Technical report:
Nordic Green to Scale

Nordic Council of Ministers

Technical report: Nordic Green to Scale

Jan Ivar Korsbakken and Borgar Aamaas

TemaNord 2016:545

Technical report: Nordic Green to Scale
Jan Ivar Korsbakken and Borgar Aamaas

ISBN 978-92-893-4720-4 (PRINT)
ISBN 978-92-893-4721-1 (PDF)
ISBN 978-92-893-4722-8 (EPUB)
http://dx.doi.org/10.6027/TN2016-545

TemaNord 2016:545
ISSN 0908-6692

Standard: PDF/UA-1
ISO 14289-1

Layout: Hanne Lebech
Cover photo: Dag Spant

Print: Rosendahls-Schultz Grafisk
Printed in Denmark

NORDIC ECOLABEL
5041 0457
Ecolabelled Printed Matter
Rosendahls

Nordic co-operation
Nordic co-operation is one of the world's most extensive forms of regional collaboration, involving Denmark, Finland, Iceland, Norway, Sweden, the Faroe Islands, Greenland, and Åland.

Nordic co-operation has firm traditions in politics, the economy, and culture. It plays an important role in European and international collaboration, and aims at creating a strong Nordic community in a strong Europe.

Nordic co-operation seeks to safeguard Nordic and regional interests and principles in the global community. Shared Nordic values help the region solidify its position as one of the world's most innovative and competitive.

Contents

Preface

This technical report serves as a basis for the flagship report on the Nordic Green to Scale project. The project was led by the Finnish Innovation Fund Sitra, in cooperation with the Nordic Council of Ministers Climate and Air Pollution Group KoL, CICERO, CONCITO, the University of Iceland Institute for Sustainability Studies and the Stockholm Environment Institute. The technical report was written and the analyses carried out by researchers at CICERO.

Introduction

Background

The Paris agreement sets the World the challenging task of limiting greenhouse gas emissions enough to keep average global temperatures "well below" 2 °C above pre-industrial levels, and "pursue efforts" to limit the increase to 1.5 °C. It does not, however, mandate any specific emission cuts from individual countries, instead relying on countries to set their own individual targets through Nationally Determined Contributions (NDCs).

The preliminary Intended Nationally Determined Contributions (INDCs) submitted ahead of the negotiations do not put the World on a path that is close to any of the various emission scenarios determined by the Intergovernmental Panel on Climate Change (IPCC) to be likely to limit global warming to below 2 °C. But the Paris agreement does include a mechanism for periodic review and "ratcheting up" of national ambitions. The hope is that this over time will create a snowball effect, in which countries learn from and are inspired by each other's efforts and successes, and eventually arrive at action plans that are sufficient to achieve the 2 °C or 1.5 °C goals.

In this process, the Nordic countries can play an important role. The Nordic countries are well placed to lead by example, due to their highly developed and relatively strong economies, high levels of human development and relatively broad political and popular support for reducing greenhouse gas emissions. But in addition, they have all implemented numerous solutions and experienced several trends that have proven successful at reducing or slowing the growth of greenhouse gas emissions.

In 2015, Sitra in collaboration with Ecofys and several international partners launched the report "Green to Scale", in which they analysed how much global greenhouse gas emissions could be reduced by implementing globally 17 solutions that had proven effective in various countries around the world (Afanador, Begermann, Bourgault, Krabbe, & Wouters, 2015; Sitra, 2015). In this report, we analyse the potential reductions by scaling up 15 solutions specifically from the Nordic countries by 2030, either globally or in a suitable group of countries. We also provide an estimate of the direct net cost of scaling up each solution, as well as a qualitative overview of the most important co-benefits and possible barriers to implementation. The methodology for the quantitative estimates is based on the methodology developed by Ecofys for the original global Green to Scale report.

We choose only 15 solutions to analyse, based on several criteria, notably a long enough history of implementation in a Nordic country to have yielded proven results. There are however other solutions out there which were left out for editorial reasons or for lack of data, and still more that are currently being developed or in the early stages of implementation. Examples include electric and natural gas-powered shipping, novel solutions for carbon capture and storage (CCS), geothermal heating, and catalysts to lower N2O emissions from fertilizer production.

The Nordic countries are of course not representative for the rest of the World in terms of economic development, human capital or political institutions. They are also endowed with greater renewable energy resources relative to their population size than most countries, such as high potentials for wind power in all the Nordic countries, vast hydropower reserves in Norway, Iceland and northern Sweden, significant concentrations of geothermal heat in Iceland, and high potentials for biomass production from forests in Sweden and Finland. One can therefore rightfully ask whether the Nordic countries really can make useful examples for the rest of the World. Nevertheless, all these resources are found in many other places of the World – albeit often at smaller scales relative to population size. Some of the Nordic countries have also had great success with technical solutions such as combined heat and power (CHP), district heating, best-practice manure management and various energy efficiency measures, which are not intimately related to particular natural endowments.

We select and adjust the solutions such that they ideally should be possible to implement in the group of countries we select, even in the absence of the special conditions present in the Nordic countries. In the cases where the size of the potential reduction depends on the carbon intensity of electricity generation, heating or other processes, we adjust the potential to reflect the average carbon intensity globally or in the target countries rather than the (usually lower) carbon intensity in the originating Nordic country. And in the cases where a solution requires large capital investments, markets or political institutions that may be difficult to realize in developing countries in the 2030 timeframe, we limit the scaling to suitably developed countries, usually the OECD countries, or OECD plus certain middle-income countries.

The emission reduction potentials in 2025 and 2030 arrived at in this report in some respects represent an ideal scenario, where a large number or all countries make a concerted effort to implement the specific solutions we analyse, and where the implementation is carried out in a relatively coordinated manner to avoid that solutions are implemented in a manner which reduces their potential effect. In other respects, however, it is conservative. We only assume that other countries would achieve by 2030 what one or more Nordic countries have already achieved, even though relevant technologies in most cases are cheaper and better, and there is more experience with implementation and policy measures to build on.

Summary of results

The abatement potential varies greatly between solutions, from as little as 20 million tonnes of CO_2 equivalents ($MtCO_2eq$) to as much as 1.2 billion tonnes ($GtCO_2eq$). By adding up all 15 solutions, we arrive at an unadjusted total abatement potential of 4.1 (3.6-4.7) $GtCO_2eq$ in 2030 (See Figure 1).[1]

Note that these results do not reflect the total technical potential of each solution, but rather the effect of scaling up what has *already been achieved* in the Nordic countries, to solution-specific groups of target countries, and after subtracting a baseline level of implementation in those countries. Figure 1 should therefore not be interpreted as saying anything about the *total* potential for each solution if implemented to the full extent possible and without subtracting a baseline.

Some solutions overlap, and implementing one could potentially reduce the abatement potential available to another. This is most important for the solutions that address supply or demand of heating energy for buildings: "CHP and district heating" (Chapter 2.1), "Residential heat pumps" (Chapter 5.2), and "Energy efficiency in buildings" (Chapter 5.1). We estimate the reduction in total abatement potential due to these overlaps to be approximately 140 $MtCO_2eq$ in 2030, with a range of approximately 120-160 $MtCO_2eq$ (see Section 1.4 for estimation method and disaggregated numbers).[2]

We estimate the total net cost of implementing the solutions (after subtracting direct savings) to be 13 (–40-70) billion US dollars (in 2012 currency), or an average unit abatement cost of 3 (–12-15) USD/tCO_2 in 2030 (see Figures 2 and 3).[3] Subtracting overlaps does not reduce the potential enough to change the average unit cost significantly.[4] There is a very large range of possible costs due to uncertainties and possible

---

[1] The notation 4.1 (3.6–4.7) $GtCO_2eq$ means that we obtain a central value of 4.1 GtCO2eq, with a range from 3.6 to 4.7 based on variations in assumptions made in the analyses of the individual solutions. We use this notation to denote central values and corresponding ranges throughout this document. We estimate abatement potentials based on complete implementation in 2030, but also report the resulting interim potential in 2025, in most cases by interpolation. The total potential for all solutions in 2025 is 2.7 (2.4–3.0) GtCO2eq.

[2] The corresponding range in 2025 is approximately 50 (45–60) MtCO2eq.

