72 GWh. If this is delivered over e.g. 6 hours, it equates to a supply of 12 GW. That amounts to more than 14% of maximum consumption in Germany on a cold winter's day. It would be necessary to develop smart grids and compensation agreements with car owners. It is possible that car owners would allow more than 10% of their battery power to be taken if system needs were especially high and compensation accordingly high. Electric cars are also able to give more GW if the energy is delivered more quickly. If the cars were to be connected to the grid for a shorter time, it might be a solution for each of them to give more power to the grid more quickly.

- Heat pumps are already making electricity competitive in the heating sector, and they are likely to become better and cheaper in the years to come, due to technology developments and larger production series. If a gas power plant produces electricity and a heat pump creates heat from that electricity, the result is up to twice as much heat from each m3 of gas as if the gas were to be burned directly for heating purposes. [22]

- Extensive expansion of wind power and solar power will entail, as I have shown above, periods when total emission-free power generation is higher than (current) power consumption. Heating plants can use electric boilers and buy electricity when power prices are low due to high renewable generation. When there is no surplus of power, other energy carriers such as biomass could be used. Increased utilisation of electricity during surplus periods will increase the profitability of renewable power generation.

- Buildings can store heat for a few hours. If the price of power is especially high for a few hours, heat pumps could be switched off, and stored heat could be used. In heating systems based on the distribution of hot water, storage tanks for heat can be built. Heat storage may offer a much greater buffer and also make it possible to run a heat pump more evenly and therefore more efficiently. Storing heat is relatively cheap in larger systems. Heat storage also increases opportunities to utilise solar heat during parts of the year. Many large heating systems allow switching between energy carriers. In the future one might switch between using electricity (heat pumps or electric boilers) and biofuel. While heat pumps will run most of the time and only stop when electricity prices are especially high, electric boilers will use electricity when power prices are lower than the price of the alternative fuel. Flexible use of electricity through storage of heat and switching between electricity and other energy carriers, will contribute to reducing both the deficit problem and the surplus problem in a renewable power system. When electricity is used for heating as described here, it will result in lower emissions, efficient use of resources and greater robustness in the energy supply.

- As fossil power generation is phased out, there will be less waste heat available for utilisation. In many places, new sources of heat will have to be found. This could be a heat pump, maybe based on heat in the ground. Of course, combined heat and power (CHP) based on biofuel may also be a possibility. CHP traditionally only generates power when there is a need for heating, but such systems can as mentioned be made more flexible.

Flexible use of power in the heating system makes it possible to utilise variable access to renewable power in a far more efficient way. Wind power in Europe produces most power during the winter. Its production peaks therefore occur during the same time of year as peaks in heating needs. Increased use of power for heating during periods of good access to wind power and low power prices could mean both better profitability for wind power and lower CO_2 emissions from the heating sector.

The heating sector can vary its power consumption quickly, and where there are alternative energy carriers such as biomass, it is also possible to offer flexibility in the very long-term.

22 With a heat pump that provides 3.5 kWh of heat for each kWh of electricity, 55% efficiency in a gas power plant, 6% transfer loss in the grid on the way to the consumer and 90% efficiency associated with direct burning of gas, the solution of gas power and heat pumps will provide twice as much heat per unit of gas as if the gas is burned directly for heating.

In countries where the heating sector is large, it is able to offer a high level of flexibility, both long and short-term. Some of the flexibility will probably also be cheap to use. In order to realise this flexibility, facilities will have to be modified and sector regulations must facilitate a new way of operating systems. In addition, the *belief* that electricity should not be used for heating must be modified.

Cooling can also use electricity more flexibly than has traditionally been the case.

The integration among the three sectors of power, heating and transport is summarised in Figure 4.4.

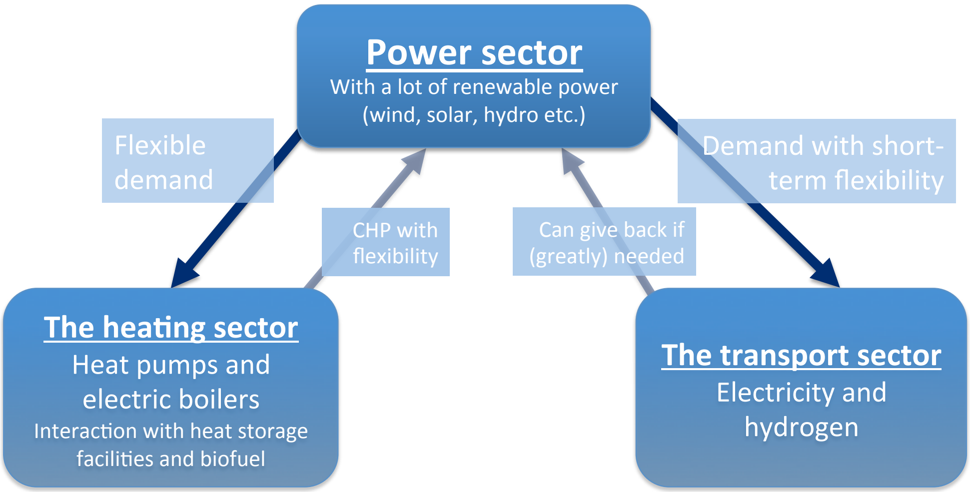

Figure 4.4 Closer interactions between the power sector and the heating and transport sectors

Most types of flexibility will be associated with certain costs and disadvantages, and investment is often required before it is possible to use the flexibility. *In most cases, both technical control systems (ICT) and financial incentives are necessary*. Efficient markets with prices that reflect the value of power when it is scarce as well as when there is a surplus, are important in order to realise efficient utilisation of the different options. There is also a need for technology development in many areas. In addition, it is necessary to develop a common understanding of how we can restructure our energy system in order to make it emission-free and robust.

For those making long-term investment decisions, it is important to have as much knowledge as possible of likely developments and possibilities.

4.3 Uncertainty creates challenges

Market players are exposed to significant political and regulatory risk: will politicians really follow up long-term climate goals? What kind of policy instruments will they use? And what kind of solutions will the authorities accept or support? Will for example nuclear power be accepted in the future?

In addition to the regulatory and political risk, there is significant uncertainty with regard to how energy technologies, fuel prices and demand for energy will develop. As we saw in Chapter 4.1, dramatic changes have taken place in the cost of a number of technologies. If we look back 15 years, we are also reminded that fuel prices have changed dramatically. The ability to predict these changes has been limited, even among professionals in the field. In 1998 and 1999, the oil price was low (see figure below). *The Economist* wrote in March 1999 that the market was drowning in oil and that prices would stay low. Figure 4.5 compares the IEA's long-term price forecasts from 2002 with actual price developments up until 2013. The IEA was unable to predict the dramatic price increase that came immediately after, and actually expected a slight downturn in the oil price from 2002 to 2010. The IEA was by no means alone in this opinion in 2002

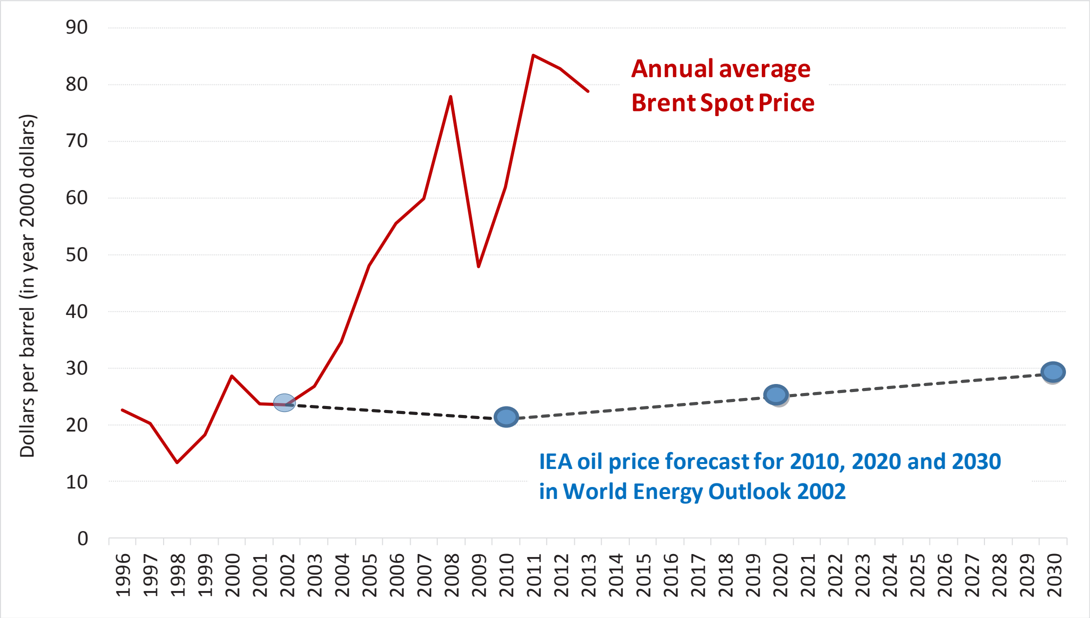

Figure 4.5 The IEA's long-term forecast for oil prices in WEO 2002 versus the actual development in the average annual Brent Spot price (all given in year 2000 dollars)

The IEA also severely underestimated global growth in renewable energy, but was too optimistic with regard to the cost development of CCS. Even optimistic experts within the solar cell industry have been surprised by the large price drop for solar panels, and many – even within the oil and gas industry – have been surprised by the revolution within production of shale gas and shale oil. In the EU, quota prices for CO_2 have fallen dramatically since 2009 and have become only a fraction of what the market and the authorities expected. In this case, the explanation is primarily that quotas have been offered in predefined volumes, while demand for quotas (emissions) were much lower than expected, partly due to the financial crisis. These examples are a reminder of the uncertainty attached to the development of new technologies, commodity prices and demand, and illustrate how difficult it is to predict the future, even for experts.

The discussion above and in Appendix 2 shows that there are a many different technologies that can contribute to creating a robust, emission-free energy sector. Ambitious investments in R&D and development of immature solutions can help bring costs down a lot for a number of technologies, as we have already seen examples of. But it is difficult to know how much of a price drop we can expect for each technology. *The profitability of each technology will depend heavily on which other solutions are developed, and how the energy system is regulated.* This uncertainty is a challenge for those wanting to invest in R&D for new solutions, and for those considering investments in infrastructure such as power plants, transmission lines, district heating, energy solutions in buildings and transport solutions. It is important that investment decisions take this inherent uncertainty into account. At the same time, it is important that authorities and market players are not paralysed by the uncertainty.

This gives rise to two main recommendations:

1. *Better knowledge of likely developments allows better R&D strategies and better investment decisions.* Both market players and authorities should have the best possible knowledge base regarding likely and possible developments. This knowledge must be based on insight into technological possibilities and consistent scenarios of how the energy system may develop, given different circumstances. Early research and testing of new technologies and solutions may provide important knowledge of which possibilities can be developed more easily and what could be more demanding. It is especially important to achieve quick clarification of possibilities in areas where such clarification is cheap and may have great significance for long-term investment decisions and priorities within R&D. One example might be mapping the potential and cost of utilising the flexibility in the heating system.

2. *Authorities must be willing to state a clear direction for developments and establish framework conditions that make market players act in line with this.* Uncertainty means a risk of bad investments. This risk may lead to an inability to act, with everyone waiting for everyone else. The authorities must develop measures that prevent such an inability to act, and contribute to the best possible investment decisions. Developing a sustainable energy system means *restructuring the energy system*, by replacing components in an order that makes sense, based on the best knowledge we have at any given time.

5. WE NEED BROAD LEARNING PROCESSES

In order for our climate policy to succeed, we need a broad, ambitious, long-term focus on developing new solutions. We need a strategy to promote learning processes, and we must take into account the value of learning and developments in technology when considering which measures and initiatives to support.

Carbon pricing may become an important means to promoting long-term change, but will not be sufficient to develop new solutions as quickly and efficiently as is necessary. This is partly due to the fact that carbon pricing is not an ideal instrument for promoting development of immature technologies.

Societies that are ahead in the development of climate policy, contribute to important learning regarding how to best organise the process of becoming a society with low emissions. By their example, these pioneer societies can also serve as a source of inspiration for other countries. Progress starts when someone moves forward.

5.1 Learning curves – learning and economies of scale

Learning curves (see explanation in Chapter 4.1) describe the connection between *accumulated production over time* and *a drop in unit price*. The cost reduction is due to both genuine learning/technology development and economies of scale (when larger production leads to lower costs). Conceptually, the distinction between learning and economies of scale is clear. Empirically, however, there may be some cases where it is harder to distinguish between the two factors. For instance when production is scaled up, a lot of informal learning takes place regarding how best to organise a production process.

In some cases, basic research and technology developments in other areas may also contribute to lower costs. Developments in ICT and materials technology, for example, may contribute to new solutions in many areas. For instance, ICT has enabled automation and remote control of smaller hydro power plants, which has reduced operational costs considerably.

5.1.1 RESEARCH, DEVELOPMENT AND LEARNING BY DOING

Innovation is created through development of both disruptive technologies and many small improvements. Often, fundamentally new solutions are based on long-term research.

In her book, *The Entrepreneurial State,*[23] Mariana Mazzucato describes how important publicly-financed long-term research has been in the development of radical new solutions. For instance, she points out that all the important technologies that make an iPhone possible, such as the microprocessor, li-ion batteries, the internet, GPS and touch screens, were developed in publicly-financed research programmes. Mazzucato convincingly documents

23 Mazzucato (2013a). Mazzucato (2013b) provides a 14-minute introduction to her thinking.

that publicly-financed research programmes have been the most important driving force where big innovations are concerned. *Business and industry often operate on a short time scale and require very high rates of return. This does not allow for large technological innovations*.[24] (See more on this in 5.3.1.) In the US, much long-term technological research has been related to space exploration and the defence industry. Mazzucato also makes the point that what is required is a strong, competent public research sector able to steer innovation in the right direction, and that this has actually generally been present in the US. She is also of the opinion that a green revolution is dependent on proactive authorities establishing good, long-term framework conditions for the development of new solutions, as the US have previously had for the development of solutions for defence and space exploration.

The role of the public sector is not limited to financing bold, long-term research programmes. Support for R&D which could lead to many small improvements is also important. Many such improvements throughout the value chain can, over time, add up to major progress. This type of research and development will often be *closely related to existing products or markets* and provide improvements in interaction between R&D and production in companies. *Existing markets provide an arena for testing new solutions, gaining experience and identifying further opportunities for improvement.*

By supporting demonstration and testing programmes, and by *establishing* markets for new solutions, authorities can stimulate faster, wider-reaching innovation. Gradual introduction of new solutions not yet commercially viable (e.g. wind power over the last 35 years) offers several advantages:

- *Practical experience stimulates innovative thinking.* Development means testing of solutions, gaining experience of what works and what does not work. Challenges and opportunities are identified, and a process of many changes, great and small, is begun. This will also apply to subcontractors and potential suppliers who identify business opportunities related to the new markets.

- *The problem of the short-term focus in business and industry is reduced*. While the business world rarely has the stamina to develop solutions that will only provide income after 20 to 30 years, the establishment of a market for new solutions (for instance a programme for wind power development) stimulates active innovation. In such situations, the road from idea to implementation is much shorter, and it is easier to find someone willing to help finance the industrial aspects of the innovation. (In addition to the problems of a short-term perspective, another problem is that developers only reap some of the benefit from their new solutions. See more on this in Chapter 5.2.)

When subcontractors expect increased and *lasting* demand from a new sector, they have an incentive to invest in production facilities and innovation. This results in both better quality products and cost reductions. Development of wind power has for instance promoted expertise regarding optimal placement of wind turbines in the terrain in order to utilise wind in the best way possible, and regarding better turbines and IT systems that optimise power generation in relation to variable wind.

Learning by doing refers to both technological advances and improved skills where workers are concerned, so that for instance workers installing water based heating and heat pumps, or those installing solar power panels, learn to do their work more quickly, and with fewer mistakes.

24 The required rate of return indicates what percentage annual income an investor must expect before he is willing to invest.

Learning curves focus on the connection between *volume and cost*, but there is reason to believe that *time to gain experience* also plays an important part. Figuring out what works well takes time, and many practical design flaws only become apparent after some years of operation. This is a strong argument for starting this type of learning process quickly, while production volume should not be increased too much before user qualities have been tested over time. It is better to discover significant weaknesses in a design before production volumes and costs have been scaled up too much.

5.1.2 ECONOMIES OF SCALE

The learning effect is not the only reason why larger production volumes often mean significantly lower costs:

- Larger series often provide *better utilisation of manufacturing equipment* and therefore lower costs. Large-scale production may for instance make it worthwhile to invest in efficient production lines involving conveyor belts and/or robots as part of production. Smaller series rarely justify such investments. Tesla is planning to build a battery factory that will double global production capacity. This is expected to result in a cost reduction of at least 30%. Such investments are only possible when demand is high.

- A related effect is that greater prevalence of a product in many cases results in *better utilisation of infrastructure* needed for the product. Owning a phone has greater value if your friends also have phones. Petrol and diesel cars can be used efficiently and have high value to consumers because there is a large network of roads and service facilities supporting their use. Development of this service system is financially possible because many people own cars. In order for vehicles based on hydrogen to become widely used and have a long radius of action, a sufficient number of stations must be built for filling hydrogen and there must be servicing opportunities. Correspondingly, stations for quick-charging electric cars must be built in order for electric cars to be able to replace old-fashioned cars in all their areas of use. Only when there is a high number of electric cars will this infrastructure be properly utilised. Other examples are special ships for installation and maintenance of offshore wind turbines, and the need for large sales of LED lights to allow a large selection of hues and different levels of brightness, and in order to create a lucrative market for fittings and other accessories. (This is often called network externalities.)

- When a product gains a large market share, it may also become integrated in standardised solutions, and thereby become cheaper. Relevant examples could be water based heating, solar heating or solar cells being built into prefabricated building elements. This could simplify installation and bring costs further down.

- There are certain *fixed costs* in connection with starting new production series. For instance, it may cost several billion to develop a new car model (a new concept). Large series means that these costs can be shared among many cars.

- *Cheaper purchasing.* Manufacturing, purchasing and transportation of materials and components used in the manufacturing of a product are often cheaper when orders are bigger. The logistics of deliveries, following up customers and systems for information, may also become cheaper per unit with bigger volumes.

- A larger market may also offer space for *increased competition*. This may contribute to lower costs.

In Germany, the total costs of investing in solar panels have been below half of that in the US. This is mainly due to differences in so-called soft costs, such as installation, purchase and approval. Much higher sales in Germany have contributed to bringing these costs down (Rocky Mountain Institute, 2013).

As mentioned above, learning curves reflect both economies of scale and learning throughout the value chain, as well as improvements in technology in other areas. Increased production of a commodity contributes to an important part of learning as well as to benefits from economies of scale. There may be different opinions regarding how important increased production is in bringing down costs compared with increased research efforts, and the answer may vary from case to case. Both are likely important in achieving radical price drops. It is also important to remember that the existence of a market of a certain size – both now and in the future – is an important motivation factor for research efforts and innovation in the affected industries. The idea of spending research money on something which *may potentially* find a market far into the future is less motivating.

In a Working Paper published by the IEA (Philibert, 2011), Cédric Philibert discusses the factors behind the cost reductions for solar panels and concludes: "*Increased deployment has thus been, through various channels, the most important driver for cost reductions*".

Figure 5.1 illustrates how different factors may interact in the development of a new technology.

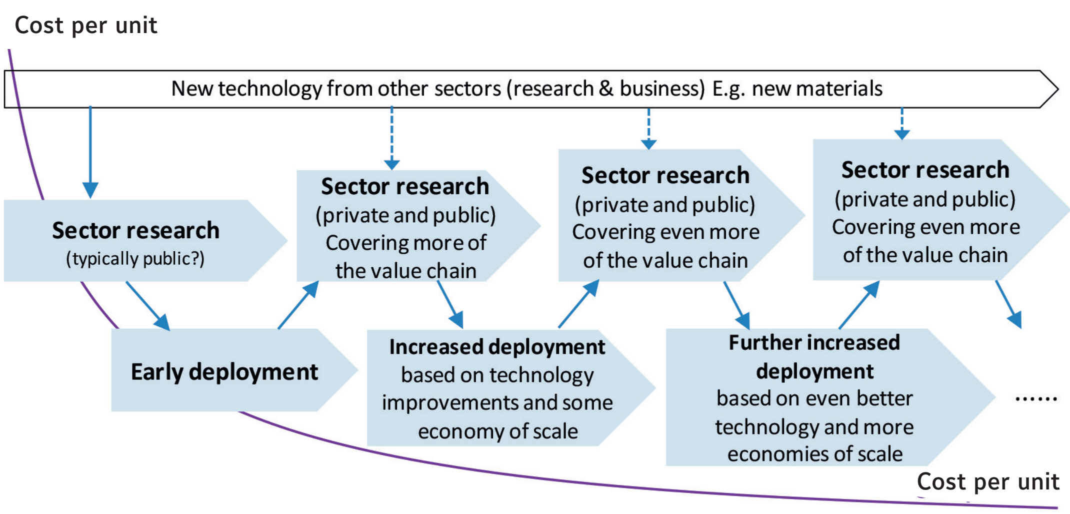

Figure 5.1 Positive interaction between research, economies of scale and increased development

5.2 Pioneers only receive some of the rewards

Where patenting is possible, the holder of the patent will reap a share of the societal benefit for the duration of the patent rights (usually 20 years). When patent protection runs out, anyone can use the patent free of charge. A lot of learning cannot be patented.