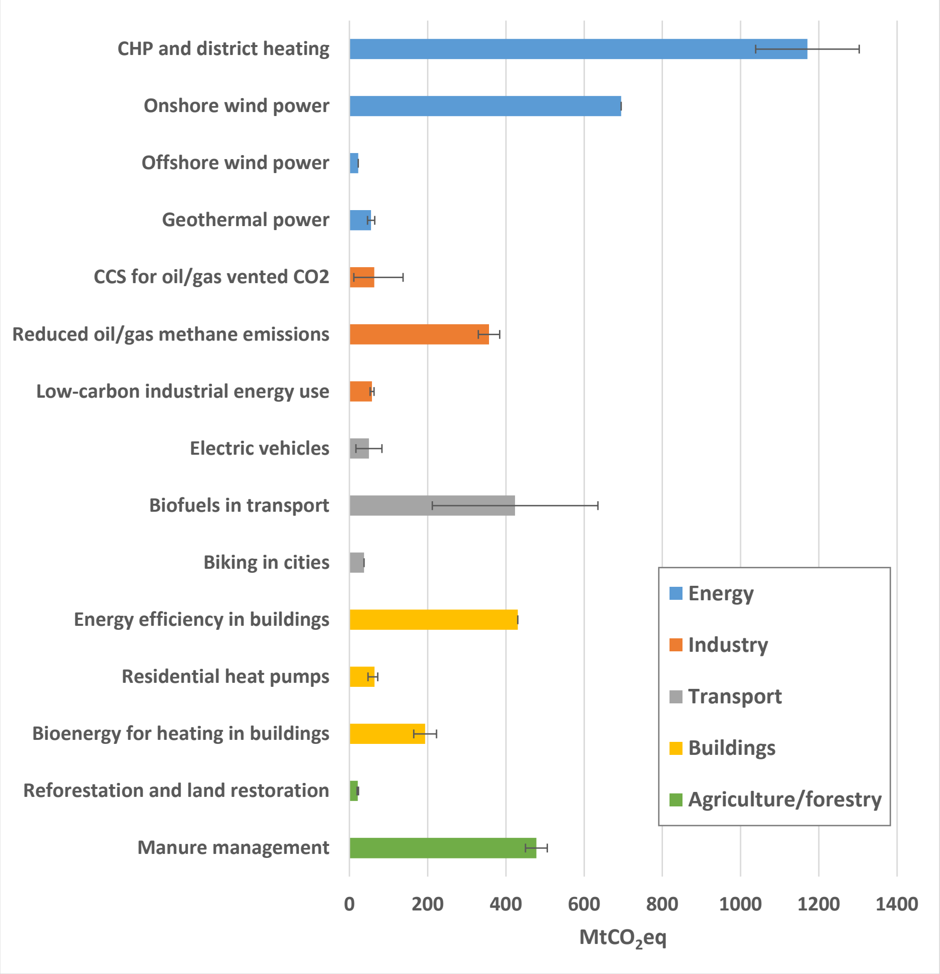
[3] Corresponding costs in 2025 are 26 (–14–68) billion USD total, and 10 (–6–23) USD/tCO2 unit cost.

[4] Within the numerical precision used here, the upper end of the range changes from 15 to 16 USD/tCO2, otherwise there is no change.

variations of assumptions in different solutions, from significant savings (negative cost) to considerable expenses. In particular, the solution "CHP and district heating" contributes significantly to the range due to large cost differences depending on the mix of retrofitting and applying the solution to new buildings (See Chapter 2.1).

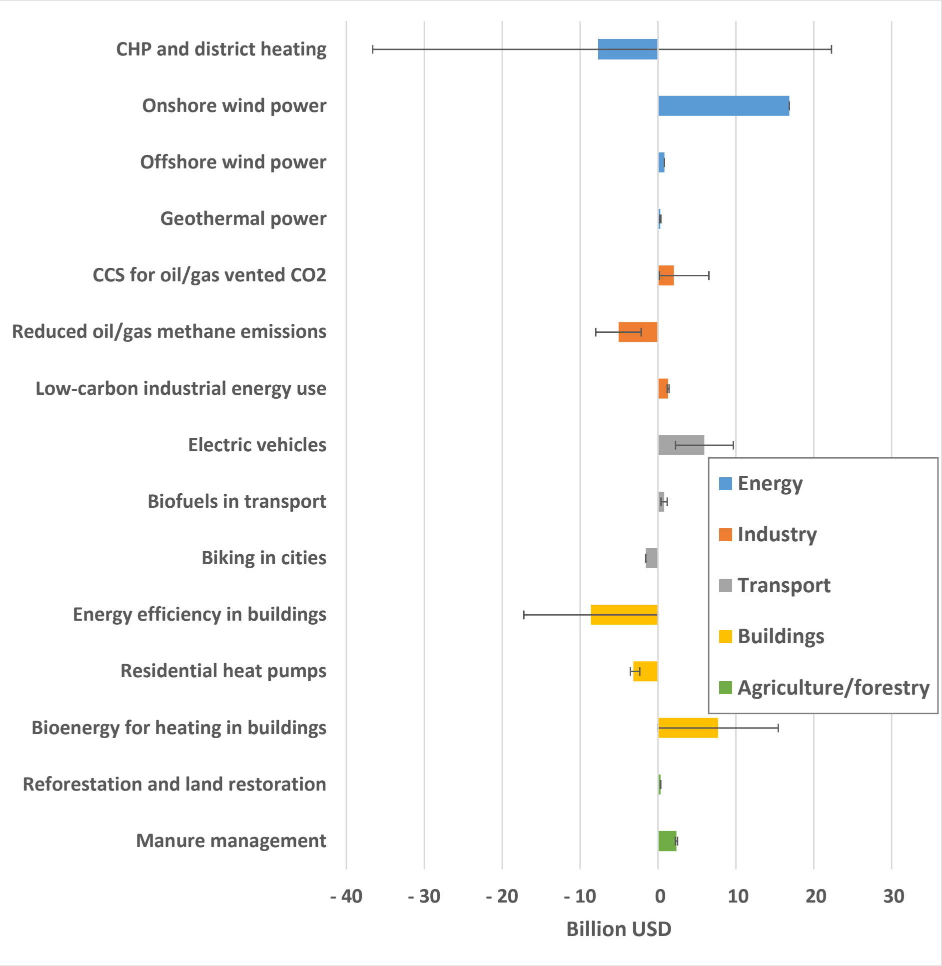
Note that the costs do not include most co-benefits such as improved health or ecosystem services, only direct savings (see Section 1.3). The monetary value of such co-benefits are usually difficult to quantify, but the societal cost of the solutions would in most cases be significantly lower than the estimated abatement cost if co-benefits were included.

Figure 1: Total abatement potential of the 15 solutions analysed, in 2030



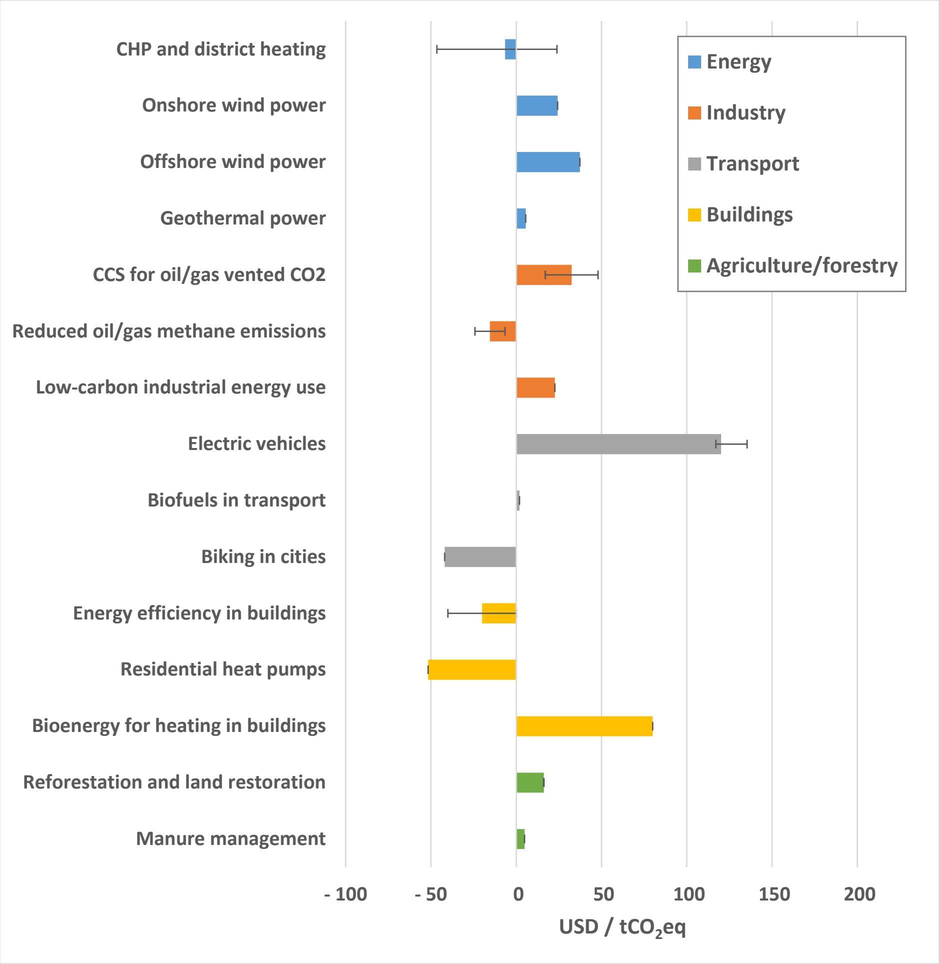
Note: Ranges reflect possible variations in assumptions used in the calculations.

Figure 2: Total abatement cost for each of the 15 solutions, in 2030



Note: All figures in 2012 US dollars.

Figure 3: Unit abatement cost for each of the 15 solutions, in 2030



Note: All currency in 2012 US dollars.

1. Methodological approach

1.1 Choice and classification of solutions

The solutions used in the analysis were selected from a long-list of proposals according to four main criteria, roughly in prioritized order:

- Nordic distinctiveness: The solutions either had to have been pioneered by one or more Nordic countries, or the scale of implementation had to be in some way distinctive relative to other regions.
- Proven potential: Each solution must have had a proven track record, with a long enough history and significant enough scale in at least one Nordic country to assess potential emission reductions if scaled up to other countries.
- Analysis feasibility: Sufficient data had to be available, from published and easily obtainable sources, to assess both the degree of implementation in the originating country, and the emission reductions of scaled up globally or to a target group of other countries. All estimates also had to be doable without a major modelling effort. Some highly specialized solutions were excluded on these grounds, as were a few macroeconomic measures such as Finland's emission-based taxes and the effects of the Nordic electricity market.
- Scalability: Each solution had to be at least in principle possible to implement in a large part of the rest of the world.

Large abatement potential was desirable but not an absolute requirement. As can be seen from Figure 1, several solutions were included even though they turned out to have very moderate abatement potential.

In addition to the criteria above, the project also strived to maintain a reasonable balance both between the different Nordic countries and between different sectors when selecting solutions.

We classify the solutions into five different sectors:

- Energy.
- Transport.

- Buildings and households.
- Industry.
- Agriculture and forestry.

The solutions in the "Energy" sector primarily address electricity and heat generation. One measure (CCS) which overlaps with upstream oil and gas production but also addresses other industrial production is classified as "Industry". Finally, the measure "CHP and district heating" in practice evolved into two related but separate solutions (Industrial CHP, and CHP with district heating for buildings), which could fit in either the Energy, Industry or the Buildings and households sector. We classify this as part of the Energy sector.

1.2 Scaling-up of abatement potential

For each solution, we select a group of countries where we think it is feasible to implement the solution in question. This "group" is assumed to be the whole world in many cases where we do not find compelling reasons why many countries should not be able to implement the solution.

We then find the degree to which the solution has been implemented in the originating Nordic country and scale this up to the selected group of countries according to one of the two following approaches (with some custom adjustments where necessary):

- Find the share of the technical potential that has been achieved in the originating country, or other measure of implementation relative to the maximum achievable degree of implementation. Then assume that each country in the target group achieves the same share / degree of implementation relative to its respective maximum, by 2030. Make a linear or exponential interpolation to find the degree of implementation in 2025.[5]
- Find an appropriate measure of the growth rate of the solution in the originating country, either in the last 12 years (equal to the time between 2018 and 2030), or at a time when the solution in the originating country was at a stage similar to where

---

[5] The choice of interpolation depends on the solution. In general, we use an exponential interpolation for solutions that are likely to experience significant economies of scale, such as new technologies with rather small units of implementation, whereas linear interpolation is generally used where buildout is more discrete and requires large infrastructure investments.

the average of the target countries is now. Then assume that the target countries achieve that growth rate starting in 2018 and through the period 2018–2030.

We then calculate the associated net emission reductions. Examples include the amount of emissions associated with generating the calculated amount of electricity using the average carbon intensity of electricity generation in the target countries in the case of increased onshore or offshore wind generation; Or the difference between emissions from petrol burnt in internal combustion engines and emission from generating the electricity consumed by electric vehicles in the case of increasing the market share of electric vehicles.

From this estimated abatement potential, we then subtract a baseline level of emission reductions, corresponding to the level of implementation that is already expected to take place in a baseline scenario. For our baseline scenario, we use the New Policies Scenario (NPS) from the 2015 edition of the International Energy Agency's (IEA) World Energy Outlook (IEA, 2015). If the figures we need are not included in the model used to produce the NPS or if these figures have not been published, we attempt to use the broadly similar 4 Degree Scenario (4DS) of the 2016 edition of the IEA's Energy Technology Perspectives (ETP) instead (IEA, 2016a). If the 4DS also does not contain the information we need, we make a best effort to construct a baseline using an appropriate alternative scenario from other sources.

We explicitly adjust for differences in carbon intensity of electricity generation in the originating country and the target countries, for solutions that imply increased use of electricity. Where possible, we also use the projected energy mix and carbon intensities of the target countries in 2025 and 2030 (according to the baseline scenario) rather than current values.

We do not require that every country implement the solution in exactly the same way as was done in the originating Nordic country. Instead, we assume that each country in the selected group will adapt the details to national circumstances as needed, but in such a way that they achieve the same degree of implementation (to be defined below) as in the originating Nordic country.

Further, in some cases the methods above may lead to an unrealistically or even impossibly high degree of implementation in some individual target countries, such as wind power reaching a share of total electricity generation above what any electricity system could be expected to handle with current technologies, or renewable heating energy supply exceeding total demand. In these cases, we apply a "sanity check", by defining certain limits that we do not expect any country to go beyond (e.g., onshore wind not reaching more than 40% market share in one country). We adjust the abatement potential downwards accordingly in countries where our results cross those limits. In cases where making such checks entails a major effort for each individual country, we only apply it to countries that are likely to make a significant difference for the final result.

Note that our calculations primarily include emissions that are directly affected by the solution. We also include indirect emissions that are both significant *and* relatively straightforward to define and quantify, such as emissions caused by changes in electricity consumption. We do *not* assess a wider carbon footprint, such as temporary emissions caused by construction activity or by producing materials needed for new infrastructure. Such estimates would in most cases be complex, vary significantly with local conditions and have high uncertainty, and are beyond the scope of this analysis.

Also, note that our estimates do *not* reflect the total global technical potential for each solution if implemented to the greatest extent possible, and the relative size of the abatement potential for each solution in our analysis does *not* necessarily indicate which ones hold the greatest promise in that case. The abatement potentials we estimate are based on scaling up the current or historical degree of implementation in the Nordic countries, and subtracting an expected baseline for the target countries. Unless otherwise noted, when we use the term "abatement potential" in this report, we are referring to this above-baseline scale-up potential, not total technical or economic potentials. Some abatement potentials may therefore appear smaller than one might expect due to a relatively modest degree of implementation in the Nordic countries so far, or a relatively high baseline (i.e., if the target countries are already expected to start "catching up" to the Nordic countries by 2030).

1.3 Cost estimates

We calculate the total cost of each solution by finding a suitable unit abatement cost (in 2012 US dollars per tonne CO_2) and multiplying the unit abatement cost by the total net abatement potential.