5.2.1 DEVELOPERS GET A SHARE OF THE VALUE DURING THE PATENT PERIOD

Patent protection is an important driver for innovation, because developers have the sole right to earn money from an innovation for a limited period (usually 20 years). After this period, anyone can copy the original idea without compensating its developers.

For the duration of patent protection, the patent holder will receive a proportion of the societal benefit, but not all of it. A potential user is only willing to buy a new solution if the value for him is greater than the price he has to pay. New products offer varying degrees of benefit to different buyers. The least interested (or marginal) buyer will consider the benefit of the product to be almost equal to the price, while more interested buyers will enjoy a benefit higher than the price. Some may be willing to pay the given price many times over. (Economists call this extra willingness to pay a *consumer surplus*.)

How much income a patent owner can achieve during the patent period will depend on the specific market conditions, and any opportunities to identify users who are willing to pay more.

In addition to the points above, illegal copying (breach of patent) will contribute to a benefit that does not accrue to the inventors.

In order for a patent owner to earn money from a solution, he must demand a payment that may limit use of the patent. The ideal solution would be to have strong incentives to develop new solutions at the same time as everyone could use the solution free of charge. This is possible if someone (e.g. a rich country) buys important patents and gives everyone the right to use them and develop them further. Tesla's decision to make many patents available for free is an interesting course of action to stimulate an entire industry.

5.2.2 MUCH OF THE GLOBAL BENEFIT MAY COME AFTER THE PATENT PERIOD

Since global warming is a very long-term challenge, the benefit to the world community of an improved solution may be important for very many years after a patent has expired. Often, the cost of a new product will continue to fall for several decades and make the product more and more common. In such cases, a very high proportion of a product's benefit may become a reality after the patent period has expired.

Companies considering developing new solutions are unlikely to place a lot of emphasis on this value, or on the benefit enjoyed by others while the patent protection is still in force.

A calculation can illustrate this point:

Assume that a patent results in a constant global benefit every year for 50 years, and that the patent rights gives the owner 60% of the benefit for the 20 years of patent protection. After that, the owner receives no more income from the patent. In absolute term the patent owner gets 24 % of the revenue. But since the patent owner receives his revenue in the first 20 years, his share of the present value of the revenue is somewhat higher. With a 4% required rate of return (in real terms), the present value for the patent holder is 38% of the total societal present value of the innovation (viewed over 50 years).

If the income flow rises as time passes because the alternatives become more expensive (due to e.g. higher carbon prices) or because the product is sold in increasingly large volumes, the relative share that comes to the original developer may drop. If global benefit rises by e.g. 4% per year due to more widespread use, the original developer's share of the total benefit will only be 24%.

5.2.3 MANY TYPES OF LEARNING CANNOT BE PATENTED

General ideas can be hard to patent. (One example is the concept of the smart phone.) Informal learning that takes place in companies can also be difficult to patent. Informal knowledge can be observed by others and copied, or it can be spread by employees who take their expertise with them into other environments. One company's solutions may also inspire new and *better* solutions in other companies. We can call this *learning by watching*.

Those who work on developing and testing of new solutions will also discover a number of solutions that *do not* work well. Others will be able to learn from these pioneers' mistakes and can avoid repeating them, and may be inspired to find better solutions and pursue other technology leads. Observing what *does not* work teaches us important lessons and saves us from having to make the same mistakes, but offers little to those who make the discovery. Anyone who develops new solutions must assume that some leads will not yield useful results.

For some of the factors behind economies of scale (cf. 5.1.2), it is also the case that those who stimulate initial developments make it easier for others to follow. Where consumers need to get used to a product to build up trust, and where infrastructure must be developed to support a new type of product, suppliers that come later, can reap many benefits from others who have paved the way.

Where development of renewable energy (and most other development) is concerned, there are often a number of environmental disadvantages, both for people (visual nuisance and noise) and negative effects on biodiversity. Experience with developments and researching the effects of different measures, can reduce conflicts between renewable energy and the environment. This type of knowledge is important in order to limit the total costs to society and the disadvantages of renewable energy. It will often be difficult to patent this type of knowledge, and it may not be desirable in many cases.[25]

5.2.4 MORE KNOWLEDGE OF WHAT IS POSSIBLE AND IMPOSSIBLE LEADS TO BETTER INVESTMENTS

Efforts to reduce costs through learning processes and increasing production *develop and identify* options for future climate and energy policy. *Early testing of various solutions in*

25 The Norwegian research centre CEDREN runs a comprehensive research programme of this type. See http://cedren.no

some countries offers authorities and market players in every country better information about future options and probable costs of various solutions.

This type of information has great value for long-term investment decisions within energy, construction and other infrastructure. Many facilities built today will still be in use by 2040 and 2050. The profitability of different solutions is often affected significantly by the development of competing solutions. Although there may be new solutions no-one has predicted, today's solutions usually cannot be "uninvented": Solar cell production *has* become as advanced and efficient as it is, wind power on land *has* become commercially competitive in some markets, a revolution in battery technology for electric cars *has* happened and is still happening, and it is now possible to see that this may have immense consequences for markets. As such knowledge becomes available; any wise investor will take it into account when making investment decisions, to reduce the risk of a loss. This also applies to investments in R&D, where knowledge of what others have achieved, makes it possible to steer R&D investments in a better direction.

It takes time to build up value chains, it takes time to gain the necessary experience, and it takes time to implement the comprehensive creative processes of many great and small innovations that are often necessary to bring a new complete solution into being. Some people argue that we should focus on cheap measures, such as making the switch from coal power to gas power, and later, when every country is on board and carbon prices are high, we will tackle the expensive measures. We should indeed implement the cheap measures now, but we also need to develop the solutions that can take us all the way to our target, *because developing these solutions will take a long time.* We do not know in advance how long it will take, and we do not know what will be most successful. In any case, as we have seen, knowing the possibilities that will likely be available in a few years' time has great value for many investment decisions being made today. Getting a jump on learning processes will give us some of this knowledge. When some countries lead the way in developing technologies and more comprehensive system solutions, they make planning easier for others.

Many products and solutions will be used globally. Both companies that develop innovative solutions and countries that finance R&D may experience that others reap at least as much benefit as they do themselves. When those who develop new knowledge and contribute to lower costs only reap a small part of the total benefit, it will result in less efforts and funding in these areas globally. In general, only projects where developers (or the countries supporting the development) expect *their own benefit* to be greater than the costs, will be carried out. *This is a key challenge in climate policy*.

5.3 Huge benefit potential – far into the future

Here, I will illustrate the economics of learning curves using an idealised example. Let us imagine an immature emission-free technology where production of the first unit costs 100, while the established climate-damaging alternative only costs 10 per unit.[26] (We will assume that the two alternatives are perfect substitutes.) In addition, we will add a carbon cost to

26 Since it is the difference in costs between the two alternatives that matters, I have chosen to keep the cost of the old option constant. This solution could also improve and become cheaper, but there is less reason to expect this since it is a mature technology. The cost of the old option may also increase with time, as we have seen for fossil fuels which have become much more expensive since the year 2000 as more expensive fields must be employed. The costs of local pollution from fossil fuels may also be (considered) higher as people become richer.

the climate-damaging product. In my example, the carbon price starts at 2 and rises 4% per year throughout the time frame. I will discuss the situation both with and without the carbon price.

We will assume a learning rate of 20%, i.e. that each doubling of accumulated manufacturing of the new product results in 20% lower unit costs. We will also assume that the cost of the new technology cannot be lower than 5. Further, we will assume that production will grow by 20% per year until it stabilises at an annual production of 460 units after 39 years. Based on these assumptions, we will have a cost reduction over time similar to what we have observed for onshore wind power the last 30 years. Figure 5.2 shows what happens to manufacturing, unit costs and carbon prices over a period of 70 years.

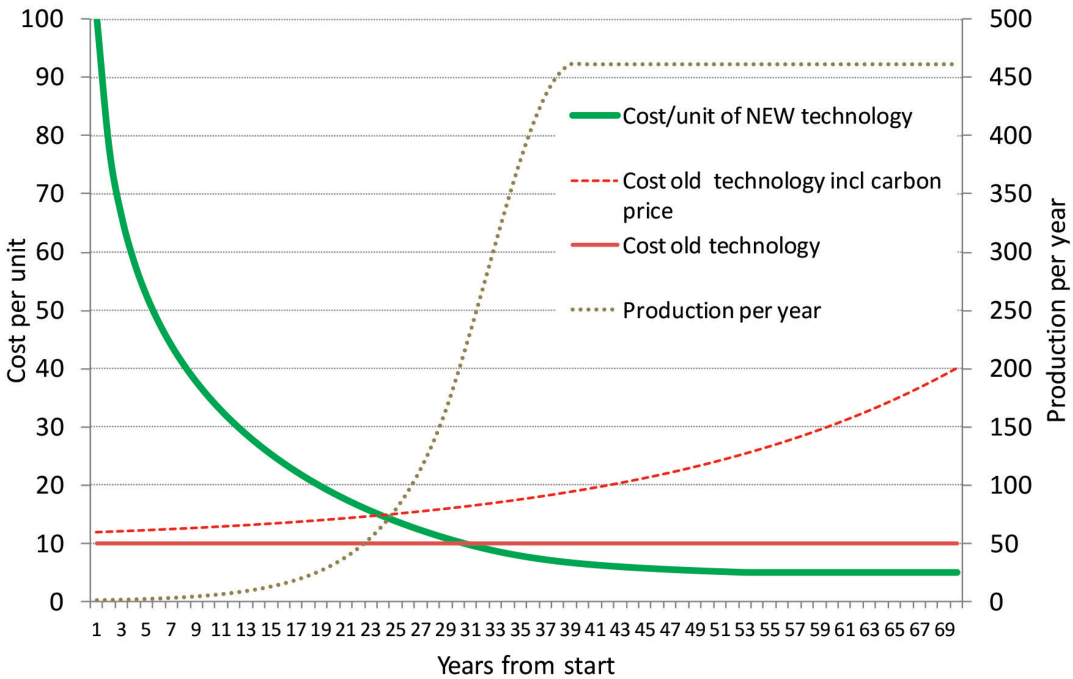

Figure 5.2 Development in production and derived cost development assuming a learning rate of 20%

Based on the chosen conditions, the new technology will be more expensive than the conventional option (without the carbon price) for a whole 30 years. If we take into account the carbon price, that will be low to start with, the new technology will be more expensive than the old technology for 23 years. Even though it might take a *long time* for the new technology to become commercially viable, development of this technology may be highly profitable in a global perspective, and possibly for one country alone as well. This high profitability in the long-term is due to the fact that the volumes manufactured in the first few years are small compared to the volumes produced later. When the market potential is high, the present value of future savings may be considerable. In Figure 5.3, I show cash flow year by year (net expenses or net income) discounted to year 1 with a required rate of return of 4% (in real terms).[27] The cash flow is found by multiplying the price difference between the two technologies by the manufactured volume. Cash flow is discounted by 4% per year to make the figure show how much future expenses and income will be weighted in an estimation of present value based on a required rate of return of 4%.

27 Here, to discount means to adjust future expenses and costs by the applied discount rate (required rate of return on investments). With a discount rate of 4%, an income of 100 that comes in a year's time, will today be valued at 100/1.04 (=96.154). An income of 100 in two years will be valued at 100/1.042 (=92.456), etc.

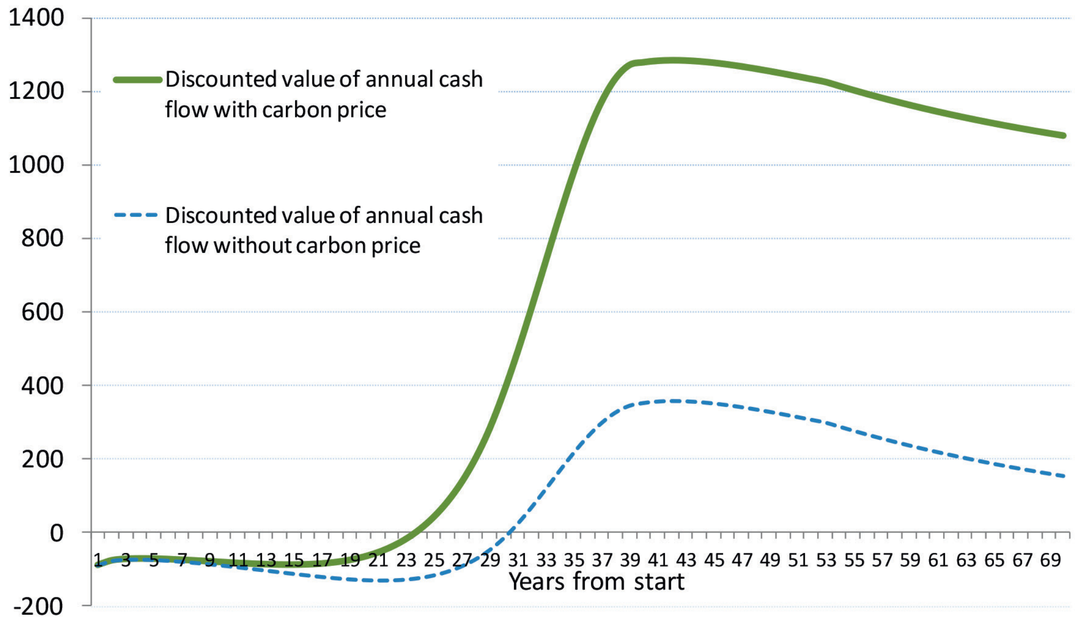

Figure 5.3 Future cash flow discounted by 4 % p.a. with and without carbon pricing

With carbon pricing (cf. Figure 5.2), the new technology will become competitive more quickly, and long-term income is significantly higher. When cash flow becomes positive and rises after a time, it is because the falling costs of the new technology provide increased income per manufactured unit, and the number of units increases. When carbon pricing is taken into account, this effect is enhanced because rising carbon prices also make the polluting alternative more and more expensive. As shown in the figure, the curves drop again after some years. This is primarily due to the production volume and price differences (without carbon prices) being stabilised in this example, at the same time as discounting reduces the value of later income.

Figure 5.3 shows that even without the climate problem (carbon price zero), the new technology would be economically profitable in a global perspective, since the present value of the net income after 30 years is greater than the present value of the net costs until that point in time. A long-term perspective is necessary in order to identify this profitability, however.

Figure 5.4 shows the accumulated present value of the income flow in Figure 5.3. (Year 3 = year 1 + year 2 + year 3, etc.). This illustrates the length of time necessary in order for the measure to achieve a positive net present value.

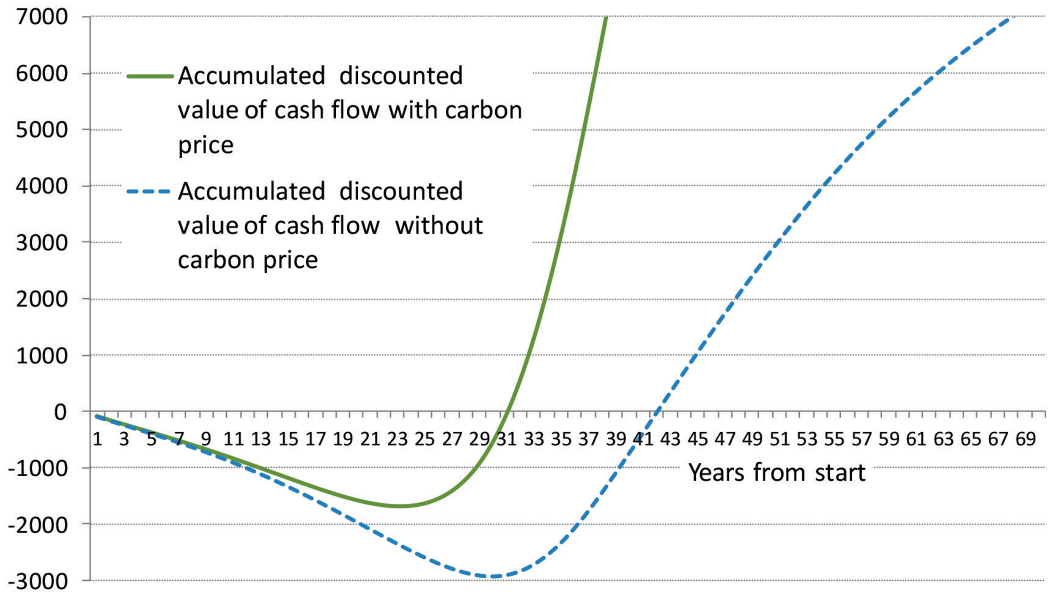

Figure 5.4 Accumulated cash flow discounted by 4% p.a. with and without carbon pricing

It is clear from Figure 5.4 that with carbon pricing, the present value will be positive if we have an analysis horizon of more than 31 years. Without carbon pricing, we must have an analysis horizon of more than 42 years. In both cases, the present value is very high if we operate with a 70 year perspective. With other parameter values, we might have found that technology developments were only profitable with carbon pricing, or found them not to be profitable even with carbon pricing. Compared with the cost development that has been observed for a number of technologies, the numbers in the example are not unreasonable. It is not unlikely that the development of solar cells, wind power and a number of other technologies will be very profitable for world society in the long-term, even if we were to ignore the climate and environmental benefits these technologies can offer. It is also worth noting that the ceiling for future production in this mathematical example was set relatively low, to 460 times the production of the first year. Greater deployment when the cost of the new solution drops below the old option will provide more income and higher profitability.

The calculation in the diagram above shows the length of time that may be necessary in order to identify profitability during the introduction of a new technology. In the example, we looked at global benefit. When developers only enjoy some of this benefit, their interest in investing will be more limited. High rates of return in private companies and much uncertainty regarding future climate policy may further reduce interest in pouring efforts and funding into the development of new solutions.

The long time frame often required to mature new solutions necessitates public support (as Mazzucato points out – cf. 5.1.1) and policy instruments that encourage long-term development. Uncertainty regarding future climate policy must be tackled, as must the fact that companies often have short time horizons and a high required rate of return when considering investments. We will examine this issue more closely in Chapter 5.5.

5.4 How can we minimise development costs?

5.4.1 SOME LOCATIONS ARE BETTER SUITED TO EARLY DEVELOPMENT OF NEW SOLUTIONS

Maturing a new technology (cf. the calculation in Chapter 5.3) has a net cost in the early phases because the costs of the new alternative are higher than those of the cheapest established mode of production. Development costs can be brought down if we can find areas where it is cheaper to start using the new technology and/or areas where it has greater value because the alternatives are more expensive.

Let us take solar and wind power for example:

- *The costs* of development and operation can vary somewhat from place to place, but the cost per generated kWh will primarily be different because resources vary. Wind power will be cheaper in places with lots of regular wind. Similarly, the cost of solar power will be lower where there are good sun conditions.
- *The value of the power* delivered by solar and wind power will depend on the cost of alternative power generation (the market). Some areas have higher power prices, for various reasons.

Solar cells were used early on in space exploration because the alternatives were very expensive and at times non-existent. After a time, solar cells also came to be used to supply electricity in places that were not connected to the grid. Here too, the alternatives are very expensive.

For everyday consumer items, for instance new consumer electronics, groups with a high willingness to pay (so-called "early adapters") will have an important part to play in the beginning. They buy the initial volumes at a high price, thus contributing to costs falling so that the number of consumers can rise.

Figure 5.5 illustrates the reduction in net development costs when a new product is deployed / put to use in areas with extra high willingness to pay and/or lower costs than in other areas. The height difference between the solid green curve and the solid red line (with cost 10) up to 30 years shows the cost difference per unit at different stages of development in an area without specific advantages.

The dotted green curve illustrates *lower costs* for development in especially favourable areas. Examples: especially good sun conditions for solar power, lots of steady wind for wind power, and low development costs.

The dotted red line illustrates that *the value of the product is higher* in areas with higher alternative costs. Examples: a small island where a new type of wave power together with batteries (and/or solar and wind power) is able to replace expensive power from a diesel generator, introduction of electric cars in a city with severe pollution problems.