Where available, we set the unit cost of the solutions we analysed to be equal to the unit cost of a corresponding solution in version 2 of the Global Greenhouse Gas Abatement Cost Curve of McKinsey & Company (McKinsey, 2009), converted to 2012 US dollars. Although now somewhat old, the McKinsey cost curve is still the most comprehensive single consistent analysis available which is broad enough to cover a significant fraction of the solutions we analyse. We therefore opt to use it where possible instead of patching together many more disparate analyses. We assess whether the cost levels in the McKinsey cost curve are still appropriate for each solution, by comparing any relevant data points we could find in their documentation to more recent analyses. We also tried to adjust their cost figures to fit recent developments, in the cases where it was both necessary and possible. Some solutions, however, are simply not covered by the McKinsey cost curve, or their analysis is clearly outdated. In these cases, we either adopt and adapt estimates from other sources, or construct an independent estimate.

In general, our cost estimates reflect direct investment and operational costs, minus direct savings associated with implementing the solution. We do not quantify total societal costs, or calculate significant but hard-to-quantify elements such as savings from improved health or real and perceived costs associated with longer commutes or reduced comfort levels.

Instead, we make a qualitative assessment of the most important co-benefits of each solution, as well as important political or societal barriers that might hinder or reduce the implementation of the solution, and important enablers that are required for implementation.

1.4 Overlaps between different solutions

In some cases, different solutions address the same emissions base, and implementing one may lead to a lower abatement potential for the others. Where reasonable, we assume that solutions will be implemented in such a way as to minimize overlap. In some cases, however, overlap is difficult to avoid. We here describe these overlaps, and how we estimate the required adjustment in the total abatement potential. To follow the description of the calculations, it will be helpful to have read the chapters describing the relevant solutions first.

The only solutions that overlap directly and unavoidably with each other are the ones that address energy use for heating in buildings. These are CHP and district heating (Chapter 2.1), Energy efficiency in buildings (Chapter 5.1), Residential heat pumps (Chapter 5.2), and Bioenergy for heating in buildings (Chapter 5.3). The CHP/district heating, residential heat pumps and bioenergy for heating solution all compete with each other to reduce the carbon intensity of heating for buildings, while the energy efficiency solution reduces total heating demand. The solutions that reduce carbon intensity also reduce the abatement effect of lower demand as well as potentially making it impossible for the other carbon intensity-reducing solutions to achieve their full potential. The energy efficiency solution, meanwhile, reduces demand, and therefore the effect of any reduction in carbon intensity of heating energy.

The four overlapping solutions only affect each other where they are implemented in the same regions. The regions for each solution overlap, but are not identical:

- CHP and district heating (for buildings): All OECD countries.
- Energy efficiency in buildings: USA, Japan, and EU countries only.
- Residential heat pumps: EU countries that are also OECD members.
- Bioenergy for heating in buildings: Canada, Russia and Mongolia (of which only Canada overlaps with any of the other regions).

We then have to consider three separate regions based on the overlaps:

- *Canada* (CHP and district heating, and Bioenergy for heating): Given the way we calculate the abatement potential, the overlap does not lead to any reduction in total potential. There are two cases to consider: 1) A given amount of heat is transferred from the baseline heating energy mix to CHP with district heating, using a different energy source than biomass, or using biomass that is already part of the baseline (i.e., which would have been used anyway, regardless of the Bioenergy for heating solution). Here there is no overlap, by definition; 2) A given amount of heat is transferred from the baseline heating energy mix to CHP with district heating, *and* that CHP plant uses biomass as a result of the increased biomass use required by the Bioenergy for heating solution (i.e., it would have used a different, most likely fossil energy source if that solution had not been implemented). In this case, transitioning to CHP cuts the emissions associated with the heating to zero plus a small amount of emissions from parasitic load (since assign the CHP emissions to electricity generation in the way we define the solution), while switching to biomass creates a further reduction in emissions with no reduction in total potential. That reduction is now associated with electricity generation rather than heating, but is nevertheless an equally large reduction in total emissions.
- *USA and Japan* (CHP and district heating, and Energy efficiency in buildings): Here, summing the abatement potential of the two solutions separately gives a too high total abatement, because the reduction in carbon intensity from the former solution is multiplied by a too high energy demand, while the reduction in energy demand of the latter solution is multiplied by a too high carbon intensity. If we assume that there is no correlation between the implementation of the two solutions (i.e., energy efficiency improvements in a given building do not depend on whether or not it receives district heat, and vice-versa), the difference between implementing both solutions simultaneously and the sum of implementing each individually is equal to the reduction in average carbon intensity of heating energy due to the CHP solution, multiplied by the reduction in heating energy demand

from the Energy efficiency solution (both limited to the US and Japan only).[6] We do not have detailed numbers for the US and Japan for all parts of the CHP solution (which was scaled up to urban areas of all OECD countries), but apply scalings based on their share of OECD totals where necessary. We then obtain an average overlap of 30 (26-35) $MtCO_2$ in 2025 and 79 (67-91) $MtCO_2$ in 2030 (the ranges correspond to the range of abatement potentials for the solutions).

- *EU* (CHP and district heating, Energy efficiency in buildings, and Residential heat pumps): Three solutions apply in EU countries, and the interactions between them are complex. There is little reason to install heat pumps in buildings with district heating, so we disregard direct overlap between the CHP and district heating solutions.[7] The heat pump and energy efficiency solutions potentially interact quite strongly. Both reduce heating energy demand, and the building stocks to which they are applied will probably overlap, even though implementing one makes the other somewhat less economical. Further, the heat pump and energy efficiency solutions will reduce each other's potentials in the same way as described under USA and Japan. Because we assume no overlap between district heating and heat pumps beyond the baseline, all of the required expansion of CHP+district heating is applied to buildings where no extra heat pumps are installed, and hence its abatement potential is reduced only by the demand reduction due to the energy efficiency solution.
  We estimate the total reduction in abatement potential by applying the solutions in sequence (the final result does not depend on the order). First, we apply the CHP+district heating solution, which attains its full potential as described in Chapter 2.1, since no other solutions have been applied yet. Next, we apply the residential heat pump solution, which again attains its full potential as in Chapter 5.2, as we assume that the extra heat pumps are only installed in houses and buildings that are not already connected to district heating. Finally, we apply the energy efficiency solution, which first has its potential reduced slightly by the reduction in demand due to heat pumps, and then again (by far more) due to the

---

[6] Alternatively, one can think of the procedure as implementing the solutions one after the other, e.g., first the energy efficiency and then the CHP+district heating solution. In this case, the energy efficiency solution would attain its full potential as described in Chapter 5.1. But the potential of the CHP+district heating solution would now be reduced proportionally to the reduced heating demand. That reduction is equal to multiplying the reduction in heating demand due to the energy efficiency solution and the reduction in carbon intensity due to the CHP+district heating solution, as described above.

[7] Heat pumps are not constrained to be installed in densely populated areas where district heating is most economical. There is therefore no reason why district heating should reduce the potential for installing heat pumps or vice-versa. The only exception is if installation levels of both become so high that they exceed the available building stock, but this is not the case for the level of implementation attained in our calculations.

lower carbon intensity in buildings where CHP-powered district heating has been installed. The total reduction is 23 (19-26) $MtCO_2$ in 2025 and 58 (49-67) $MtCO_2$ in 2030, of which the overlap with CHP represents 94% in 2025 and 88% in 2030.

The total reduction due to overlaps between solutions addressing building heating is thus *53 (45-61)* $MtCO_2$ *in 2025* and *137 (116-158)* $MtCO_2$ in 2030.

Most overlaps cause a reduction in total abatement potential. However, in some cases of indirect overlap the total potential may be higher. This is the case for solutions that reduce the carbon intensity of electricity generation, combined with solutions which require increased electricity use. The former are represented by onshore and offshore wind power solutions as well as the geothermal power solution (Chapters 2.2, 2.3 and 2.4), while the latter are represented by electric vehicles and residential heat pumps (Chapters 4.1 and 5.2).

We do not assess or adjust for these overlaps due to changes in the carbon intensity of electricity, since we do not want to make the potentials of the non-power sector solutions dependent on implementing ambitious measures in the power sector. Further, the effect would be quite small, given that the power sector solutions only reduce total power sector emissions by 772 (763-782) $MtCO_2$ in 2030, out of a total of almost 15 $GtCO_2$ in the baseline scenario, or only 5%.

However, in the case of electric vehicles, where the carbon intensity of electricity matters greatly for the net abatement potential, we do make a calculation in the chapter describing the solution (Chapter 4.1) where we show how much the potential would increase if the power sector were to follow a scenario compatible with the 2 °C target, i.e., even more ambitious than the power sector solutions we analyse.