If one area meets both criteria, the development cost per unit at each stage of development will equal the difference in height between the two dotted lines. Example: An area with expensive power and especially good wind conditions.

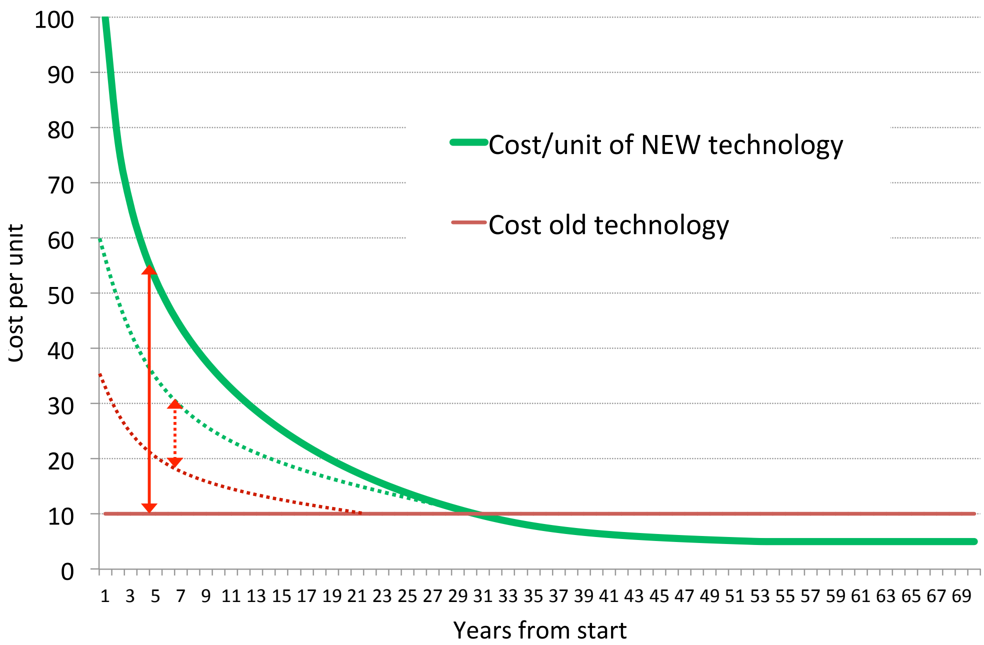

Figure 5.5 Good deployment strategies can reduce the cost of developing new technology

It is cheapest if early development of a new technology can take place in areas with good resources, low investment costs and a high willingness to pay for the end product. As the costs of the technology fall due to learning and large scale production, it can be put to use in areas with less favourable resources and/or lower production value.

In a European context, *lower development costs* could have been achieved if the bulk of solar panel efforts had been concentrated in Southern Europe instead of in Germany, which does not have especially good sun conditions. But for several political and financial reasons, such as resistance to nuclear power in Germany, high environmental awareness among the population and a strong engineering industry, *a window of opportunity* opened up for ambitious, early focus on solar panels in Germany. Germany's commitment to the development of solar panels has been important in bringing costs down, and has thereby paved the way for other countries to develop solar power at much lower costs. In a global perspective, costs could have been saved if more of the early development of solar panels had taken place in countries with better sun conditions, but the advice not to make the perfect the enemy of the good applies in economics, too.

When costs fall with increasing development, it may be most efficient to concentrate efforts on a few selected technologies, at least at first. If efforts are spread too thin across different technologies, the result may be that a sufficient cost reduction cannot be achieved for any of them. This problem is discussed in Torvanger and Meadowcroft (2011). This argument particularly applies where different technologies cover almost the same function. But as shown in Chapter 4.2 and in Appendix 2, there is a great need for *complementary* emission-free technologies in the energy system in order to reduce the consequences of random variation in renewable power generation, and there is also a need for many different technologies that can deliver flexibility. In order to meet such needs, it makes sense to pour efforts into several technologies in parallel.

The fact that different areas have different resources may also be an argument for developing several technologies in parallel. It is then possible to prioritise based on where the best opportunities for each technology are found – as I have described above in connection with the diagram.

5.4.2 WHAT IS THE MOST EFFICIENT INTERACTION BETWEEN DEPLOYMENT AND R&D?

It has been debated in Germany whether the focus on renewable energy has provided sufficient innovation. It is difficult to trace such connections unambiguously, but Morris (2014) shows that the country has seen a significant increase in the number of patents within solar and wind power in parallel with the development of these industries in Germany.

The funding used for research on renewable energy in Europe represents only a small percentage of what is invested in renewable energy. It should be considered whether a higher research percentage (both basic research and more applied research including pilots) could increase the total value of investments in renewable energy.

It is important to ensure that the development of renewable energy and other efforts lead to much innovation. It may be worthwhile to standardise products and increase the size of production series to bring costs down, but it is also important to stimulate testing of new and improved solutions, for instance bigger wind turbines. A too narrow focus on short-term cost-effectiveness in subsidy schemes for renewable energy (or other climate solutions), may lead to all investors going for familiar, safe solutions, with no testing of new ideas that could bring us new advances sooner. An interesting discussion of the efficiency in innovation policy can be found in IEA-RETD (2014).

Rich countries who really want to increase their research efforts, could locate some of their extra efforts in developing countries with high industrial and research capacity, e.g. India. There could be several reasons for doing this: (1) research and development work may be cheaper in such countries, (2) technology transfer is important, (3) the technology may be better suited to needs in developing countries and (4) having good professional environments for emission-free technologies and the associated industry may increase the countries' motivation to implement climate measures. (Domestic research environments and industries may be an important lobby for implementing measures.)

Cost-effective innovation is important for cost-effective, powerful climate policy.

5.5 Measures for long-term restructuring and learning

We have seen that development of new technologies can lead to great gains, but these gains often only become tangible after several decades of effort. This means that a long-term perspective is required in order to succeed. Thus, efficient measures that promote long-term efforts are also necessary.

In this chapter, I will discuss two factors that may discourage long-term restructuring and technology development: a) high required rates of return in the industry and b) regulatory uncertainty regarding long-term climate policy. Challenges in connection with high required rates of return and uncertainty are especially prevalent where a quota system for CO_2 (EU ETS) is preferred as the key motivator for long-term restructuring and technology development.

5.5.1 HIGH PRIVATE HURDLE RATES MAY REDUCE COST-EFFECTIVENES

The higher your required rate of return, the less weight you give income and expenses far ahead in time. What the appropriate required rate of return (hurdle rate) is for different investments is a complex question of great significance. There are different views on what constitutes a reasonable rate of return for climate measures, but many believe *a relatively low rate* should be used in this case, maybe around 4% (real) or lower. One reason for this is that climate measures may be viewed as an insurance against possible climate scenarios with extreme negative consequences.

The more an investment contributes to our total risk exposure, the higher the hurdle rate. If the expected cash flow from an investment is not correlated at all with the economic growth or the nation's wealth, it is recommended to apply a risk-free real interest rate in the range of 2-3% to evaluate the present value. (In this case an investment does not add to the total risk.) If the cash flow (benefits) is negatively correlated to our wealth, and therefore *reduces* our exposure to risk, we should be willing to use an even lower hurdle rate.[28] *Since climate measures can partly be seen as an insurance against catastrophic climate scenarios, these measures can be viewed as a means to reducing total risk. This could equate to a very low required rate of return*. There are also good arguments why a flow of cash (or benefits) far ahead in time should have relatively low hurdle rates.[29]

While climate measures should be considered with a relatively low required rate of return and a very long time perspective, private companies often operate with hurdle rates in the range of 10%, and sometimes even higher.[30] In addition, relatively short analysis periods are often used, e.g. 20-30 years, ignoring any income after this period. If the climate problem is analysed in such a short time perspective, in practice there will be no climate policy. Due to the great inertia in the climate system, trends over the next 20 years will largely be due to emissions that have already taken place. It is an emphasis on developments in a long-term perspective that necessitates climate measures.

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28 A real interest rate is an interest rate corrected for inflation. If the interest rate on a loan is 4% and inflation is 2.5%, the real interest rate will be 1.5%.

29 Several governments, including the French and British, have recommended the use of diminishing discount rates (DDR). For the UK, the recommendation is to use 3.5% for 1-30 years, 3% for 31-75 years, 2.5% for 76-125 years and 2% for 125-200 years. The theoretical reasoning behind the use of DDR is linked to uncertainty regarding future growth, future relative prices, future income distribution and future interest levels. See for instance the Stern Review (2007) and Sterner and Persson (2008).

30 In theory, different hurdle rates should be used for different types of cash flow, depending on their risk profile. But there are many indications that businesses often use the same required rate of return for all cash flows. For private companies, expenses for climate measures and saved climate costs are only one of many items in their accounts, and companies will not automatically comply with society's desire for climate measures to be considered at lower hurdle rates. Uncertainty regarding future climate policy may also contribute to high hurdle rates in connection with emission-reducing projects.

Uncertainty regarding future climate policy and policy instruments might at worst contribute to the industry using an extra high required rate of return where climate-related investments are concerned.

High required rates of return in private companies mean more challenges in climate policy. One challenge is that private players will place much less emphasis on future emission costs than public players and planners, who operate with much lower required rates of return. When players with different required rates of return are faced with the same long-term projection for carbon prices, they will not value future emission reductions equally. Figure 5.6 illustrates this point. It shows how much players with different required rates of return are willing to invest today for the same return (for instance from saved carbon emission costs) in 20 and 30 years, respectively.

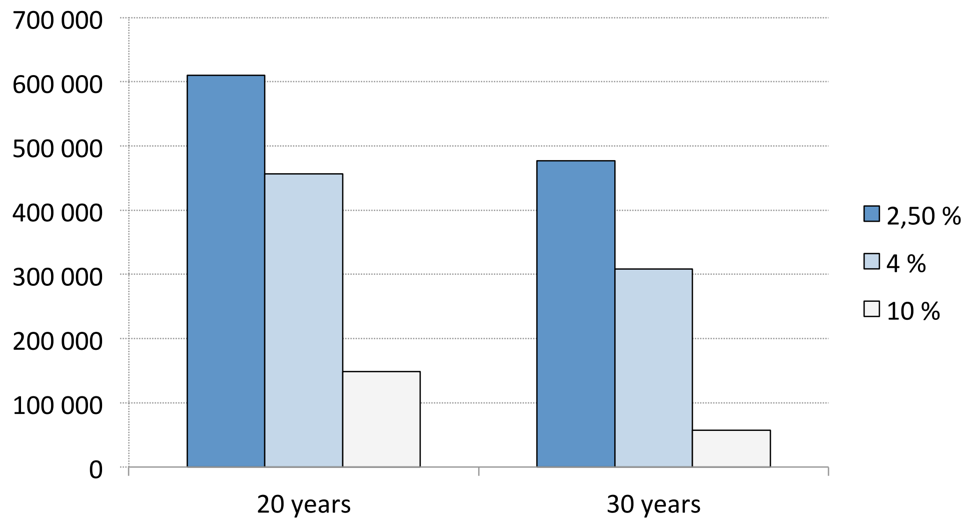

Figure 5.6 Present value of receiving €1 million in 20 and 30 years' time, respectively, based on required rates of return of 2.5%, 4% and 10%

Players with different required rates of return will value *short-term* emission reductions equally. Everyone would be willing to spend up to a million to save emissions that cost a million today. For short-term measures, then, equal carbon prices provide a cost-effective distribution of efforts among players. (I presuppose efficient markets here. Information barriers, differences in incentive or irrational players may lead to anomalies.) But players with different required rates of return will, as shown in the figure, value future emission reductions very differently, even when faced with the same price projection for emissions. While a player with a 4% required rate of return would be willing to invest just over €456,000 today to save emissions worth €1 million in 20 years, a player with a 10% required rate of return would only be willing to invest 1/3 of this to achieve the same future emission reduction. This is not cost-effective. Thus, the problem is primarily the high hurdle rates in the business world.

Hurdle rates may also vary from country to country. In a number of developing countries, political and social instability contribute to high rates in many businesses. This often leads to solutions with small investments and high operating costs, such as investing in a diesel generator for power supply instead of renewable power, which could be cheaper in the long run (based on normal hurdle rates). The problem arises because renewable energy often has high investment costs and very low running costs, while a diesel generator is less expensive to buy, but has high operating costs throughout its lifetime. When comparing two such alternatives, the hurdle rates (and financing abilities) matter a great deal.

High required rates of return also reduce the industry's willingness to invest in long-term R&D. This is in addition to the challenge that the companies only receive a small share of the value of the new knowledge. The public sector can compensate for the effect of high hurdle rates by financing long-term research and technology development (under their own auspices, or through private companies), and by supporting incremental innovation in the industry. In addition, the public sector can initiate more extensive implementation of new solutions (such as e.g. deployment programmes for wind or solar power) *in order to create a market* which facilitates testing and learning by doing in a realistic environment. When a market is created for the products, such as American authorities did for e.g. defence and space exploration programmes, learning processes are also started. Early establishment of markets for new climate solutions (or other purposes) provides practical labs for testing and learning throughout the value chain. The existence of an actual market for a new solution (such as solar energy) – and not a hypothetical market many years in the future – can to a significant degree solve the problem of high required rates of return and short time perspectives in private companies: *The road from idea to sale and profit becomes shorter*.

5.5.2 UNCERTAINTY DIMINISHES THE POWER TO ACT AND INCREASES COSTS

Uncertainty regarding future climate policy can affect willingness to invest in emission-reducing measures and R&D. The significance of this to market players will depend on the type of measures used. If carbon pricing is the most important or only measure, and future carbon prices are very uncertain, this means uncertain income for those investing in emission-reducing measures. An agreed, credible future path for the carbon price (e.g. in the form of a tax) can significantly reduce uncertainty. Guaranteed support, such as feed-in tariffs[31] (FIT) for renewable energy, could mean much lower risk for investors (see 5.5.3). Tendering competitions for developments with agreed support (e.g. investment support) may provide similar security for investors.

Certainty that policy is long-term and stable is important not just for the developers, but *throughout the value chain* which will deliver components and services to the developers. Investments in different parts of the value chain, together with competition for the best and cheapest solutions, are important in bringing costs down. For suppliers to dare to invest in facilities that can bring costs down, they must believe in the long-term opportunities.

Broad political agreement increases stability and credibility in climate policy. Credibility can be improved by linking climate policy to binding international agreements. The design of the policy instruments that will provide investment signals is also important. The EU's quota system for greenhouse gas emissions illustrates this. Since the financial crisis in 2008,

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31 Feed-in tariffs provide investors with a guaranteed payment for each kWh generated over a given number of years, e.g. 20 years. The amount is adjusted to the cost level for each technology.

the quota price for CO_2 in the EU has collapsed. While it was expected until 2008 that quota prices would stay above €20 per tonne, the crisis resulted in a large surplus of quotas and a significant price drop. In 2014, the quota price has been as low as €5 per tonne. The surplus of quotas in 2014 is greater than a year's emissions of CO_2 within the quota market. This development is largely due to the fact that the financial crisis has led to a much lower demand for quotas from the industry and power sector. When demand drops significantly and supply remains the same (inelastic), such surpluses are the result.

The only reason that the quota price in 2014 is not zero, is that quotas can be saved and their value is expected to continue to increase in future when a scarcity of quotas arises. Future scarcity is linked to the fact that every year until 2020, the total number of quotas will be reduced by 1.74% of the quota ceiling in 2010, and quicker curtailment is expected from 2021 onwards. The large surplus of quotas and the low quota price make it – all other things being equal – easier for the EU to cut the quota ceiling faster after 2020. The EU has a target of cutting total greenhouse gas emissions by 20% (from 1990 levels) by 2020. Due to the financial crisis, this target will now be reached easily. The European Commission has suggested a target of cutting emissions by 40% (from 1990 levels) by 2030. This proposal involves reducing the quota ceiling by 2.2% per year from 2021.

Until the targets for increased energy efficiency, renewable energy development and CO_2 emissions for 2030 were determined, there was great *regulatory uncertainty* regarding what type of quota prices can be expected in the longer term.[32] There is significant regulatory risk also after the targets for 2030 have been determined, e.g. whether the policy will actually be implemented and all the targets will be reached.

Discussions in 2014 regarding targets for increased energy efficiency can illustrate the problems of regulatory risk for the quota system. In the winter of 2014, the European Parliament proposed a target of 40% increased energy efficiency by 2030. If the target of a 40% cut in greenhouse gases by 2030 had been retained, and one were to succeed with 40% increased energy efficiency, plus e.g. 30% renewable energy, which the Parliament also accepted, it is *highly likely that quota prices would remain very low*. This could happen because demand for quotas would continue to be lower than supply for a prolonged period.

The target of a 40% increase in energy efficiency by 2030 may be fit for purpose if it is realistic and financially viable*, but then ambitions for emission cuts should be raised accordingly, so that the quota system can function as intended.*

If a highly ambitious target for energy efficiency (such as the Parliament's proposed 40%) were to be adopted, at the same time as there is great uncertainty regarding how much it is possible to implement in practice, this would contribute to *increased uncertainty regarding both what will happen in terms of increased energy efficiency and the fate of quota prices in the future.* For quota prices, this uncertainty will add to the significant uncertainty regarding further financial growth, uncertainty regarding global climate policy, developments in

32 For a given emission target, stronger efforts to increase energy efficiency and develop renewable energy will result in lower quota prices. Based on this, some argue that more efforts to increase energy efficiency and develop renewable energy will have no effect on total emissions, since the quota ceiling (really the target for total emissions, not everything is covered by the quota market) determines total emissions. According to this view, a push from increased energy efficiency and renewable energy only means that demand for quotas is reduced and quota prices go down. This view is correct if the quota ceiling is given. Over time, however, there is reason to assume that the quota ceiling is further reduced if the other measures are successful. Countries in the EU are not indifferent to quota prices. Progress in energy efficiency and focus on renewable energy make it easier to set more ambitious targets for emission reductions at the time of the next revision, without quota prices becoming unacceptably high.

technology, etc. Recent years have clearly shown how sensitive quota prices in the EU are to financial setbacks. Bearing this insecurity in mind, market players will hesitate to make long-term investments that assume a high quota price. *If quota prices are to function as an investment signal, the market must have confidence that price levels will remain relatively high in future.*

If the quota price is to play an important role towards 2030, as the EU Commission outlines in its proposal for targets for 2030, it probably needs to be at least €40 (in €2014 prices) in 2030. (With the fuel prices in 2014, quota prices need to be between €60 and € 80 to make production costs for coal power higher than the costs of gas power.) The fact that quota prices in 2014 have been down to €5 per tonne is an indication that the market does not have much faith in high quota prices towards 2030. If quotas are bought for €5 in 2014 and they can be sold for €40 in 2030, this means a return of almost 14% per year. The current low prices indicate that few people are willing to bank on a significant price increase in the longer term. And if there are few who are willing to believe quota prices will rise significantly, there are probably also few who are willing to invest in projects where profits are dependent on a high quota price.

Technically, the EU's quota system has worked, and has contributed (somewhat) to reaching (or exceeding) the target of 20% emission reductions in 2020. But the steep price drop from 2008 has illustrated the uncertainty of future quota prices and that this type of carbon pricing has great weaknesses when it comes to promoting long-term investments in zero emission solutions. A policy instrument that sometimes gives strong signals for restructuring, and at other times almost stops working completely, may lead to paralysis or to very irregular investment activities. *A sufficient long-term perspective is not achieved. Restructuring is slower and less cost-effective.*

A tax instead of a quota system may provide greater price security for investors, but it is important that there are solid political commitments behind the long-term decisions regarding tax levels. A quota system can also be modified by for instance having a floor and a ceiling for the quota price with an indicated development of these limitations in the future. For instance, the price floor in the EU could be €20 in 2020, with a consistent increase to €30 in 2030, €40 in 2040 and so on. In practice, this could be achieved by no longer issuing quotas (or buying back quotas) if the quota price drops to the price floor. If the price falls to the floor, the result will be a faster reduction in emissions than implied by the quota ceiling. California (and the UK) has introduced a price floor in its quota market, perhaps based on lessons learned from the European quota market.

Demand for quotas can, as mentioned, become lower than expected if one is more successful than expected in terms of increasing energy efficiency and developing renewable power, or if economic growth is slower than expected. If a sufficiently high price floor for the quota price has been defined, the result is that emissions are cut by more than the target (for instance 40% in 2030). In such a situation, exceeding the target is a reasonable result, as it turns out to be easier to cut emissions than was thought at the planning stage.

A new mechanism has been suggested from 2021 to withdraw a part of the quota surplus from the market and transfer these quotas back as the surplus lessens. Such a mechanism could help to reduce uncertainty to a degree. See the European Commission (2014) for more information about this mechanism.