There is also some possibility of interference between power sector solutions and reduced total potential. However, this is only an issue if the extra renewable power generation due to any of the power sector solutions (wind power and geothermal power) replace each other rather than baseline power. This is unlikely to happen, given that the new capacity will be new enough throughout the analysis period that it will not be replaced.

Finally, the solutions "Electric vehicles" (Chapter 4.1) and "Biofuels in transport" (Chapter 4.2) could potentially overlap, as electric vehicles reduce the demand for fossil fuels in transport and hence the total potential for substituting biofuels for fossil fuels. However, the biofuel solution has been formulated in a way that technically avoids this overlap or makes it very small, by requiring the target countries to reach a certain share of biofuels in total energy use for transport. Reduced fossil fuel demand due to a larger share of electric vehicles then does not significantly reduce the absolute amount of fossil fuels displaced by biofuels, but simply requires biofuels to displace a higher relative share of the fossil energy use.[8] If Chapter 4.1 required a very large above-baseline increase in the share of electric vehicles, it could of course become very challenging or even impossible to achieve the required biofuel share. But in our case, the electric vehicle solution only requires an increase in electric vehicles over the baseline of 0.2% of total transport sector energy demand in the target regions. This should have a negligible impact on implementing the biofuel solution.

1.5 Non-CO_2 greenhouse gases and global warming potentials

Most of the solutions discussed in this report have a reduction in CO_2 emissions as their main or only abatement effect. Two solutions, however, primarily result in lower emissions of greenhouse gases other than CO_2: Reduced methane emissions in oil and gas production (methane, Chapter 3.2), and Manure management (nitrous oxide, Chapter 6.2).

We convert reductions in non-CO_2 gases to CO_2 equivalents by multiplying by global warming potentials (GWPs) established in the IPCC's 5th Assessment Report (AR5) (Myhre *et al.*, 2013). Because different greenhouse gases have different lifetimes, the GWP for each gas differs depending on the timescales used. CO_2 is a very long-lived gas, which does not normally decay. It is only be removed from the atmosphere by being absorbed by natural sinks, and is completely removed only on a time scale of millennia. Nitrous oxide (N_2O) is also fairly inert, but through various pathways (in particular reacting with ozone in the stratosphere) is converted into molecular nitrogen (N_2) and oxygen, with a mean lifetime of 121 years. Methane on the other hand is relatively short-lived, and is gradually oxidized into CO_2 when exposed to oxygen in the atmosphere, with a mean lifetime of only 12 years.

We use 100-year GWPs in our calculations, as this is what is most commonly used in the literature, including the sources we use. Further, in the context of limiting the global temperature increase in 2100 to less than 2 °C, a 100-year GWP can be argued to be more relevant than shorter GWPs.

However, in scenarios where severe climate effects appear within only a few decades, a shorter timescale such as a 20-year GWP may be more suitable, especially for a

---

[8] This is not completely true, since an increased share of electric vehicles also reduces the total energy demand in the transport sector, due to the higher efficiency of electric motors. For the small numbers we are dealing with, however, this effect is tiny.

short-lived gas such as methane. If desired, our mitigation potentials can easily be converted to a 20-year timescale by dividing our CO_2-equivalent figures by the 100-year GWP and multiplying by the 20-year GWP, found in Table 8.7 of Myhre *et al.* (2013).

The 100-year GWPs we employ are 30-36 for fossil methane, and 265-298 for nitrous oxide, depending on whether climate feedbacks are included (upper value) or not (lower value) (Myhre *et al.*, 2013).

1.6 Considerations regarding bioenergy, sustainability, and carbon neutrality

Three solutions in this report require substantial use of bioenergy: Low-carbon industrial energy use (Chapter 3.3), Biofuels in transport (Chapter 4.2), and Bioenergy for heating in buildings (Chapter 5.3). Large increases in use of biomass for energy purposes is controversial for many reasons, related both to sustainability and to the net climate impact. We do not reduce the abatement potential in any of the solutions based on such concerns, but present the main concerns here, and compare the bioenergy required to a few assessments of the global sustainable potential for bioenergy use.

Sustainability concerns include competition for agricultural land and adverse impacts on food production and food prices, disruption of ecosystems due to cropland expansion or direct harvesting of biomass from ecosystems, as well as secondary effects on water use, soil and water retention, and several other issues. Controversies regarding the climate impact include whether biomass combustion can truly be considered carbon neutral as is done in most climate mitigation scenario work due to timing differences and imbalances between combustion and regeneration of the biomass, as well as a multitude of secondary climate effects such as greenhouse gases released from associated land-use change, changes in albedo and other physical properties of the land, fossil emissions from energy use when growing, harvesting, transporting and processing the biomass, and many more. For a comprehensive discussion of sustainability and climate effects of bioenergy use as well as a literature overview, see Section 11.13 of the contribution of Working Grup I to the IPCC's 5th Assessment Report (Smith *et al.*, 2014).

Concerns about the true climate neutrality of biomass affects all bioenergy use. Because burning biomass releases CO_2 into the atmosphere which stays there for a significant amount of time (at least one year but in most cases more) before being fully reabsorbed even if harvesting and regrowth are in perfect balance, there is likely to be a net increase in average atmospheric CO_2 concentrations unless the biomass is grown on previously less productive land (so that the CO_2 on average is absorbed before being released rather than the other way around). However, there is little consensus about how to assess net climate impacts of bioenergy, and the results will depend sensitively on details of how and from where the biomass is sourced.

Details of implementation at that level is beyond the scope of our analyses. Also, we do not include full lifecycle emissions when assessing emissions reductions from reduced fossil fuel use, and for consistency should therefore not include processing and transport emissions for increased bioenergy use either. In most of our calculations we therefore simplistically assume that bioenergy use has zero net climate impact, as is done in most integrated assessment modelling scenarios, even though this is probably not quite the case. We do however make a moderate adjustment based on IPCC recommendations in the solution "Biofuels in transport" (See Chapter 4.2).

Sustainability concerns mainly affect the solution "Biofuels in transport". The two other solutions ("Low-carbon industrial energy use" and "Bioenergy for heating in buildings") both assume use of existing residues from the forestry industry and thus no additional biomass extraction. There is a risk that, when implementing both solutions at once, the biomass demand may exceed what is available from the forestry industry, or that local forestry residues may be insufficient in some countries that have a low share of paper made from domestic wood, and high shares made from recycled paper or imported pulp. But in either case, the required total bioenergy of approximately 3-4 EJ is relatively modest compared to estimated sustainable potentials.[9] The 2012 Global Energy Assessment by IIASA estimates the global potential for forestry residues to be in the range 19-35 EJ per year (see Section 7.7.3.2 of GEA (2012)).

"Biofuels in transport" is of slightly greater concern. Firstly, biofuels in transport require additional biomass extraction, and in the form of liquid biofuels. These are currently more likely than solid biofuels to be made from crops grown on agricultural land. So-called second- and third-generation biofuels (made from non-food crops on marginal land, or from specially engineered crops such as algae) are being actively developed to avoid competition with food production, and may well be available at scale during the time period of our analysis. But they have currently not yet entered large-scale production for market.

Further, the amount of bioenergy required, while modest compared to most estimates of sustainable technical potentials, is still large enough that it could put pressure on future bioenergy supplies, especially considering the large scale of bioenergy use in most integrated assessment modelling scenarios that aim to keep global warming below 2 °C. The solution requires 12-15 EJ of biofuel consumption in 2030 (7-10 EJ above

---

[9] The figures are 3.4 (2.9–3.9) EJ in 2025 and 3.5 (3.0–4.0) EJ in 2030, of which Bioenergy for heating represents approximately 80% in 2025 and 70% in 2030.

the baseline of IEA's 4DS scenario). This is considerable compared to total "modern bioenergy" use of just 11.3 EJ in 2008,[10] and 4-5 times greater than 2008 levels of bioenergy use for transport (Chum *et al.*, 2011). It is, however, modest compared to current levels of "traditional" bioenergy use (37-43 EJ/year, see Chum *et al.* (2011)). Estimates of sustainable technical potential range anywhere from less than 50 to several thousand EJ per year, but there seems to be a relative consensus of at least 100 EJ per year (see section 11.13 of Smith *et al.* (2014)). Sustainability should therefore not be an absolute limitation to the solution in our analysis, but may still be of some concern when combined with other future bioenergy demands. See further discussion in Section 4.2.8). When implementing any of the bioenergy-related solutions from this report, it is therefore important to ensure that only sustainably sourced bioenergy is used, and that assessments are made of possible emissions associated with any land use change caused by the extra bioenergy use.

---

[10] Excluding gathered wood for cooking and heating, and other "traditional" categories of bioenergy use.

2. Energy sector solutions

2.1 CHP and district heating

2.1.1 *Description of the solution*

In both Finland and Denmark, a large majority of buildings in urban areas is served by district heating networks, and a high share of the heat is supplied by waste heat from combined heat and power (CHP) plants. Additionally, in Finland, most heat for industrial use is also supplied by CHP. Thermal power generation (generating electricity by burning fossil fuels, biomass or other combustible substances) inevitably wastes large amounts of energy as waste heat – from 40% for highly efficient gas plants to as high as 85% for some types of waste burning or very old coal plants – as the laws of thermodynamics severely limit how much of the heat energy released during combustion can be transformed into electricity or other high-grade forms of energy. CHP offers the benefit of utilizing this waste heat, thus reducing the need to burn additional fuel solely to generate heat, and avoiding the additional CO_2 emissions associated with that heat generation.

The solution here is taken to be the use of CHP to provide heat for space or water heating in buildings through district heating, and to industry through heat from nearby power plants or on-site generating units. The degree of implementation is taken to be the percentage of total heating energy that is supplied by CHP in this manner. Due to the very different nature of industrial heat and district heating for buildings, we treat the two separately.

A related concept, district cooling, may make more economic sense and provide as great or greater abatement in some warmer climates. However, the implementation of district cooling is currently very small in the Nordic countries, and therefore not appropriate to include on methodological grounds. There is also little data available on district cooling at the level of detail needed for our analyses. The global potential is also likely to be smaller, given that the amount of energy spent on cooling in urban areas worldwide is only 10% of what is spent on space and water heating (IEA, 2016a). [11]

---

[11] This number is expected to rise as the average income in countries with warmer climate grows, but is nevertheless only projected to reach 15% by 2030 (IEA Energy Technology Perspectives 2016, 4DS scenario).

As long as there is enough electricity demand to absorb all the electricity that needs to be generated to also supply enough heat to satisfy demand for district heating or industrial heat, the CO_2 emissions caused by heat from CHP is assumed to be zero, as the CO_2 released when generating the heat would have been released anyway in order to meet electricity demand. The abatement is then in principle equal to the CO_2 that would have been released by the same heat production if CHP were not used. Generating electricity through CHP does however require some extra electricity to be used by the plant itself (so-called "parasitic load", typically 5% or less for efficient plants). We compensate for this by reducing the abatement potential by an amount equal to the extra CO_2 released by having to generate slightly more electricity.

Energy data cited in the following are for 2013 and taken from the 2016 version of the World Energy Balances of the International Energy Agency (IEA, 2016b), unless otherwise noted. Energy-related projections used for baselines and for calculating abatement potentials in 2025 and 2030, are taken from the New Policies Scenario (NPS) of IEA's World Energy Outlook 2015 (IEA, 2015) or – where necessary – from the 4DS scenario of IEA's Energy Technology Perspectives 2016 (IEA, 2016a).

2.1.2 *Impact in originating country*

Industrial CHP

Both the absolute and relative scales of industrial CHP are high in Finland but minimal in Denmark. We therefore look at Finland only for this part of the solution. According to an IEA study (IEA, 2008b), CHP accounted for "almost 80%" of heat inputs to industry.[12]

Heat inputs account for only 14.2% of final energy consumption (FEC) for industry in Finland (61.8 PJ of 436 PJ), or 20.8% when excluding electricity. This is, however, far higher than the global average of 4.7% for all industry (6.4% when excluding electricity), and several industries in Finland have a much higher ratio of input heat to TFEC than the respective industries globally (IEA, 2016b).

In the scale-up, we use four industries: The paper and pulp industry (7.9% delivered heat), and the chemical, food and wood products industries (31.5%, 39.9% and 36.5% delivered heat, respectively). The paper and pulp industry does not have a high share of delivered heat, but its characteristics make it well suited for CHP, and it also has by far the highest FEC and absolute consumption of delivered heat of all Finnish industries (IEA, 2016b). The other three industries all use heat at a temperature suitable for CHP,

---

[12] "Heat input" here refers to heat which is generated offsite or in a different process than the one consuming the heat, rather than heat from direct combustion of a fuel, not direct use of a fuel to generate heat as part of the same process that consumes the heat.

and in Finland they have far higher shares of delivered heat than the average for the same industries globally.

We take the degree of implementation within each industry to be the share of CHP-derived heat in final energy consumption excluding electricity in that country, i.e., heat from CHP divided by non-electricity final energy consumption. We exclude electricity because electricity is usually more expensive than other sources of heating energy, and in industry is therefore usually used for non-heat purposes. We therefore assume that, to the extent electricity is used for heating at all, it is mostly for specialized purposes where delivered heat cannot easily be substituted.

We do not have exact data on the share of CHP in final energy in each individual industry in Finland. But the best estimate from Statistics Finland of heat consumption from CHP (both generated onsite and delivered from external CHP plants) allow us to estimate that CHP-derived heat made up 72% of total non-electricity final energy consumption in the paper and pulp industry, 28% in the chemical industry, 7% in the food industry, and 14% in Wood industry (Statistics Finland, 2016b).

CHP / district heating for buildings

In Finland, approximately half of all building heat was supplied through district heating networks in 2012, but the share is over 80% in dense urban areas, and as high as 93% in the Helsinki metropolitan area. Typically, 70%–75% comes from CHP (Pales, 2013).

In Denmark, approximately 60% of all consumers receive heat through district heating (Danish Energy Agency, 2016b), but this rises as high as 90% in the area around Copenhagen (IEA, 2008a). The share of CHP in district heating has been stable at around 80% since the late 1990s (Danish Energy Agency, 2016a; IEA, 2008a).

When calculating the global potential for CHP+district heating for buildings, we will only consider urban areas. Considering the shares in urban areas in Finland and Denmark, we use a range for the degree of implementation based on 80% district heating of which 70% from CHP at the low end, to 90% district heating of which 80% from CHP at the high end. This gives a net range of 56%–72%, and we adopt the midpoint (64%) as the central value (see also Table 1).

Table 1: Current shares of district heating and CHP in Denmark, Finland, and estimated baseline for target region (urban OECD)

	Denmark (current)	Finland (current)	Urban OECD (baseline)
Market share of district heating	60%–90%[13]	50%–93%[14]	6%
Share of CHP in district heating energy supply	80%	70%–75%	79%
Adopted net share of district heating *with* CHP in urban areas[15]	72%	56%	5%

Note: The share for district heating (DH) in urban OECD is the share of DHJ in total building heating energy, while the shares for Denmark and Finland are the shares of buildings with DH installed. We use the latter as a proxy for the share of DH in building heating energy in Denmark and Finland. See main text for other assumptions.

Source: Pales (2013), IEA (2008a, 2014, 2016a), Danish Energy Agency (2016a, 2016b).

2.1.3 Scale-up method

Industrial CHP

We assume that industrial CHP is introduced in the four industries listed in the previous section, in all countries. The investments required for CHP are not prohibitive relative to the investments to build the industrial plant itself, in particular when resulting fuel savings are taken into account. We assume that even low-income countries will have the capability to use CHP to at least the same degree as they have the capability to build energy-intensive industry in the first place, and hence do not exclude any countries from our analysis.

We calculate the global abatement potential by estimating how much heating energy from other sources must be replaced by heat from CHP globally to reach the share that CHP-provided heat has of final energy consumption in each of the selected industries in Finland. We then multiply that energy amount by the average CO_2 intensity of all final energy (excluding electricity) used for heat in each sector. Finally, we estimate the extra CO_2 emissions caused by the parasitic load and subtract that to obtain a net abatement potential.

The amount of energy to be replaced by CHP is estimated by taking the amount of non-electricity FEC in each industry globally (from IEA statistics) and multiplying it with

---

[13] 60% for the country overall, but up to 90% in urban areas. See main text.

[14] Approximately 50% for the country overall, but over 80% in many urban areas, and 93% in the Helsinki metropolitan area.