A less volatile carbon price will give a stronger investment signal. Increased faith in future carbon prices promotes restructuring and cost-effectiveness.

The quota system in the EU can be improved, but given the other challenges I have highlighted above, it is important to supplement carbon pricing with subsidy schemes and other regulatory measures to achieve efficient development of new solutions and to implement important long-term investments.

5.5.3 FEED-IN TARIFFS HAVE PROVIDED SECURITY FOR INVESTORS AND FLEXIBILITY FOR AUTHORITIES

Many countries have been inspired by Germany's Energiewende and the feed-in tariffs (FIT) employed by Germany. The German policy continues to have solid public support, and the measures have in addition meant low risk for investors. Often, local communities have joined in as investors. The low risk for investors has been important in encouraging investments and possibly also for the steep price drops.

FITs work by giving investors a guaranteed payment for each kWh they generate for 20 years. Payment is adjusted to the cost level of each technology, so that investors are able to expect an acceptable return. Developments in subsidies for solar panels are especially interesting. Since the cost of the panels has dropped significantly over time, the tariffs for *new* facilities have been reduced periodically. Those who have already invested receive their agreed return, while new investors have to accept lower payment. This system has offered investors security *at the same time as* the authorities have been able to adjust policy regularly to take into account cost developments and other relevant changes. For a review of developments in the subsidy system and interactions between policy and market conditions, see Hoppmann J., et al. (2014).

The combination of low risk for investors and flexibility for authorities could not be as easily achieved with a more general instrument like an equal subsidy to all renewable energy. Since solar panels were originally much more expensive than other renewable sources of power, a system of equal support for different technologies would result in either unreasonably high payments for those investing in wind and biopower (and therefore much higher costs for consumers), or there could be lower levels of support and one would have missed out on the deployment of solar energy. *When the goal is to develop specific technologies, instruments aimed directly at this goal will prove most effective.*

Developments regarding solar panels illustrate the limits of using carbon pricing alone as a policy instrument: if the quota price in the EU were to trigger investments in solar panels – especially during the early stages – quota and power prices would have to be at a level unacceptable to the population, and remain at such a level for over 20 years. Other technologies such as nuclear power, wind power and to some extent gas power would have enjoyed ludicrous profits if power prices were that high, while consumers would have had very high energy bills. Power intensive and emissions intensive industry competing with countries outside the EU would be shut down and replaced by increased production in countries without strict climate policies (and an increase in emissions outside the EU could follow).

German consumers have paid the bill for solar panels through FITs, but there is a big difference between consumers paying a high price for solar power and consumers having to pay such a high price for all the power they buy. They would have had to do so if the power market were to trigger investments in solar panels.

For many years to come, very high carbon prices will be necessary if the carbon price is intended to drive development in e.g. offshore wind power. To trigger investments in offshore wind power based on today's cost level, power prices of around €0.15 per kWh would be necessary, in addition to confidence that this price level would continue throughout the facilities' lifetime.

The advantages of FITs which I have described do not mean that this system is perfect. As the share of fossil power declines and the share of variable power increases, it becomes increasingly important to stimulate power generation which is able to deliver power when the market needs it the most. (Cf. the discussion in Chapter 4.2 and in Appendix 2.) Subsidies that value each kWh equally, cannot provide such incentives. It is therefore clearly necessary to further develop these regulations.

It is desirable that renewable power generation is exposed to market prices so that investors are encouraged to choose technology, design and locations that maximise the societal *value of the power* instead of maximising the *number of kWh*. It should be possible to achieve this while also ensuring profitability for immature technologies, and limiting the risk for investors.[33]

In the power market, prices vary from hour to hour. This is because the price at any given time reflects the cost of the most expensive generation technology that must be started to cover the demand for power. (Cf. explanation in 4.2.2.) A much higher carbon price than we have today would mean significantly higher power prices during periods when the most polluting power plants must be run. This will stimulate reduced consumption when the benefit is greatest, and strengthen incentives to build renewable power generation able to deliver more power during these periods.[34] (Cf. discussion in Chapter 4.2 and in Appendix 2.)

5.6 Societal learning processes are important

5.6.1 INTRODUCTION: WHY ARE SOCIETAL LEARNING PROCESSES IMPORTANT?

Societal learning processes are relevant to the development of policy, laws, regulations and institutions, and the development of people's attitudes and understanding of appropriate policy and policy instruments. Attitudes change based on experience and in interaction with the development of rules and institutions.

Societal learning may have great significance for our ability to implement powerful and cost-effective climate policies. In order to limit global warming to 2°C, pervasive changes are necessary with regard to how we produce goods and services and also to some degree

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33 Some of this is achieved by for instance providing investment support (specific to each technology) to cover some of the investment costs and letting market prices take care of the rest of the income. Alternatively, in addition to the income from power sales, annual support can be provided, adjusted to ensure a reasonable return. If market prices rise sharply, for instance as a result of much higher carbon prices or higher fossil prices, support can be reduced, and vice versa. Such models can ensure investors a reasonable return and prevent them from making unreasonable profits.

34 Design and location of solar and wind power plants can be adjusted. In addition, higher prices in some periods will increase profits from biofuel and biogas, adjustable hydropower, storage technologies for power and development of transmission capacity.

what we produce (cf. Chapter 2). Generation and use of energy must change at a fundamental level, the transport sector must stop using fossil fuels and may need to be organised differently, and parts of the agricultural sector and many types of industry will be affected. *Such changes do not only require new technology, they require new organisational and market models and new policy instruments.* The tax system must be reoriented in a green direction and we need new ways of thinking about planning buildings, towns and cities and other infrastructure. Developing good models for organisation requires time and practical experience. It may also take time for the public to accept new solutions.

Looking back over the last 50-60 years, we can see that big changes have taken place in many societies with respect to norms and rules, for instance concerning gender equality, parenting methods and male participation in parenting, acceptance of sexual minorities, etc. In many cases, changes to laws and rules and changes in the population's attitudes have reinforced each other. Countries have also influenced each other; some countries have led the way in terms of policy and inspired developments in other countries. A good illustration is how reforms in other countries are often used to support arguments for similar changes in one's own country.

Laws that prohibit smoking in public places such as restaurants and bars are a good example of the interaction between legislation and attitudes, and of how policy design can affect decisions in other places around the world. New York outlawed smoking in bars and restaurants in the summer of 2003 and several countries followed suit in the years that followed. Norway introduced its smoking ban on 1 June 2004. *Two months prior to this date, 54% of the population was positive to the ban, while as much as 76% of the population was positive to the ban in October 2005*, according to *Store Norske Leksikon* (a Norwegian encyclopaedia). Many who were initially opposed to the ban, probably felt it was a good reform after its introduction.

Organisation can affect people's attitudes in many ways: In Denmark and Germany, steps have been taken to allow the local population to be co-owners of new renewable power generation to a significant degree. Widespread co-ownership appears to strengthen support for development and energy reforms in general. This works both ways – large companies without local anchoring may face greater scepticism. Mechanisms for compensating local populations for disadvantages brought about by a development may also affect people's attitudes. In addition, research shows that the manner in which processes preparing for development are carried out, has great significance. And after development, attitudes often change and many become more positive to the changes. This is discussed e.g. in the book *Renewable Energy and the Public. From NIMBY to Participation* (Wright, 2011).

5.6.2 LEARNING PROCESS: WHAT ARE THE BEST INSTITUTIONAL SOLUTIONS?

Relevant areas for learning (development of knowledge) are for example how markets, subsidy schemes, construction standards, tax systems and carbon pricing should be designed in order to reach climate targets and other targets in a cost-effective manner.

The weaknesses of the European quota system (EU ETS), made especially visible after 2008, demonstrate the challenges of organising a system for carbon pricing. As I see it, a system of agreed-upon, rising *taxes* on greenhouse gas emissions would work better, primarily because this would mean less uncertainty for market players, and allow simpler interaction with other measures.[35] Or there could be a quota system with minimum prices. There is probably little agreement among economists as to how a carbon pricing system should be designed. Opinions will depend on e.g. how different models are thought to work in practice, and how much weight is given to different strengths and weaknesses. Practical experience with carbon pricing is therefore an important basis for gaining a better picture of which theoretical weaknesses are highly significant for efficiency and which are less important. Similarly, experience with different subsidy schemes for renewable energy and measures for increasing energy efficiency may give us a better understanding of which measures are most effective in different situations.

Example: The development of efficient energy markets is a learning process

In Europe, the development of a well-functioning power market with trade across countries is important in order to replace fossil power generation with renewable/emission-free power generation. As mentioned in Chapter 4.2, a greater share of unregulatable power will require more trade and efficient exploitation of flexibility in power generation and with consumers. Efficient markets are required in order to coordinate decisions regarding power generation and consumption for many thousand power plants and millions of consumers.

England and Wales deregulated their power markets in 1989 and Norway followed suit in 1990. (In Norway, there were elements of a market going back to the 1970s.) Other countries have followed over time, but 2014, the EU has still not completely reached the goal of establishing an internal market for power. England and Wales made some changes in the regulation of the power market just after the turn of the millennium, and a new reform is currently underway. These changes may reflect changed market conditions, and/or a learning process where regulations that have not worked satisfactorily, are changed.

In connection with the EU's goal of an internal energy market, a comprehensive and challenging process is taking place to establish all the necessary rules. In such processes, one can make use of experience from countries that have had markets for many years, but because market structure and political conditions vary, exact copies of established models are not always possible. It will take time to develop good models for the organisation of the European power market, and models can be adjusted as time goes by, based on experience and because a changed physical structure in markets may require different organisation.

With increasing development of variable renewable power generation and downscaling of fossil power generation, the power system is facing new challenges. Among other things, consumers must contribute more to balancing consumption and generation. This may mean changes in market design and the roles various players and submarkets should have.

Practical experience and theoretical studies contribute to a gradual improvement in market design and other regulations to make our use of resources more efficient.

5.6.3 INTERACTION BETWEEN CHANGE AND ATTITUDES

In deregulated power markets, power prices will be high in some situations and at certain times. This may create resistance in the population and lead to demands for government

35 Both a planned tax path and a quota system with a planned path for emission reductions involve political risk. But the quota price is also exposed to a lot of other uncertainty, e.g. macro-economic developments, technological developments in a number of areas and the degree of success achieved through other climate measures such as increased energy efficiency and development of renewable energy.

action in order to limit price increases. If the high prices are a result of actual scarcity (and not of weaknesses in market design), measures to keep prices down will mean less efficient use of resources and in the long-term, higher costs for consumers. High prices are necessary to encourage increased flexibility among consumers and producers.

Based on Norwegian experience, it appears that some years after the introduction of a power market, the population is more willing to accept power prices being higher at certain times.

Why is it so hard to get rid of subsidies for fossil energy?

The existence of substantial subsidies for fossil energy in many countries – and the challenges of removing them – show that people may resist change even if the changes in question would mean significant benefits for the country's economy and for the environment. The IEA (2013) estimated total subsidies for *consumption* of fossil energy the world over at $544 billion in 2012. (In addition, there are a number of subsidies for fossil energy generation, e.g. for coal mining.) This is six times higher than the total support for renewable energy. Much of this support goes to keeping fuel prices down in poor countries. Such subsidies bring with them a number of problems: they increase CO_2 emissions and reinforce local environmental problems, and mean significant financial losses for the countries paying the subsidies, by e.g. using money from public budgets to the detriment of measures that would benefit the general public and provide growth. In countries where fossil energy is not produced, subsidies also increase dependence on imports. Subsidies also significantly favour the wealthier strata of society. The Economist (2014b) has referred to research from IMF which shows that only 7% of subsidies reach the poorest 20% of households, while a hefty 43% of subsidies benefit the richest 20%.

Indonesia and Malaysia have relatively recently reduced their subsidies for fossil energy, and other countries are considering following their lead. Even though objectively, there are very strong reasons for removing subsidies for fossil energy, it has proven politically difficult in many cases. In many countries, attempts to remove subsidies have led to major protests. In some countries, authorities have been forced to reverse or decelerate changes, while other countries have been successful in abolishing or reducing subsidies. For a short review, see the World Economic Forum (2013). Malaysia and Indonesia have also seen significant protests against the changes. In the article mentioned above, The Economist writes:

> *Whether more countries will follow the lead of Indonesia and Malaysia, however, does not depend only on economics. On New Year's Eve thousands turned out in Kuala Lumpur, Malaysia's capital, to protest against the cuts. And in Indonesia public opinion has put politicians under pressure to roll back some of the reforms this year. When it comes to cutting subsidies, politics can still trump even the best economic or environmental arguments.*

Developing *practicable* strategies is important when it comes to ending subsidies for fossil energy. Relevant elements in such a strategy may be to create broad political majorities in support of restructuring, and make use of information campaigns in advance. It may also be wise to earmark savings for popular, important community goals, to make it obvious that the money will be spent on better things. Gradual phasing out will probably be met with less resistance than a sudden termination.[36]

36 Economists dislike earmarking because it places restrictions on use of resources. If earmarking is necessary in order to bring about an important reform, however, its benefits may outweigh the disadvantages.

When some countries lead the way, others can learn from their experience. Support for national reforms may also be stronger once other countries have shown that the new solutions really work.[37]

Rush hour tax gives great gains in big cities

In most of the world's big cities, traffic congestion is a significant issue, and leads to big economic costs in the form of lost time and increased pollution. If separate lanes are not built for public transport, buses also get stuck in traffic jams. Traffic jams can therefore make it difficult to create an attractive public transport option. (Underground railways take a long time to build, and are also relatively expensive.)

Economists' (almost unanimous) answer to the problem of traffic jams is that scarce resources should be rationed based on pricing (tax) and not through traffic jams, provided the cost of collecting the tax is acceptable, and that low-income groups are not unreasonably affected. Technology that allows us to cost-effectively tax driving in cities has existed for over 20 years. Those against such a measure often allege that a rush hour tax will target weak groups, but it is difficult to see how a congestion charge would have especially unfortunate effects on the distribution of wealth. Drivers are in general not a weak group, and to the degree unacceptable effects exist, it should be possible to compensate for them. It is also important to remember that some groups may be hit hard by the disadvantages of low mobility. But such disadvantages are not new to us, so we often take them for granted.

While a congestion charge is a rationing mechanism where most of the payment is revenue for the public sector, rationing by means of congestion puts drivers at a harsh disadvantage without generating any revenue for society.

Some big cities have introduced congestion charges (Singapore 1975, London 2003, Stockholm 2007 and Gothenburg 2013), and achieved considerable improvements in traffic flow and air quality. Given the immense costs of traffic congestion in big cities, it is remarkable that so few cities have introduced such measures. A cost-benefit analysis of the congestion charge system in Stockholm in 2009 estimated the annual net benefit of the system at SEK 683 million. (Brunstad and Vagstad, 2010)

A congestion charge would probably be very profitable (to society) in most cities even if only the value of the drivers' lost time was taken into account. In order to develop the cities of the future with a pleasant local environments, low CO_2 emissions and efficient public transport, congestion charges may be a necessity.

In Stockholm, a congestion charge was first introduced as a trial in 2006. Any continuation was to be approved at a referendum after the trial period. The result was a yes from the ma-

37 In 2004, there were 45 countries that had introduced subsidy schemes for renewable energy. In early 2014, there were 137 countries that had introduced subsidy schemes and 148 countries that had set targets for development (REN21, 2014). (Renewables 2014 Global Status Report) In 2014, Saudi Arabia has also announced a goal to build 41 GW of solar power by 2032. Authorities in Saudi Arabia also envisage building 9 GW of wind power by 2032. It is of course difficult to determine to what degree a country's reform is triggered or inspired by that of other countries, but there is little doubt that many countries have studied the subsidy schemes in Germany and in other countries before implementing their own reforms. It is natural to want to learn from the strengths and weaknesses of reforms, and reforms that work well may also inspire action. It is easier to argue for implementation of a reform that has already been tested in other countries than to argue based on theory alone. See also Treuer, G.A., E.U. Weber, K.C. Appelt, A.E. Goll, and R.D. Crookes. 2014. "Weathering the Storm: Status Quo Adjustments Explain Successful Policy Implementation." Political Behavior in press.

jority, and the charge became a permanent fixture from 2007. Having a trial period may be a good idea in other areas too. We have seen that once good reforms have been implemented, they often gain support from the public. After implementation, the drama surrounding the disadvantages of reforms tends to fade, and in the case of a congestion charge, the local population can see the value of better mobility and a cleaner city.

For economists, widespread resistance to obviously beneficial reforms such as congestion charges and removal of subsidies for fossil energy should be thought-provoking: *In order to realise solutions that serve society well, there must be a strong focus on broad learning processes as well as on what is ideal from a theoretical point of view*.

Tax conservatism

Resistance to changing taxes and fees is not limited to environmentally-friendly reforms; rather, it is symptomatic of a more general tax conservatism where the public accepts the types of tax and taxation rates already in place, but is opposed to new taxes, even when they are financially beneficial to the public and are compensated for in other areas. This is a type of resistance to change (often referred to as *status quo bias* in psychology), and is not because the current taxes and fees are the best possible ones. A comparison of taxes and fees in Norway and Sweden can illustrate this: Even though Norway and Sweden are quite similar as societies go, it would be very difficult to get Norwegians to accept a much higher housing tax such as Sweden has, or get Swedes to accept the high Norwegian vehicle taxes. If such high vehicle taxes had been introduced today, Norwegians would not have accepted them either. These fees have historical roots back to rationing of car sales to limit imports after World War II. The Norwegian population is used to these taxes, and most people have therefore accepted them.

Fuel and vehicle taxes that could start riots in the US are acceptable in many European countries because people have got used to such taxes over a long period.

Tax conservatism is an example of the path dependency, which I mentioned in Chapter 1.

5.6.4 RESISTANCE TO HIGH CARBON PRICES – WHAT ARE THE IMPLICATIONS?

There are at least three reasons why politicians might be against too high carbon prices:

1. *Tax conservatism* can create resistance to high carbon prices. This type of resistance can probably be overcome in time through wise political leadership. A gradual increase has a greater chance of acceptance.

2. *Weaker competitiveness for industry* that has large emissions or uses a lot of energy (carbon leakage). This could become a reality unless competitors in other parts of the world have a similarly high carbon price. This is a real problem that must be dealt with.

3. *Effects of distribution*. High carbon prices will mean considerable income for some (such as owners of nuclear power and hydropower) and considerable costs for consumers. In principle, many such effects can be corrected, but this is not always simple in practice, and can take time.

There may also be other factors keeping some countries from wanting high carbon prices. In the EU, those against nuclear power could be worried that high power prices (due to high carbon prices) could promote the use of nuclear power. In the EU, there are also concerns about becoming increasingly dependent on gas imports for the power sector (cf. Putin and the Ukraine crisis). Coal power is often considered to offer better security of supply. It is possible that a combination of more renewable power, big efforts to increase energy efficiency and slower phasing out of coal power might be seen as better, because it means less dependence on imports, and it would also provide more jobs in the EU. These points show that climate and energy policy is ultimately the result of many different considerations.

When it is impossible, for various reasons, to fix the carbon price as high as is desirable, it becomes important to use other instruments in addition. Support for renewable energy development is then not just a way to promote learning effects, and instruments for promoting increased energy efficiency are not just a means to correcting barriers and market failures in connection with energy use. Such instruments also compensate for the fact that the carbon price cannot be fixed as high as would be desirable from a climate perspective.

Some will object that this is not cost-effective. True, this may not be as cost-effective as a policy with no restrictions on carbon pricing, but it could be far more effective than delaying restructuring.

Climate policy is a restructuring project that requires a natural order in which things should be done. It is cost-effective to replace old, polluting infrastructure with emission-free solutions as and when facilities need to be replaced anyway. Capacity in various value chains for development of solar power, wind power, transfer grids, etc. must be built up over time and utilised consistently and efficiently. If, instead, we were to plan to make big efforts suddenly in 10-15 years, costs would be much higher, and it would in practice prove impossible to reach our goals because supply chains could not be built fast enough. Furthermore, we also need to learn along the way.

It is preferable to get the carbon price up to a sufficiently high level and make it a reliable instrument. (At the same time, we must also deal with challenges of carbon leakage, cf. point 2 above. Read more about this in Chapter 6.) As long as the carbon price cannot be as high as we would like it to be, the other instruments are important in order to keep up the pace of restructuring the energy system. In addition, there is always a need for such instruments to promote goal-oriented technology development and to overcome market imperfections at the consumer end.

When several measures are used to bring down emissions, the carbon price will only express part of the value society places on emission reductions (the shadow price of emissions). This may be significant when considering how much weight emission reductions should be given when planning e.g. public projects.

5.6.5 THEORETICAL EXPLANATIONS OF RESISTANCE TO CHANGE

The resistance to change that I have described above, can be explained theoretically based on studies of how *individuals* react, and on *institutional conditions*.