[15] We use the urban figures for both countries to define a range which we scale up. For Finland, we use the share of DH in urban areas in general (80%), and the lower range for share of CHP in DH energy supply (70%).

the estimated share of CHP in that industry in Finland. We then subtract an estimated current share of CHP in that industry globally (see more under "Baseline" below).

We could find no data on the share of CHP in delivered heat to industry globally. We therefore assume that the amount of heat delivered to industry from CHP is equal to the output heat from autoproducer CHP plants (i.e., plants which produce electricity for on-site use, rather than for distribution through a public utility grid), which is 19% of all delivered heat to industry. This may be too low, since public utility CHP plants can also deliver heat to industry, and could lead to somewhat overestimating the total abatement potential.

We then calculate the CO_2 intensity of non-electricity final energy in each sector (using sectoral CO_2 emissions data from IEA statistics), and multiply this with the amount of heat energy replaced by CHP, to get the theoretical abatement potential given 2013 data and CO_2 intensities.

We thus obtain an abatement potential for 2013, which we scale to obtain the potential for 2030, and find the potential in 2025 by assuming linear growth towards the 2030 implementation level. IEA has not published energy consumption figures for the NPS at the detailed industry sector level that we need. We therefore assume that non-electricity FEC in the selected industries will grow at the same rate as the projected total for all industry (18% from 2013 to 2025 and 24% to 2030). We further assume that the CO_2 intensity of non-electricity FEC in each industry will fall at the same rate as the total for all industry (–4.7% from 2013 to 2025 and -5.9% to 2030). We then scale the 2013 abatement potential by those two factors in turn, see results under "Net abatement potential".

Finally, to estimate the parasitic load, we first find the average ratio of electricity to heat generated in CHP plants (1.20), and multiply this by the extra amount of industrial heat supplied by CHP, and thus obtain an estimate for the amount of electricity generated. We assume that 5% of this is parasitic load, and find the corresponding extra emissions by multiplying the parasitic load by the average CO_2 intensity of final electricity consumption globally in 2025 and 2030 in the New Policies Scenario (151 tCO_2/TJ and 139 tCO_2/TJ, respectively).

CHP + district heating for buildings

Due to the high investments required, we conservatively assume that CHP+district heating is only implemented in OECD countries.[16] We include only urban areas, since

---

[16] This is a quite conservative assumption; Many middle-income and even low-income countries may well have the resources and will to invest in district heating, and urban Northern China already has a high share of buildings connected to

the investment per connected building is likely to be prohibitively high in most rural areas.[17] We include countries regardless of climate; District heating can be used for water heating as well as space heating, and in warm-climate countries where heating demand is minimal, the methodology we use will imply that lack of demand in a given country gets carried through and results in a correspondingly low potential in the country in question.

We calculate the abatement potential by estimating the CO_2 emissions saved by increasing the global share of the combination CHP+district heating in total energy use for space and water heating in urban areas in OECD countries, to match the Danish/Finnish share of 64% (range 56%–72%) in 2025 and in 2030. There is not sufficiently detailed data available in the New Policies Scenario for our purposes. We instead use the broadly similar 4DS scenario from IEA's Energy Technology Perspectives 2016 (IEA, 2016a), which has more detailed data on energy consumption in urban buildings.

To calculate the CO_2 emissions saved, we fist calculate how much energy currently used for space and water heating in OECD urban areas must be replaced by district heat from CHP, in order to achieve the Danish/Finnish range by 2030, and interpolate the result to obtain the amount to be replaced in 2025 (see results under "Net abatement potential" below). We then multiply this by the average CO_2 intensity of energy used for heating (excluding energy already coming from CHP) in the same areas in the same years. Finally, we estimate the electricity lost to the parasitic load caused by CHP operation, and multiply this by the average CO_2 intensity of electricity generation before subtracting from the abatement potential.

To calculate the CO_2 intensity of heat generation, we first need to separate out the part of final energy which is already supplied by CHP+district heating from the total amount of energy used for space and water heating in urban OECD, and then split the remainder into electricity and other, directly used energy sources (such as natural gas, coal, biomass, etc.). The CO_2 emissions from the latter are reported directly in the ETP 2016 report. For the former, we multiply the electricity used by the average CO_2 intensity of electricity generation in OECD countries.

The amount of energy delivered through district heating in urban OECD is reported directly in ETP 2016, and we assume that 79% of this is supplied from CHP plants (see "Baseline" below).

---

district heating. However, due to the high investment requirements, and to challenges in accessing data on district heating in most non-OECD countries, we here limit ourselves to OECD countries.

[17] This also may be a conservative assumption; Even in areas not classified as "urban", there may be many pockets of dense habitation where district heating could make economic sense. However, the converse is true for urban areas; some parts of areas classified as "urban" may have parts that are less densely populated, or where other characteristics make district heating economically infeasible. We assume that these two effects cancel each other.

The available 4DS data do not allow us to calculate explicitly how much of the remaining energy comes from direct combustion for heat and how much comes from electricity in OECD countries. But the global share of electricity in final energy for heating is 22%, and we assume the same share for urban OECD. The 4DS contains data for total emissions from direct combustion for heat in buildings in urban OECD areas, and also allows us to calculate the emission intensity of electricity generated for use in the same areas. Combining the two gives us a CO_2 intensity of non-CHP-derived final energy for heating of 78 tCO_2/TJ in 2025 and 73 tCO_2/TJ in 2030.

Finally, to estimate the parasitic load, we follow the same procedure as outlined under Industrial CHP. We use the average CO_2 intensity of final electricity consumption in OECD countries in the 4DS in 2025 and in 2030 (110 tCO_2/TJ and 92 tCO_2/TJ).

2.1.4 Baseline

Industrial CHP

There is no explicit data on industrial CHP in the New Policies Scenario. However, according to ETP 2016, the share of CHP in heat generation has not increased for the past decade, and is described as being "stagnant". We therefore adopt as our baseline that CHP will have the same share of industrial delivered heat in 2025 and 2030 as in 2013. This is assumed to be 19% and was already subtracted in the procedure described in 2.1.3 above.

With this assumption, the baseline global share of CHP in total non-electricity FEC is merely 1.9% in the paper and pulp industry, 3.3% in the chemical industry, 1.9% in the food industry, and 2.0% in the wood products industry, compared to 9%, 42%, 48% and 40%, respectively, for the same industries in Finland.

CHP + district heating for buildings

To obtain a baseline for the amount of heat from CHP+district heating used for space and water heating, we first obtain the amount of commercial heat (assumed equal to district heating) consumed by buildings in OECD urban areas in 2025 and 2030 (from ETP 2016). We then multiply by an assumed share of CHP in district heating (see below).

The amount of commercial heat delivered to buildings in urban areas in OECD countries is 1,469 PJ in 2025 and 1,511 PJ in 2030. For the share of CHP, we use the reported share of CHP in district heating for 2011, which is 79% (IEA, 2014). Heat generated from CHP in OECD countries has not grown at all for the past 10 years, and the share of district heating has also been stagnant (IEA, 2016a). We therefore use 79% as the baseline share for both 2025 and 2030.

The figures above imply a baseline amount of heat energy delivered through CHP+district heating of 1,161 PJ in 2025 and 1,193 PJ in 2030.

2.1.5 *Net abatement potential*

Industrial CHP

To meet estimated Finnish shares of CHP by 2030, CHP in industrial final energy consumption must increase 70 percentage points (p.p.) (3.3 EJ) in the paper and pulp industry by that year, 24 p.p. (2.7 EJ) in the chemical industry, 4.9 p.p. (0.24 EJ) in the food industry, and 12 p.p. (0.93 EJ) in the wood products industry.

We calculate the net CO_2 emissions intensity of non-electricity final energy use in the four industries as being 33 tCO_2/TJ, 66 tCO_2/TJ, 55 tCO_2/TJ and 32 tCO_2/TJ, respectively (IEA CO_2 Statistics).

Multiplying these factors and factoring in the growth of total industrial non-electricity final energy consumption and CO_2 emissions to 2025 and 2030, before finally subtracting the extra emissions from parasitic load, the net abatement potentials become as follows (all numbers in $MtCO_2$):

Table 2: Net abatement potentials, industrial CHP

Industry	2025	2030
Paper and pulp	58	95
Chemical	112	182
Food	8	13
Wood products	2	3
Total	*179*	*292*

Note: All numbers in $MtCO_2$.