A number of studies have been carried out within social psychology and experimental economics that describe loss aversion (people find it much harder to *lose* something they have than *not to win* something of a similar value) and a related effect, called *the endowment effect*.[38] This effect can be explained in connection with an experiment where students were given either coffee or chocolate, and then asked whether they wanted to swap what they had received for the other item. No matter which of the two items the students received, most were unwilling to swap what they had received for the other option. A number of similar tests in many countries produced the same pattern. This pattern reveals irrational behaviour with reference to standard economic thinking, and appears to be deeply rooted in human nature. An amusing indication that this pattern has deep biological roots, is evidence of similar reaction patterns in chimpanzees.[39]

The endowment effect is a barrier to change, but also offers an optimistic interpretation: While economists often interpret people's resistance to change as having to do with *permanent preferences*, here we are dealing with a more transient type of resistance. A while after a change, individuals may well be more satisfied with the new order of things. The large increase in support for the smoking ban after its introduction can be understood based on this. In a number of surveys, similar changes have been found with reference to attitudes to wind farms: following installation, far fewer people are against the wind farms, and more people express positive attitudes.[40]

Resistance to removing a subsidy may be reinforced by a lack of clarity about what you get in return, and who benefits from the change. An economist would argue that fewer public expenses (for fossil subsidies) would lead to lower taxes or increased public benefit in important areas, and that all in all, society would benefit from removing the subsidy. But at a subjective level, individuals may feel that money saved in one place, just goes into a black hole.

Institutional issues can reinforce the effects created by individual loss aversion and the endowment effect. If it is not clear what savings will be spent on, it will be difficult to mobilise interest groups who *may* benefit from the reform, to fight for it. Those who *know* they will be worse off due to a reform, will mobilise actively, however, and will often have established organisations able to fight their corner. (A parallel to this is that well-established industries often have strong organisations with spokespersons and lobbyists, while potential growth industries do not have the same strength to promote their views.)

Preferences change and we are influenced by others' opinions and actions

In almost all economic analyses and presentations, consumer preferences are dealt with as something fixed. We assume consumers have a genuine, individual inner ranking of different products, irrespective of how long they have had them and what products other people

38 Daniel Kahneman, the psychologist and behavioural researcher who received the Nobel Prize in Economics in 2002, describes these effects in his book Thinking, Fast and Slow. See e.g. Chapters 26-28, especially the paragraph "Defending the Status Quo" in Chapter 28. Here Kahneman writes, "plans for reform almost always produce many winners and some losers while achieving the overall improvement. If the affected parties have any political influence, however, potential losers will be more active and determined than potential winners". (Kahneman, 2013)

39 This is described in the article "Endowment Effects in Chimpanzees" by Bronson, et al. (2007). Their observations serve to strengthen a hypothesis that our unwillingness to give up something we already have (in exchange for something that is at least as good or better from a newcomer's point of view), may be biologically founded. For a short news article, see Choi (2007).

40 See for instance TNS Gallup/Enova (2009) (in Norwegian) and Damborg and Krohn (2001).

have. Psychological research indicates that these assumptions do not match up with reality. In any case, we all know from history and our own lives, that taste and preferences change. There are many indications that our desires as consumers are influenced by what others do and have, that we develop habits, and that becoming accustomed to something changes preferences. Fashions are a good example of this.

In blind tests, people often prefer flavours other than what they have stated prior to the test. Luxuries which imply status at one point in time, may at other times seem ridiculous.[41] Things are often valued *because they give the owner higher social status*: In one situation, owning a Hummer (a large, fuel-guzzling expensive SUV) may give status, but changed attitudes in society may make it embarrassing to drive such a car, if you do not need to.

Advertising and other factors of influence also play a role in determining what we prize as good and beautiful. In the article *"Marketing actions can modulate neural representations of experienced pleasantness"*, Plassmann et al. (2008) discuss a hypothesis that marketing measures can affect the very *experience* of a product. The authors tested a group's experience of the quality of wine and found that people felt the quality was better when they thought the price was high, compared to when they thought the price was low.[42] MRI scans of the test subjects indicate that not only did they *report* better taste, *they actually experienced better taste*. This shows that our experience of a product can be strongly influenced by what we think and believe about a product's quality and value, and which attitudes and associations are linked to it.

Taste and preferences are to a significant degree mouldable through social imitation. This is also confirmed when we look back, and are amazed at the strange fashionable clothes and hairstyles we let ourselves be persuaded to wear a few years back. Phenomena such as these are discussed in e.g. Cialdini (2001) and Ariely (2008). There is also research that indicates that families are more likely to install solar panels if their neighbours have done so. For a short news article with references to more research, see Plumer (2014).

The fact that preferences to some degree are mouldable and influenced by developments in society, may mean that we will over time accept greater changes in a climate-friendly direction than one would think based on current consumer behaviour.

When people's choices are interpreted as a result of permanent preferences, their willingness to pay for a product will be interpreted as a result of a permanent, true value for the consumer, and a corresponding loss of benefit will be assumed if consumers need to forego the product. But for products where demand is largely based on habit and perhaps on the social status afforded by the product, a change will not necessarily lead to a permanent loss of benefit.

Social psychologist Cialdini is interested in what he calls "social proof": When other people value something, we often assign great value to it. We imitate other people, and more than

41 "In the mid-1880s, aluminium metal was exceedingly difficult to produce, which made pure aluminium more valuable than gold. So celebrated was the metal that bars of aluminium were exhibited at the Exposition Universelle of 1855. Napoleon III of France is reputed to have held a banquet where the most honoured guests were given aluminium utensils, while the others made do with gold." Wikipedia (2014b)

42 In the summary of the article, its authors write: "We propose that marketing actions, such as changes in the price of a product, can affect neural representations of experienced pleasantness. We tested this hypothesis by scanning human subjects using functional MRI while they tasted wines that, contrary to reality, they believed to be different and sold at different prices. Our results show that increasing the price of a wine increases subjective reports of flavour pleasantness as well as blood-oxygen-level-dependent activity in medial orbitofrontal cortex, an area that is widely thought to encode for experienced pleasantness during experiential tasks."

anything, we imitate people who have high status in our eyes and people who are similar to us. We take on the actions, body language and speech patterns of our role models, and are far more open to arguments and ideas that come from people with high status and authority. Cialdini has an example so delightful it deserves to be repeated: He first refers to several studies of learning in troops of monkeys. Here, new knowledge of better sources of food or useful methods of catching food prove to spread very slowly throughout the troop if low-status individuals are the ones who make the discoveries. It can take over a year for the whole troop to start using the new methods. However, if the leader gets hold of the new idea, it can spread throughout the troop in a matter of hours. Cialdini then draws lines to something that happened in the Chicago Bulls basketball team in 1995. Two players had for a long time been eating energy booster bars before games without other players taking much notice. Then the team's leader and star player Michael Jordan started eating them, and before long, all the players were eating the bars before games.

Scurvy, tobacco, sugar and the climate: why are we so slow to learn?

In 1740, English admiral Lord Nelson's squadron set sail on a three-year voyage. Out of a crew of 2000, half died of scurvy. In 1747, doctor James Lind showed that patients who were given lemons recovered from scurvy in a matter of days. *But lime juice was not introduced as part of the Royal Navy's daily diet until 48 years later.* There are innumerable similar examples illustrating that people, institutions and societies learn slowly and that many years pass before new insight penetrates society and is used. Sadly, researchers and academic professions also appear to learn unnecessarily slowly in a number of cases.[43]

Knowledge of the harmful effects of tobacco have been known for decades, but smoking has only declined very slowly, much slower than what could be explained by *individual* addiction. Similarly, we have known about the health effects of refined sugar for a number of years, but only in recent years have we seen a decline in the use of sugary drinks in some countries. (In some countries, the tobacco industry and sugar industry may have contributed to confusion and doubts about research and may have affected public policy, but in many countries, clear information has been readily available to consumers.) Can our slow learning provide insight into our hesitant approach to the climate challenge? And will there come a point when denying the climate problem is impossible? How will it affect our ability to act?

43 Cialdini's book, Influence: Science and Practice, recounts comprehensive socio-psychological research which shows that in many situations, people do not behave the way economists expect. Daniel Kahneman talks about "theory induced blindness" among economists. In his book Thinking, Fast and Slow he describes experiments that clearly show significant weaknesses in economists' basic assumptions concerning rational behaviour, and comments on the response among economists thus: "You might think that this surprising outcome would cause much anguished soul-searching among economists, as a basic assumption of their theory had been successfully challenged. But this is not the way things work in social science, including both psychology and economics. Theoretical beliefs are robust, and it takes much more than one embarrassing finding for established theories to be seriously challenged." (Quote from Chapter 33, Reversals, subchapter Challenging Economics.) The point to notice here is that the research quoted by Cialdini and Kahneman is not new. Much of this research goes back several decades. Cialdini's book was first published in 1984.

Over 50 years ago, Thomas Kuhn wrote the book The structure of scientific revolutions, where he claims that regular practice within sciences is to stick to a paradigm (a theory or general model), even if it has been falsified beyond a doubt. One only changes paradigms when there is enough pressure on the old paradigm and there is an attractive alternative.

5.6.6 GAME THEORY DOES NOT EXPLAIN ALL TYPES OF INTERACTION

Many game theory analyses offer a fairly pessimistic view of the prospect of establishing an ambitious international climate agreement. It can be tempting to interpret the absence of success in international climate negotiations as a sign that these analyses are right, but perhaps the issue is more complicated. I do not doubt for a second that self-interest may play a big part in our choices and that game theory can provide useful insights. But I do not believe that all our actions and choices can be explained completely through a model of rational players that promote their own interests. It is hard to imagine that *only* self-interest has motivated the EU, around half of US states, many cities and many countries around the world to place themselves under climate commitments and start programmes for developing renewable energy.

A number of controlled experiments have been carried out showing that in many cases, people do not act as predicted by game theory, and the joke is often made that only students who major in economics respond as predicted by the theory.[44] This could have significant practical implications. Economists often explain the depletion or over-exploitation of common natural resources (such as grazing land, fishing resources in the sea, or the atmosphere) by a phenomenon called the *tragedy of the commons*. The thinking here is that when no one owns the resources, everyone will overexploit them ("it is better that I use this resource than that someone else takes it"), and the result is a bad situation for everyone. This is a plausible explanation model which may have a lot of truth in it. But it is far from obvious that it explains everything. In his article *Overexploitation of renewable resources: The role of misperceptions,* Erling Moxnes shows that overexploitation also occurs in cases where there is a shared system for exploitation, and that test subjects asked to use a resource also overexploit it without the *tragedy of the commons* theory being able to provide an explanation: "*All subjects err on the side of overexploitation. Behaviour seems to be dominated by inappropriate, static mental models and inefficient heuristics*." (Moxnes, 1998)

What does it mean for climate policy if *tragedy of the commons* is not the only explanation of why too little is done? And what does it mean if some of what is done is not based on self-interest?

We have seen many examples of the fact that people and institutions learn slowly, even when it is clearly in their interest to adopt a new solution. (Cf. the Royal Navy and scurvy.) Furthermore, social psychology research shows that we are influenced by others' actions, most of all by the actions of those we look up to and those who are similar to us (role models).

44 A game that has been tested a number of times in different cultures is the following: two players cannot communicate with each other, there is only one round, the players are anonymous and will not meet later. They are given the offer of sharing a sum of money, for instance $100. Player A has been asked to determine how to divide the money between them, and can therefore give more to himself. Player B can either accept this division and receive his share, or say no. If he says no, neither of them receives anything. Based on conventional economic thinking, Player B will say yes to any division that gives him something, e.g. $5 out of the 100, since $5 is better than nothing. If the players were to maximise their own financial gain, we would expect A to take almost all the money for himself and B to agree to this, since some money is better than no money. But this is not the typical result of the game: A takes far from everything, and in many cases B says no if the share he is offered is too small. One interpretation is that B sacrifices his money to punish A's greed. B is not necessarily irrational if he says no, but he is obviously not just in it for the money.

A funny point is that chimpanzees sometimes act more in line with game theory predictions than people do. This is discussed in a lecture by Colin Camerer: "Neuroscience, game theory, monkeys" on ted.com. (Carmerer, 2013)

Results at an individual level cannot simply be transferred to countries. But when looking at different countries' policies and the nature of debates regarding reform, it appears as though policy, too, is in many cases affected by what other countries do. This may partly be due to the fact that successful reforms make it easier to follow, but it may also be because our understanding of what is possible, right and necessary, is affected by what other countries do. The fact that other countries are implementing measures serves as an argument in domestic debates. This is not the only factor influencing politics, but in some cases, it may be a deciding factor.

There are several modern events where ideas and actions appear to have spread fast between countries. One example is the hippie movement and the students protest and riots from 1968 and the following years. Another example is the Arab Spring that started in Tunisia in December 2010 and gradually spread to other Arab countries.

More ambitious climate policy in one country can promote increased efforts in other countries because the costs of climate measures are reduced (technology development and economies of scale), because better models for implementation of cost-effective climate policy (successful reforms and institutions) are developed, and because of moral role models setting good examples.

5.6.7 WHAT HAS CHINA LEARNED FROM ITS SPECIAL ECONOMIC ZONES?

From 1976, under the leadership of Deng Xiaoping, Chinese economic policy gradually became more pragmatic and market-oriented. The Chinese leadership must have observed the much greater prosperity that had been created in market-oriented Taiwan and Hong Kong. From the early 1980s, China gradually opened more so-called *special economic zones* based on foreign investments, a significant degree of market economy and the use of cheap Chinese labour. An important objective for the zones was to increase exports to gain foreign currency, but there was also an intention to learn from foreign industry's technology and organisation. In addition, the zones provided an opportunity to experiment with different economic reforms and gain practical experience. [45] [46]

Due to their great financial success, the zones have probably made it easier to gain *support* for financial reforms throughout the rest of China. It is easy to create resistance against untried and theory-based proposals for reform, but it is difficult to argue against proven success. It was Deng Xiaoping who said that it does not matter whether a cat is black or white, as long as it catches mice. Deng may also have thought that successful reforms in some zones would be the best argument – and the best strategy – for later reforms in the rest of China. *Nothing succeeds like success*.

5.6.8 SOCIETAL LEARNING PROCESSES CONTRIBUTE TO COST-EFFECTIVE CLIMATE POLICY

We have seen above that societal learning takes place at many levels, and has to do with both development of knowledge regarding *suitable forms of organisation* (markets, laws, subsidy

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45 "The country's special zones can serve as experimental units in economic structural reform and as schools for learning the law of value and the regulation of production according to market demands." Dixin, Xu (2009)

46 Economist Paul Romer has developed interesting thoughts on how the lessons from Hong Kong and Chinese economic zones can be used to develop new, independent towns that can provide growth in poor countries. He presents his thoughts in several lectures available on ted.com, e.g. Why the world needs charter cities. (Romer, 2009)

schemes, taxes) and regarding *attitudes* in society. We have also seen that there is often interaction between changes in systems and institutions on the one hand, and changes in attitudes on the other. Resistance to changes in regulations will often be reduced and replaced by acceptance and support after the changes have been implemented and the dust has settled. This has important implications for what is a cost-effective and powerful climate policy: when some countries, states, areas or cities are ahead in terms of climate policy reforms, they provide a *knowledge basis* for better (more cost-effective) reforms in other places, and *inspire* others to follow. This makes climate policy more cost-effective over time.

Even though pioneers' climate measures *viewed in isolation* are expensive when compared with measures that could have been implemented in other countries (if these countries had been willing), pioneers' measures can still promote a powerful and cost-effective global climate policy.

Role models and technology for different types of countries

Knowledge that comes from reforms in one country will often be most relevant in countries that are politically, culturally, institutionally and financially similar, as well as being similar with regard to the energy system and other important factors. Perhaps we are also most *inspired* by reforms in countries similar to our own, which are therefore easier to identify with. Hence, there is a need for many countries, states and cities with different characteristics to lead the way in terms of reforms and share their experience with others.

Denmark has selected the island of Bornholm, population 43,000, to test the sustainable energy system of the future, and especially to test out smart grids for the power system. Copenhagen is to become the world's first carbon neutral capital (Braw, 2014) and in many ways, Denmark as a whole is an important pilot country for energy restructuring, further ahead and with more ambitious goals than Germany. China has a number of cities where sustainable solutions are being tested (Schmitz, 2013). Beijing, with a population of approx. 20 million inhabitants, has recently decided that coal power, which currently covers 25% of the city's power needs, will be phased out by 2020 to limit air pollution. Dubai is planning a whole new city with very low emissions (Masdar City, outside Abu Dhabi). Perhaps the EU should select one of the larger islands in the Mediterranean as the first society to have a completely renewable energy system? It could become an important laboratory for gaining experience, and not least an important source of inspiration.

Many of the areas that have made great strides in the direction of emission cuts, are relatively wealthy. It is also important to develop pioneer areas among poorer countries, and perhaps especially in poor countries that are seeing great financial growth (emerging economies). In order to develop model societies here, it may be necessary for rich countries to provide financial and technological support. Developing good solutions for countries on their way out of poverty is urgent. It is particularly important to avoid large investments in solutions that lock societies in to high greenhouse gas emissions for several decades, for instance by establishing new coal power plants. Therefore, there is a need for measures that can work quickly in many countries. In addition, it is important to think further ahead and develop knowledge that makes it possible for these countries to combine long-term economic growth with low and falling emissions. Here, pioneer areas and countries can play an important part, together with new technology.

If technology development is mainly driven by industrialised countries and regions, there is a danger that the resulting solutions will be less suited to the needs in poor countries and emerging economies. Luckily, solar panels can provide significant contributions in many developing countries, but for both solar cells and other technologies, there may be a need to develop and facilitate solutions that are especially adapted to the needs in developing countries. This also applies to good methods for financing investments. Support for such restructuring can be efficient aid policy as well as powerful climate policy.

The role of rich countries as pioneers does not need to stop at their borders. Norway has led the way in supporting rainforest conservation. This contributes to conserving biological diversity, is beneficial to indigenous peoples and is also a very cost-effective climate measure. Learning is also important in areas such as this, in order to determine the best methods to ensure we achieve our goal.

5.7 Dynamic and global cost-effectiveness

Many assessments of economic efficiency are based on a static perspective: Technologies and costs of measures are assumed to be fixed and people's preferences are assumed to be constant. When examining an isolated problem in a smaller geographical area and for a short period, such assumptions may be reasonable. Then there will hardly be any interaction between the measures considered and changes in technology, costs and preferences. The climate problem, however, is of a different character entirely: It is global, affects almost all areas of society, has no simple solution and has a time perspective of over a hundred years. This makes learning crucial in developing good solutions. New technologies and knowledge that can be used over many decades and throughout the world can offer immense gains in the long-term.

As we have seen in this chapter, technology development and large-scale expansion of new solutions provide important and mutually reinforcing contributions to bringing down the cost of climate solutions. We have also seen that learning is about more than just technology development: Societies that lead the way in restructuring, contribute to increased knowledge of how restructuring can be done most efficiently, and they can also inspire others to act. Both these effects can contribute to increased global cost-effectiveness in climate policy.

It may be appropriate to use the term *dynamic and global cost-effectiveness* to describe analyses that have a global perspective and take into account the fact that measures can affect cost and technology developments, and develop other useful knowledge.

The fact that some analyses ignore learning effects, may be due to a primary focus on the costs and benefits for one's own country in a short-term perspective, and less focus on learning effects that benefit the world community as a whole. Even though learning effects may also be of high value for individual countries and especially for large blocs such as the EU, the US and China, the value is obviously much greater in a global perspective.

The debate over cost-effectiveness would be tidier if it was clarified whether the topic is cost-effectiveness in relation to clear-cut, short-term national goals or cost-effectiveness in a global and long-term perspective. The conclusions as to what is cost-effective might differ significantly.

6. LIMITED PARTICIPATION IS A CHALLENGE

6.1 A broader, more robust climate strategy

The work of organising global agreements for emission cuts is complicated. Historically, countries have had different degrees of responsibility for greenhouse gas emissions, they are affected differently by climate changes, have different financial ability to implement climate measures and climate adaptations, have different costs associated with emission cuts, and have different governments and institutions.

If we are to succeed in our goal of limiting global warming to 2°C, all countries will eventually have to get on board with comprehensive climate measures. In the UN system, the term *"common, but differentiated responsibilities"* is used. This means that all countries have to be on board, but that the distribution of duties may be different, especially during the first decades.

We need a strategy that spurs more action now and in the future. This chapter offers suggestions for such a strategy. We can probably learn from what has happened until now: Much implemented climate policy has been based on local and national initiatives, and shaped by location conditions. Maybe it is wise for global climate policy to be adapted to the differences between countries, and even to exploit these differences in order to achieve more. An example can illustrate this last point: Saudi Arabia is no fan of global climate agreements that could bring down oil prices, but it is still planning to build 25 GW of concentrated solar power (and 16 GW PV) by 2032. A focus on concentrated solar power could provide an important contribution to further developing this technology. For Saudi Arabia, this may be viewed as a long-term effort to exploit a national resource (vacant desert land with a surplus of sun), and a contribution to diversification of the country's economy and energy supply.

6.1.1 COUNTRIES THAT LEAD THE WAY MAKE OTHER COUNTRIES DO MORE – GRADUALLY

Ambitious climate efforts in a country or a group of countries may contribute to other countries doing more. This can take place in several ways:

- Research, development and construction of new solutions provide learning effects and economies of scale that make emission reductions cheaper in the long run.

- Countries investing in early efforts develop knowledge of suitable organisational models, measures, market design, etc. This knowledge lowers the cost of climate policy for the countries that follow, since they can then design an effective policy more easily. It may also be easier to gain social acceptance for reforms that promote efficient use of resources (cf. removal of subsidies for fossil energy and introduction of congestion charges) after other countries have paved the way.

- Countries that make a greater effort may also *inspire* other countries to increase their efforts. There are many indications that policy is somewhat contagious. A country's policy is obviously affected by its financial interests, but it can also be affected by other motives and a sense of global responsibility. Much of the actual climate policy we observe would be hard to explain based *solely* on financial self-interest. Many actions will be motivated by a moral responsibility for the future. At the same time, it is probably easier to appeal to a sense of moral responsibility when several other countries are also doing something. Many countries who are implementing voluntary climate measures might not bother if they were the only country doing anything.

The fact that increased efforts in one country encourage other countries to do more is a good argument for increasing our efforts. If, for instance, increased efforts by our country now – via the mechanisms above – resulted in an equal increase in emission cuts in other countries, our efforts would have twice the effect on the climate.

Denmark was a pioneer in the development of wind power. The emission reductions that occur because Denmark accelerated the global development of the wind industry by several years could – over time – be many times greater than Denmark's total greenhouse gas emissions.

As we saw in Chapter 5.6, people and institutions learn slowly, even when it would *clearly be in their own interest* to change their behaviour, and for various reasons, some will learn more slowly than others will. When some countries or states are early in developing good institutional solutions and cheaper technology for emission cuts, it becomes easier for more hesitant parties to make quick emission cuts when they understand the need for change.

Emissions outside the OECD are growing quickly because of high economic growth. China now has higher emissions per capita than the EU. The EU's emissions of greenhouse gases represent less than 10% of global emissions. Based on this, it has been pointed out that even if the EU were to cut emissions to zero, global emissions could continue to grow. Technically, this statement is true, but you could say the same of China, the US, India or any other country. In order to reach the goal, every country has to be part of the change – even if it happens at different paces.

Emission reductions in the EU are obviously important. But perhaps the EU's most important contribution is to be a role model in climate policy. The EU as a whole can contribute globally by developing good models for cooperation and market integration within energy, and in a number of other areas. And the EU can contribute by developing and improving climate technologies that other countries can use later.

Denmark was important for the development of wind power. As pioneers and role models, even small countries can be important. Germany and some other countries have had a very important role in bringing down the cost of solar panels. Now these technologies are expanding globally. Still, it is of course desirable to establish international cooperation to expedite the development of knowledge and bring costs down faster.

6.1.2 A STRATEGY THAT FOCUSES ON BOTH TECHNOLOGY DEVELOPMENT AND EMISSION CUTS IS MORE ROBUST

In order for our climate policy to succeed, it is necessary to work both for binding agreements regarding emission cuts, and for ambitious international cooperation to develop technology and other relevant knowledge. In the debate regarding international agreements, much attention has been given to emission reductions, but probably not enough attention has been given to the need for a radical increase in work to develop the necessary technology and knowledge.

Perhaps some – both economists and others – have thought that *if* we establish binding agreements that effectively limit emissions and give high carbon prices, this will ensure the necessary technology development. Such a strategy poses two challenges:

- It is difficult to achieve an ambitious, binding agreement regarding emission cuts, especially if the necessary technology for cutting emissions does not exist, or if it is very expensive.

- Carbon pricing is not the most effective catalyst for technology development. A binding international agreement regarding emission cuts, and a common carbon price, will not give an optimal level of technology development (and other knowledge). (See Chapters 3 and 5.)

A strategy that promotes ambitious cooperation on technology and knowledge, as well as binding emission cuts, will be more robust than an agreement that only emphasises emission cuts. Jeffrey Sachs, a professor of sustainable development, noted columnist and special advisor to the UN Secretary-General, has spoken in favour of much greater emphasis on development of new technological solutions:

> *"The world needs a concerted push to adopt to low-carbon electricity, not another "us-versus-them" negotiation. All countries need new, low-carbon technologies, many of which are still out of commercial reach. Climate negotiators should therefore be focusing on how to cooperate to ensure that technology breakthroughs are achieved and benefit all countries.*
>
> *They should take their cue from other cases in which government, scientists, and industry teamed up to produce major changes. For example, in carrying out the Manhattan Project (to produce the atomic bomb during World War II) and the first moon landing, the US government set a remarkable technological goal, established a bold timetable, and committed the financial resources needed to get the job done. In both cases, the scientists and engineers delivered on time.*
>
> *The example of atomic bombs might seem an unpleasant one, yet it raises an important question: If we ask governments and scientists to cooperate on war technology, shouldn't we do at least the same to save the planet from carbon pollution?*
>
> *In fact, the process of 'directed technological change,' in which bold objectives are set, milestones are identified, and timelines are put into place, is much more common than many realize. The information-technology revolution that has brought us computers, smart phones, GPS, and much more, was built on a series of industry and government roadmaps."* (Sachs, 2014)

It is often highlighted, and rightly so, that climate goals could be reached using currently available technology. It is for instance possible to create a power system without carbon emissions using today's technology, but in many countries, the costs of doing this would be *very* high. In many other areas, too, the alternative to ambitious technology development would be expensive solutions and/or significantly changed consumption patterns. Lifestyle changes are possible, and in some areas, it is likely that such changes will be necessary, but it will be easier to involve more countries in ambitious climate policy if the costs and requirements for change are lower.

The temptation to deny the climate problem or use other arguments to shirk responsibility is lessened when the cost of change goes down. A sufficient fall in cost would make a number of climate measures *commercially viable* in many countries, even without a climate policy. Further cost reductions for solar panels would for instance make them profitable to a greater degree and in more areas.

6.1.3 ALLIANCES OF COUNTRIES WITH POWER TO ACT AND THEIR OWN NEEDS FOR NEW SOLUTIONS

Coordinated efforts to develop new solutions may be crucial to climate policy success. But how can we make these efforts happen? Won't we face the same problem of freeloaders in this area?

In most countries, energy and climate policies have been designed with many different aims in mind. Among these aims, we find a desire to strengthen national industry and employment, reduce imports of fossil energy, increase security of supply and reduce local pollution.

In order to strengthen security of supply, many countries want to limit their dependence on oil and gas imports by developing national energy resources. In the EU, the crisis in Ukraine and increasing Russian patriotism have become an argument for increased energy efficiency and further development of renewable energy. This will reduce imports (the EU imports fossil energy for €400 billion annually) and provide more jobs within the EU. Some countries may also want to be among the first to develop future-oriented industry which could become highly profitable as more countries start to reduce emissions. In some countries, the desire to develop alternatives to nuclear power is also an important motive for developing new solutions.

In many areas, especially in cities in emerging economies, air pollution from coal power plants and traffic is a serious threat to life, health and well-being. This issue is an important driver in changing the energy system in China and a number of other countries. When cities grow, air pollution becomes a bigger issue because more activity means more emissions in the same area, and because the emissions affect more people. In addition to the fact that the problem is increasing, economic growth will create a stronger preference to prioritise measures against air pollution. All this motivates intensified action against air pollution in such areas in the future.

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47 An example: Since the 1970s, little Denmark has served as an important pioneer in developing wind power and bringing it to its current technological level. Their focus on wind power was motivated not least by a desire to limit their dependency on imports of fossil energy. In the 1970s, Denmark had power plants based on imported oil. The price shock during the oil crises and their experience that fossil energy supply actually can fail, probably served as an important mental backdrop for Danish energy policy. As time went on, it also became a goal to stimulate the Danish wind industry and the export opportunities thereof. In addition, there is an honest enthusiasm for limiting global warming.

Because various national goals affect policy design, it comes as no surprise that a number of measures do not appear to be cost-effective viewed from a climate perspective *alone*. But it is economically efficient to take all externalities into account, and it is legitimate and rational for a country to secure its energy supply against outages during crises.

To a large degree, policy based on complex motives has given us the solutions that have been developed so far.[47] Various national interests may act as *additional motives*, and encourage countries to bring about change and technology development they might not have invested in if they were only interested in global warming. In many cases, several countries will have shared interests. This can be used to stimulate cooperation to achieve faster, more comprehensive acceptance for new solutions. Here are some examples of possible alliances:

- Countries that depend on the import of fossil fuels, especially oil and gas, share concerns of high import costs and the security of supply.[48] These countries therefore clearly all share an interest in developing cheap alternatives to fossil energy. The large importers, such as the US, the EU, China and Japan have a large share of the world's industrial and research capacity, and therefore have good opportunities to develop alternative energy sources.

- Countries with serious pollution issues in related to traffic all have a need for transport solutions that do not emit harmful exhaust gases. Electrification of the transport sector may then be an important measure, especially when combined with measures to reduce emissions from power generation (coal power). These countries will have a common interest in developing better batteries and hydrogen solutions. They may also have shared interests in a number of other areas linked to development of infrastructure, e.g. wireless charging of batteries of electric buses at bus stops.

- Countries with cold climates and significant needs to heat up buildings have a shared interest in the development of cheaper, more effective measures for increased energy efficiency in buildings, more efficient and cheaper heat pumps, systems for exploiting solar heat where this is suitable, etc.

- Countries with hot climates and high prosperity have a shared interest in developing more energy-efficient air-conditioning systems and other solutions that reduce energy use and the cost of cooling.

- Countries with large resources of coal or gas may have a shared interest in developing CCS technology.

In some areas, interests may overlap. Measures to electrify the transport sector will replace oil with electrical power generation. This will then reduce the need to import oil. If the increased need for power is covered by nuclear power, renewable power or gas power, local environmental problems will be further reduced.

When some types of technology development offer clear national benefits to a country in addition to limiting global warming, the country in question will be willing to increase its efforts. Countries with particular needs and interests will therefore have an important role in the development of new solutions.

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48 The EU, the US, China, Japan, India and South Korea all import large amounts of oil. In the US, increasing unconventional oil production is likely to gradually reduce net imports.

Germany's decision to phase out nuclear power illustrates how *the political climate* in a country may also be a significant driver. Even though putting an end to nuclear power could result in higher emissions of CO_2 in Europe for a few years, it is still possible that the decision will contribute to *lower global* CO_2 *emissions* in the long run: Germany has set itself the challenging task of bringing CO_2 emissions down at the same time as eliminating nuclear power. This requires even more focus on renewable energy and improved energy efficiency. Germany has invested much prestige – politically and in other ways – in making this change a success. German energy restructuring has resulted in and will continue to result in significant learning effects, for technology and society alike. This learning will be important for other countries that follow.

Countries that may benefit from developing a new technology may be willing to put more on the line if a binding cooperation agreement has been established first. This is because the group as a whole will stand to gain more from the developments than one country alone. The free rider problem is reduced when the countries that stand to gain the most, cooperate.

Compared with climate negotiations that involve all countries, it may be simpler to arrive at an ambitious, achievable agreement with a smaller group of countries that have a clear shared interest in developing concrete solutions. Partners can vary depending on where expertise, opportunities and self-interest are greatest.

In many areas, wide-ranging international cooperation within R&D is already in place, precisely because countries recognise that they have shared interests and can achieve more through cooperation. *My point is that efforts should be stepped up dramatically*. In order to realise this, the significance of technology development and societal learning must be understood, both for solving the climate challenge and for achieving other advantages. To maximise benefits, efforts must comprise research and measures throughout the value chain, and should also include societal learning.

Different countries can be motivated to increase their efforts by combining their willingness to deal with the climate problem with their self-interest. To a large degree, it is a combination of such motives that has brought about the solutions that have been developed until now. But this needs to be systematised, more alliances need to be formed and efforts need to be intensified. Several factors are more favourable now, compared with 10 to 20 years ago: There are many more countries that have the research and industrial capacity to bring forth new solutions, and there is greater recognition of the seriousness of the climate problem.

6.2 Carbon leakage, cost-effectiveness and technology development

When a group of countries implements climate policy instruments such as a carbon price, this may contribute to increased emissions in other countries. This is referred to as carbon leakage. The possibility of carbon leakage has an impact on what is the most efficient design of climate policy instruments. In this area, too, concerns for technology development and other learning may play an important role.

6.2.1 THE CHALLENGES OF CARBON LEAKAGE IN INDUSTRY

This problem is first and foremost relevant to *energy and emissions intensive industry competing in the world market*. If a group of countries introduces a high general carbon price, it will weaken the international competitiveness of energy and emission intensive industry in the cooperating countries. This is because the energy price is driven up by the carbon price and because the industry has to pay for its own emissions. Over time, this industry may move to countries without a carbon price. In the worst case, the increase in emissions in other countries could be higher than the original cut in emissions. This may happen if the factories that are shut down have relatively low emissions and they are replaced by factories with higher emissions per produced unit. (Often, countries that introduce stricter climate regulations already have a history of environmental requirements and therefore a cleaner industry than countries with less stringent regulations.)

6.2.2 WHEN THE GOAL IS GLOBAL EMISSION REDUCTIONS, CARBON LEAKAGE MUST BE TAKEN INTO ACCOUNT

Let us begin with a calculation based on a simple set of assumptions: We will use carbon pricing as a policy instrument and ask how the carbon price should be adjusted for an industry that is vulnerable to carbon leakage. Assume that one tonne of reduced emissions in the countries affected by the carbon price will lead to a 0.6 tonne increase in other countries. Each tonne cut because of the carbon price will then result in a global *net* reduction of 0.4 tonnes. What, then, is a cost-effective carbon price for this industry?

If we are only interested in the emission reduction within the regulated area, carbon leakage does not matter, and an equal carbon price would be cost-effective. But is there a good reason to have such a goal and ignore global emission effects, when it is global emissions that really impact the climate?

If the goal is global emission reductions, the answer is that it will be cost-effective (based on our current, somewhat simplified assumptions) to give the industry in question a carbon price which is 40% of the carbon price we use for measures that do not result in carbon leakage. Then, a one tonne reduction in *global* emissions within the industry in question will be valued as highly as a one tonne reduction in emissions elsewhere in the group of countries that have carbon prices, and an efficient market will implement the cheapest measures.

6.2.3 WE CAN ACHIEVE MORE WITH SMARTER POLICY INSTRUMENTS

The example above is too simple. It does not take into account learning effects that can be spurred by measures other than carbon pricing, nor does it take into account the effect the measures may have on other countries' willingness to take on climate commitments.

For an energy and emissions intensive industry that manufactures products necessary for a sustainable world economy, e.g. aluminium and silicon, the key goal is to *develop production technologies that reduce emissions per manufactured unit and which increase energy efficiency*. We can encourage this through a suitable design of measures.

Development and testing of new technology in an industry is often linked to new investments or large re-investments. The industry will not invest if it does not believe that the long-term framework conditions are acceptable. Threats of high carbon prices in cooperating countries (e.g. the EU) and an absence of other incentives, could, at worst, weaken the rate of innovation in the industry.

When there is a risk of carbon leakage, we should choose a set of measures that spur emission cuts and technology developments without increasing the total cost level for the industry. *The key is to use both a carrot and a whip.* Here are some examples of possible measures:

- Favourable financial framework conditions could be combined with binding agreements of long-term reductions in emissions and improved energy efficiency. This could for instance take place in close interaction with research institutions and be linked to goals of specific improvements in technology and practice. Loans and funding for development and testing could be part of the measures.

- Mechanisms could be created that reward those companies in the industry that are better than average (in the countries cooperating on climate policy) and punish those that perform below average. Thus, a general incentive for improvement is provided without increasing the total cost level of for the industry. In a system with emission quotas, free quotas could be issued, perhaps combined with other measures.

- If a climate policy combines carbon pricing, support for increasing energy efficiency and development of renewable energy, the result will be a lower price level for power than if only carbon pricing is used to reach the same emission target. (The EU 2020 goal works this way.) A lower price level reduces the risk of carbon leakage, but this price level will also apply to consumption that is not vulnerable to carbon leakage. It may be more effective to have a higher carbon price that gives clear price signals in the power market, and develop special policy instruments that shield vulnerable industry from the cost effects of the climate policy.

Other countries' willingness to take on climate commitments can be influenced in two ways

- If a group of cooperating countries use high carbon prices for all emissions, this will ultimately increase the costs of their energy- and emission intensive industry. Some of the increased costs may be transferred to the world market price of the commodities. This makes it (slightly) more profitable for other countries who manufacture the same commodities to stay out of the climate cooperation. This effect is perhaps not a major one, but in any case it should be avoided. This can be achieved by using policy instruments like those I have described above.[49]

- Technology policies that make it cheaper to reduce emissions in the industry reduce the cost of joining ambitious climate agreements. In those gratifying cases where new solutions with lower emissions are cheaper than the old, polluting ones, the improvements may also spread to countries that are not part of a climate agreement.

49 Some have also suggested using import taxes for goods that have not been made according to environmental and climate requirements similar to those of a group of cooperating countries. As the name import tax implies, this is primarily applicable to emissions intensive products that the cooperating countries are the net importer of.

6.2.4 WE MUST TAKE THE DANGER OF CARBON LEAKAGE SERIOUSLY

Carbon leakage in the industry is primarily a problem associated with energy and emissions intensive industries. Still, it is important. Climate policy is more cost-effective and more powerful when we take into account the danger of carbon leakage.

Above, I have suggested some possible ways of dealing with the challenges of carbon leakage. These measures are already in use to some degree. Through research and testing, it will be possible to improve our understanding of what will lead to the best result. We need learning processes in this area too.

7. CONCLUSIONS

7.1 Climate policy is a restructuring project and a global learning process

Greenhouse gas emissions must be cut to almost zero (or perhaps become negative) by the end of this century. Climate policy must be viewed in light of the long-term goals and the need for developing new technology, new organisational models and a new understanding in the public mind.

Some important climate technologies have made great advances, but in order to succeed, many new solutions need to be developed. This requires radical acceleration of technology development and societal learning.

We must create an energy system that is both emission-free and robust. In order to gain broad public support for restructuring, costs should also be moderate.

It is wrong to view climate policy as a series of stand-alone measures in a static world. Climate policy must be viewed as a restructuring project involving a global learning process. From one day to the next, society may seem not to change at all. But looking back a few decades, we realise that technology, organisation and attitudes have changed considerably.

7.2 Two important challenges (market imperfections)

1. Those who emit greenhouse gases do not (usually) pay for the damage they inflict on others.

2. Those who develop new climate solutions only receive a limited share of the benefit their solutions offer the world at large. To a great extent, knowledge benefits everyone.

(In addition to these two general market imperfections, there are several others in connection with the way different markets work.)

The solution to the first market imperfection (1.) is to subject consumers, companies and states to a sufficiently high emission charge or an emission limit, so that they actively reduce their emissions.

The second market imperfection (2.) means there is not enough development of new technology and other knowledge that could contribute to emission reductions. The climate problem is global and will last a very long time. Its enduring nature gives us time to develop new knowledge. The severity and global nature of the problem makes development of better knowledge highly beneficial to the global society.

Countries and groups of countries can stimulate technology development and other learning through comprehensive research programmes and by initiating expansions that will spur innovation and economies of scale.

Through a gradual increase in production, many products see a large drop in costs, but many years' development is often required before the products become competitive with established solutions. Even so, such knowledge development can be highly profitable in a global context because the solutions can be used so widely and be significant for many decades.

It is important that we now start to develop solutions that we will need to a great extent after 2030.

Since countries that finance the development of knowledge only reap a limited share of the rewards, not all problems will be solved by the governments in each country tackling the challenge. Two factors can help bring efforts up to desirable levels:

1. If groups of countries with industrial and research capacity invest together as a team, it may be easier to mobilise the necessary resources. As a group, the cooperating countries will reap a much greater share of the benefit than one country alone would be able to.

2. In many cases, it is in countries' own interest to develop specific solutions that promote climate goals as well as other goals. (For instance reducing local pollution problems.) Alliances of motivated countries can be very powerful, even if they only include two to four of the most important countries within an area. Not having to include all countries might simplify negotiations and cooperation.

Increased efforts for knowledge development make it cheaper to reduce emissions. This will in turn lower the threshold for participating in binding climate policy. When some solutions become so cheap that they are profitable regardless of climate policy, the stage is set for everyone eventually starting to use them. But of course, the best thing would be widespread acceptance of ambitious climate policy, so that emission-reducing solutions were adopted in all countries even before they are cheaper than the old polluting solutions.

7.3 We learn slowly

Experience shows that we learn slowly, both as individuals and as societies. But we are quicker to adopt new ideas when others have shown that they work. As the examples of subsidies for fossil energy and congestion charges show, it can take many years to develop a policy that promotes cost-effective solutions. When someone leads the way and puts new solutions to the test, others can learn from them later on. It is easier to argue for reforms when there are successful examples to refer to. Pioneers lower the costs for those who follow. *Success breeds success.*

The fact that we are slow to learn also means that we as a society are too slow in taking climate issues seriously and taking adequate action. This has implications for deciding on the best strategy.

- When many countries are slow to act, it is all the more important that others initiate time-critical processes by developing new technologies and other tools for emission reductions. As more countries become ready to act, the tools are available.

- As the climate challenge gradually sinks deeper into people's consciousness, it may become easier to gain acceptance for high carbon prices and other measures that stimulate changes in behaviour.

7.4 The energy sector must be restructured based on a long-term perspective

Reductions in emissions and energy use are often linked to upgrading of physical capital. When we construct new buildings, power plants or transport solutions, or refurbish them, we must choose solutions that are compatible with reducing emissions to close to zero in the long-term. Investments that commit us to high emissions for many years will increase the cost of future emission reductions since it is expensive to replace infrastructure before the end of its planned lifetime.

While solar power and wind power continue to improve, there is a need for other types of emission-free power generation to ensure supply when there is little wind and the sun has gone down. There is a also a need for increased flexibility in power consumption and generation, better solutions for storage of power and energy, a stronger grid and efficient market solutions to enable resources to be utilised efficiently across countries and sectors. All these things require long-term planning, coordination and development of new knowledge, including acceptance of the new solutions in the public mind.

Comprehensive electrification in the heating and transport sector is important, both to promote a robust energy supply and to bring down the emissions of *all* energy use: At the same time as emissions in the power sector are being reduced by development of emission-free (renewable) power generation, electricity must increasingly replace fossil energy in the heating and power sector. The heating and power sector can buy large amounts of power when there is a surplus, and to some extent feed power back into the grid when power is scarce. In this way, electrification of these sectors will contribute to stabilising the power system and reducing emissions.

In order to reach the emission reduction targets in a cost-effective manner and on time, electrification of the heating and transport sector must take place in parallel with emission reductions in the power sector. Increased energy efficiency, bioenergy, emission-free power and hydrogen from power are the tools needed to eliminate emissions from the whole energy sector.

Even though it seems clear which direction the energy system will develop in, there is great uncertainty regarding which technologies will be most successful, and what will be most profitable in the long run. It is important to plan long-term investments in light of this uncertainty, but high uncertainty could also lead to investors being too cautious. We will not reach the goal if we all wait for everyone else. It is important that authorities give clear directions so that we can avoid unnecessary waiting.

7.5 Carbon pricing is important, but must be supplemented with other measures

Carbon pricing gives incentives to reduce emissions from production throughout the value chain, as well as by changing consumption patterns so that products associated with high emissions can be replaced by products linked to lower emissions. Carbon pricing may also to some degree stimulate innovation. But carbon pricing has several limitations that mean we need additional measures in order to make powerful, cost-effective climate policy a reality.

- *Carbon pricing does not create enough knowledge development because knowledge is to a large degree a public good.* Carbon pricing is a general instrument and is unable to distinguish between mature technologies without much learning potential and technologies with great potential for learning and cost reductions. This weakness is general and therefore also applies to an ideal world with a global carbon price, perfect markets and rational authorities.

  When the goal is to develop specific technologies, such as offshore wind power, carbon pricing is imprecise and unsuitable. Direct funding for the technologies we want to see developed may provide sufficient profitability to allow development to begin. At the same time, funding can be lowered for new facilities as costs fall. Auctions are also an option. Such measures provide greater security for investors and greater flexibility for authorities.

- *High hurdle rates in the industry pose challenges.* There is reason to use a relatively low required rate of return when considering climate measures, maybe in the range of 2-3%. Business and industry operate on much higher required rates of return and for this reason, will respond little to carbon prices in the distant future. We need measures that compensate for this, e.g. funding for the development of renewable energy.

- *Regulatory uncertainty with regard to future carbon prices* (or other policy instruments) weakens the industry's willingness to undertake long-term investments. A high level of trust is crucial if carbon prices are to function as an instrument for long-term change. The dramatic drop in the quota price in the EU (EU ETS) in the last years illustrates the uncertainty that a quota market sometimes brings with it. *A system of minimum prices for quotas offers less uncertainty.* Reduced uncertainty provides more stable change and restructuring. This lowers costs.

- *When only some countries use carbon pricing,* energy and emissions intensive industry in these countries could be shut down and replaced by comparable (and possibly more polluting) industry in countries without similar climate policy. When an industry makes products that we need in a world wanting to reach the two-degree target, our most important goal should be to encourage the industry to d*evelop new solutions with significantly lower emissions and energy use.* This can be achieved by employing a set of measures that support innovation and reward emission cuts without weakening the international competitiveness of the industry.

- *Several factors could contribute to the carbon price becoming lower than is desirable.* Such factors could for instance be the danger of carbon leakage, concern regarding the effects on income distribution or tax conservatism. *When the carbon price cannot be lifted as much as we would like, other measures should be brought in as a supplement to achieve the best possible result.* Examples of other measures are funding for emission-free energy, extra measures to promote increased energy efficiency or direct regulations, e.g. to prohibit new coal power plants or require permanent shutdown of existing ones. When carbon pricing is limited by *transient* factors such as tax conservatism, efforts can be spent on strengthening supplementary measures in the short-term as well as on increasing carbon prices over time.

7.6 Six points for efficient, necessary innovation

(1) Markets have a limited ability to lift long-term technology development. Mariana Mazzucato has demonstrated the great significance of long-term, ambitious, governmental-financed research for the development of technologies within ICT and medicine. When developing radically new solutions, there is often a need for a lot of public funding because the industry's perspective is too short-term, and it requires too high returns. The industry can play an important, creative role in developing new products and solutions, but this often takes place in a context where results can be obtained quickly, e.g. because the governments have created demand for new solutions. Long-term public financing of research programmes does not preclude constructive interaction with affected industries throughout the process.

(2) It is important to start production and implementation of new technological solutions even if they are expensive to start with. Production and use provide practical experience, throw up new challenges and inspire further research. When production grows, innovation is encouraged throughout the value chain and benefits from economies of scale start to emerge. The fact that the cost of solar panels has fallen by 99% in 35 years and may continue to drop, is due to improvements in solar cell technology itself, as well as improvements in each part of the value chain, including streamlining of production and installation. This progress would hardly have been achieved unless some countries, especially Germany, had led the way and developed the solar panel market.

(3) We must promote broad societal learning in connection with general climate policy and the use of policy instruments. Both market design, the design of policy instruments and institutions involves a learning process with interaction between theory and practice.

(4) No country will accept lower security of supply where power and energy are concerned. Therefore, a set of solutions must be developed to ensure the energy and power system can be both emission-free and robust. This will require a comprehensive, long-term perspective on developing the system.

(5) It is important to consider what kind of development strategies could lead to the lowest total cost. An important issue is finding an optimal balance between pure research efforts and deployment with associated innovation. Another challenge is that of starting development first in areas where the need for funding is smallest. This must be weighed against lost time if the areas with the most favourable conditions are too slow to act. It would have been cheaper to start development of solar panels in a country that gets more sun than Germany, but waiting a long time for this to happen would have meant a loss.

(6) Learning and development take time. In a number of areas, it is important to start the development of new solutions quickly so that savings can be made later. It is also important to allow time to gain experience and improve solutions before too much deployment takes place. These points indicate that it is important to make an early start on developing the solutions that we will need years or decades from now. In particular if the climate challenge proves even more serious than is currently thought, having started early on developing the necessary tools to bring down emissions will prove very valuable.

We are not used to thinking as long-term as is necessary to meet the climate challenges, either as individuals or a society. Now we have to learn.

APPENDIX 1: MORE ON CARBON PRICING

The effect of equal carbon prices is illustrated in Figure A1.1. Here, we examine the cost of emission reductions in two sectors. Each column shows the cost of a single measure within the sector in question. We assume that each measure will result in the same reduction in emissions. The measures are shown from lowest cost (left) to highest cost (right).

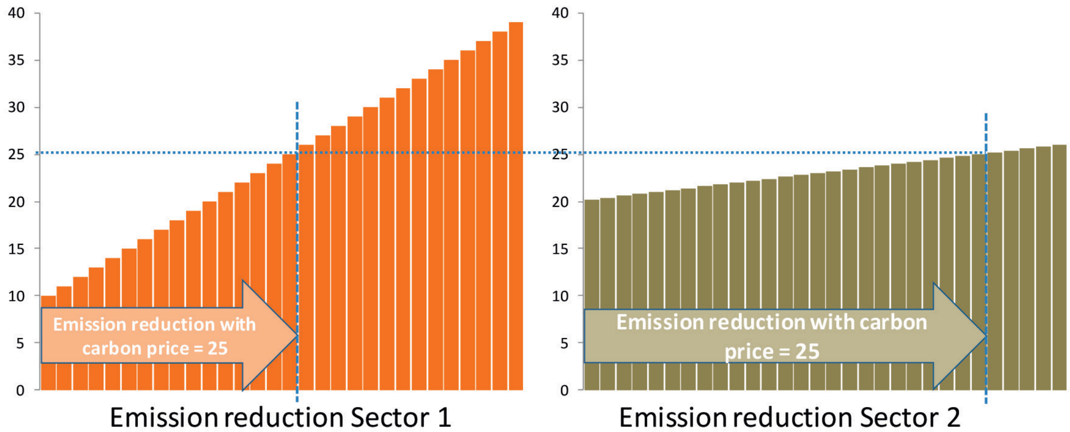


Figure A1.1 Cost of emission-reducing measures in two sectors, and the emission reduction with a carbon price equal to 25. The Y axis shows emission costs (carbon prices) and the cost of measures

If an emission-reducing measure costs less than the carbon price, it will be profitable for the company or consumer to implement the measure. The figure shows the extent of reductions each sector will implement if the carbon price is 25. A higher carbon price will make both sectors reduce their emissions further. If the carbon price rises above 27, all possible emission cuts in Sector 1 will be made. If, however, the carbon price stays below 20, no emission cuts will take place in this sector.

If the most expensive measure to be implemented (the marginal measure) in one sector costs more than a possible measure in the other sector, there is money to be saved by *swapping expensive measures for cheaper measures.* If the carbon price was for example 40 in Sector 1 and 22 in Sector 2, the total emission reduction in the two sectors would be the same as if the carbon price was 25, but in this case costs would be 17% higher in our example. The marginal measure in Sector 1 costs 40 in this example, while the marginal measure in Sector 2 only costs 22. Increasing measures in Sector 2 and reducing them correspondingly in Sector 1, will result in a saving of 18 for the first measure swap (40 – 22). Thereafter, transfer of emission cuts from Sector 1 to Sector 2 will gradually result in fewer savings, until there are no more savings to be made, as the most expensive implemented measure in each Sector has the same cost.

The reasoning above may be applied to any two sectors. *This means there is a cost-effective emission reduction when the marginal cost of emission reductions is the same in all sectors and in all countries.*

In reality it may not be possible to implement all cheap climate measures, for instance because some countries refuse to participate in climate agreements. Even so, we must aim to contribute to cost-effective implementation of climate measures as far as possible. The best combination of measures will be characterised by its *feasibility* and an ability to minimise the costs of a long-term reduction goal.

When searching out the most cost-effective combination of measures, it is important to include all relevant external effects, not just climate effects. Other relevant effects may be local and regional environmental problems (negative external effects) and the cost of immature technologies falling as a result of more widespread use (positive external effects). It must also be taken into account that when not all countries cooperate on climate policy, carbon pricing may force emissions intensive industry competing in the world market to move to countries without carbon pricing. This type of carbon leakage would mean that equal carbon prices do not result in a cost-effective reduction of global emissions. (Read more about this in Chapter 6.2.)

APPENDIX 2: MANY POSSIBLE SOLUTIONS

In this appendix, I will outline solutions that may contribute to *more even emission-free power generation* and solutions that may offer more *flexibility*. Coupled with a stronger grid connecting regions and countries, these solutions can create a robust, emission-free power and energy system. This appendix especially expands on Chapter 4.2.

The goal of this appendix is to shed light on

- *The range of possible solutions* that can be developed
- *The uncertainty* regarding which solutions will ultimately be the most profitable
- *The need for R&D and support* for extensive deployment of new solutions

A2.1 Challenges of variable renewable power

A2.1.1 FOSSIL POWER CURRENTLY ENSURES A BALANCE

In nearly all power systems, coal and gas power ensures the balance between consumption and generation. Almost all emission-free power sources are less flexible than fossil power, and wind and solar power, as we know, vary significantly over time.

Most of the costs of solar and wind power are related to upfront investment, while actual power generation is close to cost-free. Such facilities will therefore usually generate as much power as the weather and installed capacity allow.

The fixed costs of nuclear power are also high, while generation costs are low. It is therefore economic that such facilities run most of the time. Coal power plants with CCS will also have high fixed costs. For such power plants to have a chance at becoming profitable, they must generate power and make money most of the time.

Within emission-free power, solar power and wind power are expanding the fastest in Europe and many other places in the world. As we saw in Chapter 4.1, the costs of these technologies have fallen significantly, and they are likely to fall still further. It is therefore logical to focus on the challenges related to a fast development of solar and wind power. The discussion below is based on this, but it will also be relevant to countries focusing more on nuclear power.

A2.1.2 SIGNIFICANT VARIATION IN THE TOTAL GENERATION FROM SOLAR AND WIND POWER

Figure 4.3 shows how total power generation from wind and solar power for most of the EU/EEA area may vary over time in a possible future scenario.[50]

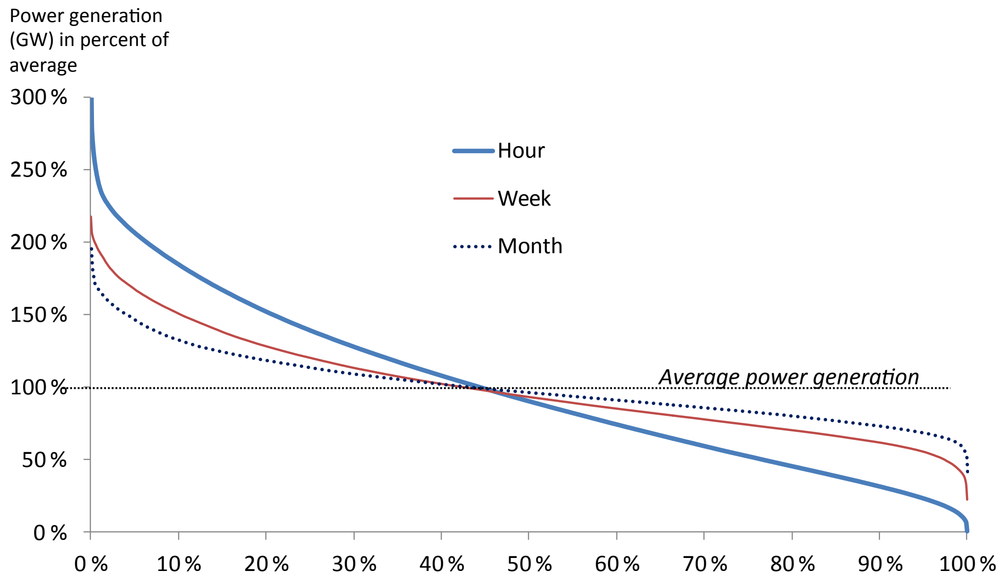


Figure A2.1 Variation in total generation from wind and solar power (y-axis) in the simulated area per hour, week and month, compared with average generation (100%).
Source: Statnett and Kjeller Vindteknikk

The figure shows that it is not only the sum of solar and wind power per hour that varies. Total power generation *per week* and *per month* also vary considerably. In the simulation, *annual* power generation varied by +/- 14% compared with the average.

We can see from Figure A2.1 that there are hours where total solar and wind power generation throughout the area is almost zero. This will typically be periods of low wind during the night. There may also be periods of minimal contributions from both solar and wind power during the daytime in winter, while power consumption in Europe is high. There will also be weeks and months where power generation is below half what it usually is.

If the simulation were to include Spain, Portugal and the Balkans, possibly even countries further east or in North Africa, production patterns for wind and solar power would be somewhat more even, but there would still be periods when solar and wind power had relatively low performance.

Building a stronger transfer grid in Europe will make it possible to even out some of the local variation in solar and wind power. A stronger grid also enables better utilisation of local renewable resources: Some areas are more suitable for solar power, and it will therefore make sense to build larger amounts of solar power in these places. Other areas have especially

50 The figures are based on a weather conditions 1950-2012. The following countries were included: Poland, Germany, Austria, Switzerland, Czechoslovakia, Italy, France, Belgium, The Netherlands, the United Kingdom, Norway, Sweden, Denmark, Finland, Estonia, Latvia and Lithuania. The simulation looks at total power generation from PV and wind power in 2030, in all 443 GW installed capacity. The portfolio includes 42 GW of old wind power, 142 GW of new wind power, 62 GW of offshore wind power and 197 GW of PV. New wind power generates more evenly than old wind power, and offshore wind generates even more evenly, because wind conditions offshore are more stable. Source: Statnett and Kjeller Vindteknikk.

favourable conditions for wind power that could be developed extensively given access to the market. The benefit of connecting different geographical areas obviously also applies to other types of variable renewable power generation such as hydropower, wave power, etc. In the Nordic power system annual inflow to the hydro power system may vary by more than +/- 25%. In years with large power surpluses, exporting power is a good way of utilising it, while import ensures supply in years of low precipitation and a local power deficit. The benefit of developing transfer capacity must of course be compared against the costs.

The fact that total wind and solar power generation varies significantly across weeks and months, means that there is a need for many different solutions in order to balance consumption and generation. While a local battery or moving consumption to other times can help significantly in dealing with short-term variations, other measures are necessary in order to meet larger, longer term fluctuations in the power supply.

A2.1.3 ILLUSTRATION: THE SIGNIFICANCE OF INCREASED TRADE AND A VARIED PORTFOLIO

Figure A2.2 shows an imagined duration curve for consumption minus variable renewable power generation, with different levels of penetration of renewable energy. In the first instance, there is little development of renewable power. The solid blue line shows consumption minus this renewable power generation. The figure illustrates two different ways of developing more renewable power generation. With both alternatives, the same amount of emission-free power is developed, to a level where the total emission-free power generation is equal to total power consumption.

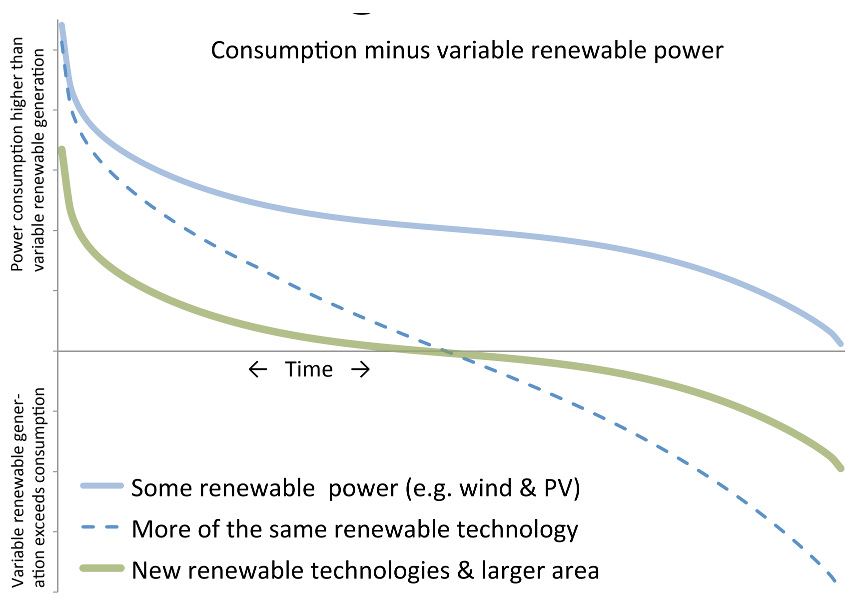


Figure A2.2 Duration curves for consumption minus intermittent renewable power generation (y-axis)

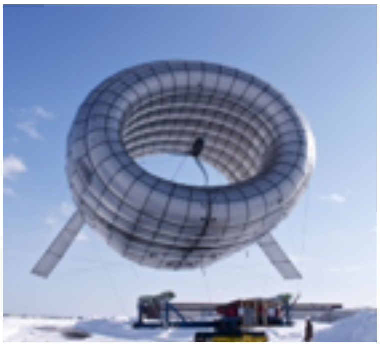
With the first alternative, illustrated by the dotted line, you build *more of what you already have, without connecting additional areas/countries*. The new renewable power generation will then follow the same production pattern as existing renewable generation. In this case, the need for fossil capacity to cover consumption peaks will not be significantly reduced, and half the time, there will be a large power surplus going to waste.

With the second alternative, illustrated by the green line, you develop new renewable power where the production pattern does not correlate as strongly with the old production, and larger areas are connected. It is better if the production pattern of the new power is *negatively correlated* with the production pattern of the old production and *even better if it is flexible*. This will make the curve for consumption minus emission-free power generation flatter, as shown in the figure.

The flatter green curve has the same amount of renewable power generation as the dotted line, but its power generation is better suited to consumption. (Adjusting consumption to power generation is also a possibility – see below and Chapter 4.2). Hence, in this case there is less need for reserve capacity (e.g. fossil power) and less power will go to waste, which it will do if sufficient demand for the power surplus is not found. In the rest of this appendix, I will review a number of possible solutions and technologies which can help us to create a balance between power generation and consumption in an emission-free power system. I have divided the contributions into two main categories: *Contributions to more stable emission-free power generation* and *New contributions to flexibility*.

A2.2 Contributions to more stable emission-free power generation

Offshore wind power offers more stable power generation than onshore wind power, because wind is more stable at sea. It is also an advantage to bring in wind power from further away than what is possible if development is limited to land areas. Currently, however, fixed-bottom offshore wind power is significantly more expensive than onshore wind power. Floating offshore wind power is in very early stages and may provide opportunities for power generation in areas that have deeper water and good wind conditions. In this way, wind power generation might be possible in a much larger area. It may also be possible for floating wind turbines to be built even bigger than turbines fixed to the bottom. In the longer term, these *might* provide cheaper wind power than our current concepts. But such a situation is currently a distant dream.



Wind turbines held high in the air by helium-filled "donuts" [51] (see picture) may in the future deliver cheaper and more even power generation, since the wind is stronger and more stable higher up. Such solutions and solutions involving floating wind turbines are currently at the stage that onshore wind power and solar cells were a few decades ago, but still they may *become* important in the longer term.

Power generation from ***tidal water*** is predictable and

51 This picture is taken from http://www.altaerosenergies.com/, which is behind the project and has more information.

independent of wind and weather, and power from ***osmosis*** *(salinity gradients) and* ***ocean currents*** can be completely stable. Currently, such solutions are immature. Power from the abovementioned sources may become important in some areas where access to resources is good. Wave power may also provide more stable power production than wind power.

Run-of-river power often provides relatively even generation over the course of 24 hours or somewhat longer periods, but may vary over longer time spans based on precipitation and season. Hydropower with *reservoir* can save water when there is a surplus of other power production and deliver more power when it is needed. (You can read more about this under flexible power production and storage below.)

In countries where there is a lot of sun, **concentrated solar power** can contribute to more stable power generation than solar cells. Such facilities concentrate rays of sun using many mirrors and reach a very high temperature at their core. The heat helps to produce power by means of steam turbines, somewhat similarly to traditional thermal power plants. Since a lot of heat accumulates in the core, the facilities can continue to generate power for a certain amount of time after the sun has gone down, and they can also be regulated in the short-term. Spain is leading in this area, with 2200 MW installed, and further growth is expected in several countries. Better heat storage facilities are under development, to make this technology cheaper and more flexible. Saudi Arabia is one of the countries wanting to focus on this type of solar power. It plans to build 25 GW of concentrated solar power and 16 GW PV by 2032.

Geothermal power uses high temperature heat from the ground to produce thermal power. Such power production has been competitive for many years in areas where the earth's crust is thin (so-called hot spots), i.e. where the temperature in the ground rises quickly with increasing depth. These power plants can produce evenly, and have some ability to regulate their power generation.

The costs of deep drilling have dropped considerably, particularly due to technology developed for drilling in the petroleum sector. In order to succeed with geothermal power outside the so-called hot spots, it is crucial to further reduce the costs of deep drilling and preferably also increase the percentage of the heat that can be converted into power. Profitability will also improve if more value can be obtained from the remaining waste heat. Globally, there is approx. 12 GW installed geothermal power and growth has been 4-5% per year. Since geothermal facilities run relatively evenly, 1 MW of geothermal capacity will provide 6-8 times the power generation (MWh) of 1 MW of solar cells and more than twice the power of 1 MW of wind power. See Cichon (2014) for a short overview of the status of geothermal power.

In many cases, the waste heat from fossil power generation is used for district heating or for industrial purposes. As and when fossil power generation is replaced by emission-free alternatives, it may be possible to use geothermal energy to provide both power and heat in some places. If the temperature from the ground is not high enough, it may still be possible to cover the need for heating, perhaps using heat pumps for support.

Biofuels in different forms are already being used to generate power. For many types of biofuels, the percentage of energy which becomes electricity is relatively low in relation to the percentage of waste heat (low electrical efficiency). Such facilities are therefore most profitable where a combination of heat and power (CHP) can be delivered. The facilities will generally generate power during periods when there is also a need for heating. In many countries, the need for heating is greatest at the same time of year as power consumption is highest.

Building larger *heat storage* facilities (e.g. a large water tank) makes it (partly) possible to separate in time the supply of power and the supply of heating. One can generate power when power prices are high, and then later on deliver heating without producing power. These power plants can also be built so they can generate power even when there is no need for heating at all. This presupposes opportunities for getting rid of excess heat (cooling), such as traditional thermal power plants have. Such developments may be profitable *if power prices are sufficiently high during some periods*.

During periods when power prices are very low, CHP plants can be shut down and stored heat can be used, or electricity can be bought for heating purposes. (Cf. Chapter 4.2.5 which discusses interaction between the power and heating sectors.)

Biogas can produce power in a conventional (and flexible) gas power plant with high efficiency, but producing biogas in volumes similar to our current access to gas is unrealistic.

Examples of other renewable technologies being researched: wind power from a type of kite in order to harness energy from wind high up, electricity from differences in temperature (thermoelectric), harnessing power from river currents (without dams), and new concepts for harnessing energy from waves.

Not all these ideas will be successful, some may become highly significant, and others may only become significant in certain areas. Technological advances, cost reductions and public acceptance are all necessary in order for new solutions to succeed. Time and efforts are required. It is important to remember that in the 90s, many believed that wind power on land would never have any significance in the European power system. Wind power was thought to be too expensive, and there would never be enough to make a difference. Several experts also believed that the power system could only handle a very limited amount of wind power. But so far, developments in wind power have exceeded expectations.

Fossil power with Carbon Capture and Storage (CCS) is currently in the pilot stage, but may become an important source of stable power generation in some areas. Such facilities will likely contribute little to short-term regulation, and due to high fixed costs, they will be designed to run most of the time. CCS may also become important for *large industrial* CO_2*-emissions*, so there is reason to hope that efforts to reduce the costs of CCS technology are successful. In many countries, however, power plants that use CCS are strongly opposed, especially due to fears of CO_2 leaks. New coal power has relatively high capital costs and capture and storage of CO_2 makes these power plants even more expensive. It is therefore hard to believe that this technology might become very cheap. Gas or coal power that uses CCS *may* however become an important solution in areas of high power consumption that are far away from good renewable resources. There may also be other concepts for capture of CO_2. One alternative could be a process where methane gas (CH_4, the main component of natural gas) together with oxygen is converted into hydrogen and CO_2. The hydrogen could then be used to produce electricity in a vehicle/vessel or to deliver power to the grid while CO_2 can be stored in e.g. old gas fields. When generating power with hydrogen in fuel cells, the associated heat can be used for heating.

Nuclear power has been part of the power system in many countries since the 1960s. Nuclear power is controversial, and it is uncertain how many countries will want to continue to focus on nuclear power. If nuclear power is phased out and replaced by more variable wind and solar power, the need for new flexibility will increase.

New generations of nuclear power technology are being developed. These will have greater safety, far better utilisation of the energy in the fuel and significantly less radioactive waste. It appears that realisation is still a little way off.

Research has been going on for decades to achieve *fusion power*, which could provide almost unlimited amounts of energy. Even though there has not been a final breakthrough in this area, there has been clear progress, and a fusion reactor of 500 MW is currently being built.[52] Commercialisation is unlikely to take place before 2040.

Lockheed Martin said in October 2014 it had in developing a power generator based on nuclear fusion, small enough to fit on the back of a truck. However, the announcement was met with scepticism among other scientists.

It is unclear how much it costs to build and run a nuclear (fission) power plant based on modern safety requirements. There is also controversy concerning what level of cost one should associate with the risk of serious accidents. While some experts operate with a cost estimation of around €0.6/kWh for new nuclear power plants, the authorities in the UK have signed an agreement regarding the building of a new nuclear power plant where £92.5_{2013}/MWh will be paid for 35 years (the Hinkley Point C agreement). This is equal to approx. €0.11/kWh for 35 years. This high price has surprised many.

Prognos AG (2014) is an interesting analysis where the *system costs* of two alternatives, nuclear power and renewable power, are compared. The analysis describes a simplified system based on the same amount of consumption and generation and a German pattern of consumption. In one of the systems, half of power consumption is covered by nuclear power, while the other half is covered by gas power (CCGT). In the alternative system, half of consumption is covered by onshore wind power and PV. Again, the other half is covered by gas power. But since solar and wind power generation vary, it would be profitable in this situation to build both conventional gas power (CCGT) and some gas turbines (OCGT). In order to compare system costs, the analysis is based on the Hinkley Point C agreement and German feed-in tariffs for onshore wind power and PV. Even though the system with solar and wind power needs more total gas power capacity (MW) to compensate for variable solar and wind power, this system still comes out cheaper than the system with nuclear power.

The high nuclear power costs in the UK agreement mean high total system costs for this alternative. As mentioned above, it is difficult to get a clear picture of what new nuclear power costs, and in relation to earlier estimations, the agreed price in the Hinkley Point C agreement is very high. Maybe others are able to build nuclear power more cheaply? On the other hand, the analysis does not take into account costs related to the risk of nuclear power accidents, and it assumes nuclear power facilities will offer perfectly stable power generation, which is not necessarily the case. The risk of unplanned interruptions in nuclear power generation leads to a greater need for reserve capacity in the alternative with nuclear power than Prognos AG has assumed. Overall, the comparison seems fair.

52 In 2010, construction commenced on a pilot power plant of 500 MW in France. This is a cooperation between 35 countries. In a lecture, Laberge (2014) provides an optimist's perspective of the status of and new technological opportunities for fusion power.

A2.3 New contributions to flexibility

POSSIBLE INCREASED FLEXIBILITY IN GENERATION

As mentioned above, flexibility may be increased in *combined heat and power plants.* There could also be some flexible gas power based on biogas, but the resources for this are likely to be limited in a purely renewable system. Methane gas can also be produced from hydrogen, which can itself be made from power during times of surplus. The conversion from power to hydrogen and then into methane gas (CH_4), where applicable, entails significant energy losses, but conversion *may* still be profitable as long as the hydrogen can be produced during periods of relatively low power prices. (This is briefly commented on in Chapter 4.2.5.) It is also possible to make liquid fuel based on hydrogen.

Hydropower with reservoir can hold back water when there is a power surplus, and generate more power in periods of greater scarcity and higher prices. In hydropower systems with reservoirs, flexibility can be increased by installing more generator capacity (more MWs) in the reservoir power plants and by developing pumped storage power. It is also possible to develop new hydropower with reservoirs, or increase reservoirs. But in some countries, such measures are controversial.

As long as there is no risk of wasting water, it costs little to exploit the flexibility of hydropower plants.

In a *pumped storage power plant,* water is pumped up from a lower-lying reservoir to a reservoir at higher elevation when there is a power surplus (low prices). Power is generated later when power prices are higher. The energy loss associated with pumped storage power is approx. 20%. It is possible to increase the capacity of pumped storage power in many countries in Europe by utilising natural lakes,[53] and artificial reservoirs can also be built. The latter is obviously much more expensive and often only results in capacity to deliver power for 6-10 hours during the day. Where there are large natural reservoirs high up in the mountains, such as in Norway, storage capacity may be great without very high costs per stored MWh or per MW generation capacity. A greater ability to regulate hydropower plants and more pumped storage power may be one of many contributions to balancing consumption and generation in Europe.

Gas turbines are a familiar technology which could play an important part in covering peaks in consumption when wind and solar power fail to deliver. Developing solar and wind power would only achieve a small reduction in the need for other generation capacity. However, there would then be *fewer hours* when high capacity is required. This has interesting implications. Agora Energiewende (2014) claims that in Germany, maximum consumption will be around 80 GW in the year 2020, *but almost a quarter of this consumption (the last 15 - 25 GW) will only take place for less than 200 hours per year*. The traditional answer to such a short-term need is gas turbines. The report states that the fixed annual costs of maintaining such a capacity would be in the range of €35 to €70 million per GW. If we assume an average gas turbine usage of 100 hours per year, fixed costs then become € 0.35 – 0.7 per kWh

53 See Assessment of the European potential for pumped hydropower energy storage (European Commission, 2013). This looks at use of natural lakes. Not surprisingly, Norway has a lot of potential, but a number of other countries also have some potential. According to Gunnar Groebler from Vattenfall, it is possible to increase the capacity of pumped storage power in Germany from the current 7 GW to 15 GW, given the right conditions. (Quoted by news agency Montel 25/03/2014.) Maximum consumption in Germany is expected to be around 80 GW in the future. Thus, German pumped storage power can currently cover approx. 9% of this and it might be possible to increase it to around 18%.

delivered. In addition, there is a gas cost of approximately € 0.07 – 0.1 per kWh plus the CO_2 cost. The cost of delivering this power is then very high per kWh, but as only a few hours are concerned, the total cost for consumers is not very high.

The fixed costs of keeping 20 GW gas turbines ready will be equal to an *average* power price increase in Germany of 0.1 – 0.2 euro cents per kWh. As an insurance against a collapse of the power system, this price is likely acceptable, but it is still important to consider whether there could be cheaper alternatives. It may for instance be possible to make consumers lower their consumption in extreme situations. This could be done through high prices and smart control of consumption, so that consumers cut consumption where it is least needed.

For an average user period of 100 hours for 20 GW, around 2 TWh of power will be generated, approx. 600 million m^3 of gas will be used, and 1.4 million tonnes of CO_2 will be emitted, equal to around 0.2% of Germany's total CO_2 emissions. Gas turbines can be started up relatively quickly and are easily regulated. They can therefore also support the power system in the event of a sudden drop in for instance wind power generation. The fact that they are fairly easy to regulate has additional value. From a climate perspective, it is of course desirable to start using biogas, which should be possible for the volumes concerned here.

Emergency generators are used by institutions where security of supply is especially important, such as hospitals and large computer and data storage facilities. Emergency generators often run on diesel and switch on automatically if electricity from the grid cuts out. (Batteries can ensure a constant power supply until generators have started.) Emergency generators can be adapted relatively simply to support the power system in situations where production capacity is too low. The same facility that ensures a local consumer's power supply can thus also support the power supply at large – and earn money doing it. With increasing demands for security of supply, more institutions may come to see the benefit of a backup supply of electricity. *If the energy system as a whole needs reserve capacity for exceptional circumstances in any case, it may make sense to locate some of this capacity in places that have particularly stringent requirements for security of supply.* The reserve capacity can then serve several purposes. In the future, diesel generators may be supplemented with larger batteries and local solar panels, or be replaced by hydrogen and fuel cells (which do not entail any local noise or air pollution).

ENERGY STORAGE AND BATTERIES[54]

I have already mentioned pumped storage power, which is currently by far the dominant type of electricity storage. Power can also be stored in the form of *compressed air*, for example in old mines. The potential is limited and efficiency is 70% – 80%.

Systems for storing power in large batteries connected to the grid can also be built. Such storage solutions will be most profitable for balancing relatively short-term fluctuations, for instance during a 24-hour or 7-day period. When batteries can be used frequently, fixed costs are divided among many charge cycles (see below). When it comes to storage of very large amounts of energy (several TWh), batteries cannot compete with for example large natural hydro reservoirs or gas storage.

54 For a more exhaustive review of possible solutions for storage, I recommend Hvidtfeldt Larsen and Sønderberg Petersen (2013).

Different battery and storage technologies will have different qualities and may therefore be suited for different purposes, from a very quick response in order to stabilise the power system, to storing power for hours and maybe days (if they become cheap enough).

Large batteries located in the right places in the grid may contribute to a more even flow of power and increase the utilisation of the grid. Batteries connected to facilities with solar cells can even out delivery of power so that this, to a larger degree, follows needs in the market. More even delivery may save costs in power generation and may in certain cases limit the need for grid investments. Batteries that are primarily installed to be used in one place in the power system might also make themselves useful in other parts of the system. One example may be if a large solar panel facility is installed in one area, and it is difficult to use all the power generated during times with lots of sun and low local consumption. Batteries may be a cheaper alternative compared with reinforcing the local grid in order to export the power. In addition, in situations of available battery capacity, the batteries can store power when power prices are low and deliver power when prices are high. Hence, batteries connected to a solar farm can and should also be used to even out imbalances other than those due to variable PV-production.

Batteries could also offer extra security of supply in some institutions, possibly in combination with emergency generators. It is important to realise, however, that batteries are currently not cheap, their ability to handle many charge cycles varies and there is some energy loss.[55]

THE PROFITABILITY OF ENERGY STORAGE SYSTEMS IS AFFECTED BY PRICE DIFFERENCES, FREQUENCY OF USE AND ENERGY LOSS

For all energy storage systems, earnings are related to the price difference that can be achieved between charging and delivery, the energy loss incurred by such a cycle, and how often the storage facility can be used. Some figures can illustrate this: Assume that a pumped storage power plant can buy 1000 MWh during the night for €40/MWh, and sell back 800 MWh (assuming a loss of 20%) during the day at a price of €80 per MWh. This means an income of 800 x €80 – 1000 x €40 = €24,000 per day. If this was repeated every day, the annual income would be €8,760,000.

If the price difference is halved by the daytime price dropping from €80 to €60, while the night-time price is still €40, income will be reduced by 2/3. The reason is that part of the price difference covers the energy loss. If the daytime price drops to €50, there is no money to be made. In this case, the price difference cancels out the energy loss exactly and the facility may as well just sit there.

If price differences are less common, enabling the facility to be run at a profit for half the year only, but with the same price difference as before (€40/€80), annual profits are halved compared with the first instance. If the energy storage facility could reduce its energy loss from 20% to 10%, and prices remained at €40/€80, the profits in this example would increase by 33%. The cost of energy loss is highest when the purchase price of power is high.

The example above shows that price differences and how frequently an energy storage fa-

55 The loss of energy is related to changing and discharging, transformation AC/DC and back, and (when relevant) transmission of power back and forth through the (local) grid.

cility is used, are of great significance for its profitability, and that energy loss may also be of significance if the purchase price for power is high.

FLEXIBLE POWER DEMAND

When there is a particularly large demand for power during short periods (cf. the example above, where 25% of the peak demand lasted for less than 200 hours), *reductions in consumption* may be the most economic measure. In order for smaller consumers to be able to contribute flexibility efficiently, consumption must be managed intelligently by ICT systems.

Consumer flexibility is closely related to electrification of the transport and heating sector. This was described in Chapter 4.2.5.

A2.4 The need for implementation and development

We have seen that there are many types of emission-free power generation that can contribute to more even power generation, and there are many solutions that might contribute to flexibility, in order to ensure the necessary balance between power consumption and power generation. A number of flexible solutions could be implemented immediately, especially in the heating sector. It is important to clarify the potential for such flexibility.

For some decades to come, gas power will be able to offer important flexibility, but in order to bring emissions in the power and energy sector down towards zero, new solutions must be developed. Given how long it takes to develop new technology and bring costs down, big efforts are needed in this area *now*. Or to quote Hvidtfeldt Larsen and Sønderberg Petersen (2013):

> *"With the prominent exception of pumped hydro storage, energy storage activities in Europe are currently confined to pilot or test plants, or even the laboratory. Large-scale energy storage has not yet been realised. However, joint European research plans as well as national plans in the EU member states clearly show that energy storage is considered an essential element of the future energy infrastructure and must be developed now to be available when market demand emerges."*

The topic of the quoted report is storage. It is of course also important to develop and map other flexibility options, especially low-hanging fruits. More knowledge of which emission-free types of power may become relevant and how other infrastructure can be developed, will also make it easier to build the solutions of the future in a cost-effective way.

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