CHP + district heating for buildings

The total amount of energy used for space and water heating in OECD urban areas in the 4DS is 23,917 PJ in 2025 and 23,760 PJ in 2030. To achieve a share of 56%–72% of this total by 2030, heat delivered through CHP+district heating must rise by 7,258-9,598 PJ (central value 8,428 PJ) in 2025 and by 11,795-15,596 PJ (central value 13,696 PJ) in 2030.

Multiplying this by the CO_2 intensities given under 2.1.3, we obtain a net abatement potential of *563 (477-649)* $MtCO_2$ *in 2025* and *879 (746-1,011)* $MtCO_2$ *in 2030*.

The net abatement potential for industrial CHP and CHP + district heating for buildings combined is *742 (656-828)* $MtCO_2$ *in 2025* and *1.17 (1.04-1.30)* $GtCO_2$ *in 2030*.

2.1.6 Abatement cost

Industrial CHP

We have not found any sources for abatement costs of industrial CHP for each individual industry included in our analysis. However, the McKinsey Global Greenhouse Gas Abatement Cost Curve v2.0 (McKinsey, 2009) contains abatement costs for new builds and for retrofits in the chemical industry for 2030 (data for 2025 or 2020 cannot be derived from the published report).

The McKinsey cost curve gives a negative abatement cost for both retrofits (–2.1 EUR/tCO_2) and new builds (–5.7 EUR/tCO_2) due to fuel savings, with a weighted average of -4.6 EUR/tCO_2 (2005 euro values). Since the characteristics of CHP are broadly similar for each industry, we do not expect extreme differences in the abatement cost between the different sectors that we included.

We convert the costs to 2012 US dollars by first converting to USD using the average EUR/USD exchange rate in 2005, and then applying a GDP deflator from the World Bank to convert to 2012 US dollars. This leads to a unit abatement cost of -*6.6 USD/tCO_2*, and a total negative cost of *-1.2 bn. US dollars in 2025*, and *-1.9 bn. US dollars in 2030*.

CHP + district heating for buildings

The McKinsey abatement cost curve contains no analysis of district heating or of CHP for heating in buildings. However, the UNEP report "District Energy in Cities" estimates a levelized cost of heating from CHP+district heating of approximately 19 USD/GJ. When retrofitting an old building, where existing heating systems have already been paid for, the abatement cost must be taken to be the full cost of the CHP+district heating system. However, when considering new builds, the relevant cost is the difference between CHP+district heating and the cost of the baseline system, which we take to be conventional locally installed boilers fuelled by natural gas. UNEP reports this relative cost as negative, at approximately -24 USD/GJ (UNEP, 2015).

UNEP uses an interest rate of 10%, while McKinsey's global abatement cost curve uses a societal interest rate of only 4%. We therefore adjust UNEP's cost estimate to an interest rate of 4% (based on UNEP's statement that approximately 50% of the levelized cost is capital, and assuming an economic lifetime of 50 years for the infrastructure). The adjusted levelized cost of CHP+district heating then becomes 14 USD/GJ, and the difference to a conventional gas-based local heating system becomes -18 USD/GJ.

When retrofitting existing buildings so that the full cost of the CHP+district heating system applies, the unit abatement cost is very high, at 281 (260-311) USD/tCO_2 in 2025 and 263 (244-290) USD/tCO_2 in 2030.

To take into account the lower net cost (that is, net savings) when building CHP+district heating at the same time as a new building is constructed or an old one is refurbished, we assume a simple model where the total building stock grows relatively conservatively by just over 1% per year,[18] and another 1% of the stock is replaced or refurbished to such an extent that the cost for new builds applies.[19] The net unit abatement cost then becomes *11 (–28-39) USD/tCO_2 in 2025* and *-7 (-46–24) USD/tCO_2 in 2030.*[20] The.total abatement costs are *6 (-13–25) billion USD* in 2025 and *-6 (-35–24) billion USD in 2030*.

The overall unit abatement cost for both industrial CHP and CHP + district heating in buildings is *6 (–22-29) USD/tCO_2 in 2025* and *-7 (.35–17) USD/tCO_2 in 2030*. The total costs for both solutions are *5 (–14-24) billion USD in 2025*, and *-8 (-37–22) billion USD in 2030*.

The range in both unit and total abatement costs is large. The main reason is that the cost is the sum of a large positive and a large negative number, namely the high net cost of retrofitting some buildings and the large net savings of installing district heating from CHP in new builds. Even small variations in the assumptions about the rate of new construction and replacements create a large range for the net difference between these two elements. In addition, the range for the abatement potential further increase the range for the total cost.

2.1.7 Important enablers

The most important enabler for both industrial CHP and CHP+district heating for buildings is incentives to establish the necessary infrastructure, such as the district heating network itself, and co-generating units in industrial plants. This is especially true for district heating for buildings, where the capital expenditures are especially high, and where the infrastructure deployment needs to be coordinated with construction of buildings and development of new residential areas in order to minimize the effective cost. Industrial CHP will also benefit from policy to locate relevant industrial plants and public utility CHP plants close to each other, particularly in industries where on-site electricity generation is not high enough to generate the amount of heat needed.

---

[18] Based on projected growth in building heating energy and energy efficiency improvement in major OECD regions from IEA (2016a).

[19] Based on an assumed average economic lifetime of buildings of 50 years, and that approximately half of those are refurbished to such an extent that it can be considered a completely new construction.

[20] The lower cost in 2030 is primarily due to a larger share of new builds and replacements in the stock to which district heating is applied.

CHP+district heating in buildings will also be much cheaper and easier to deploy if developers work together with urban planners and policy makers to ensure that the construction of district heating networks, CHP plants and buildings is coordinated so as to maximize deployment with new builds and minimize the need for retrofitting.

2.1.8 Possible barriers

Both industrial CHP and district heating networks are capital intensive, and can have a relatively long payback time, especially in the case of residential district heating. This is particularly the case if interest rates are high and/or energy prices low. Furthermore, in buildings where the owners do not pay the energy costs themselves (e.g., buildings that are primarily rented out and where the tenants pay all utility costs), there is little incentive to save on energy costs for the parties that make the decisions and who may have to bear the capital costs for connecting a building to a district heating network.

Further, CHP and district heating is also subject to competition from all measures aimed at reducing heating energy demands in buildings, such as improved insulation, solar heating or other passive heating systems. Any reduction in demand for active heating will reduce the total potential for reducing emissions by moving to CHP and cutting the need for burning fuels exclusively for heating. There is therefore a significant overlap with measures for improved energy efficiency in buildings, including the solution "Energy efficiency in buildings" in this report. See Section 1.4 for a discussion and quantification of this overlap.

Moreover, energy efficiency measures undermine the economics of district heating, since it implies less heat being sold, without any significant corresponding reduction in capital costs. This is already set to become an issue in the Nordics, with the move towards low-energy or almost-net-zero energy buildings, and the requirements imposed by EU energy efficiency targets. Even though the net abatement cost for CHP with district heating is relatively low – or even negative when coordinated with construction of new buildings – measures for improving insulation in both new and existing buildings produce similar or even higher net savings according to the McKinsey abatement cost curve. Improved building energy efficiency may therefore be even more attractive from an economic and decision-making standpoint, given that it has similar or better economics, combined with fewer actors to coordinate and less complex infrastructure.

2.1.9 Major co-benefits

All forms of CHP lead to lower total energy use and lower associated emissions, which reduces air pollution and associated health risks where the energy is derived from fossil fuels (in particular coal). Further, district heating networks allow for more flexible changes in what fuels are used for heating than with gas-, oil- or wood-based heating system installed locally in each building.

2.2 Onshore wind power

2.2.1 Description of the solution

Both Sweden and Denmark have been very successful in building onshore wind power. Denmark was an early mover and currently has the World's highest share of wind power in its electricity supply, at over 40% of total generation (approximately 25% from onshore and 15% from offshore). In Sweden, the success story is the large percentage growth seen almost every year over at least the last decade, exceeding 30% in most years since 2007. In Sweden, wind turbines have largely been built due to green certificates, while Denmark has a history of using feed-in tariffs.

We take the solution to be replacing fossil electricity production with electricity produced by onshore wind, with the degree of implementation being the share of total technical potential for onshore wind power currently utilized (measured in terms of generation, not capacity). Offshore wind is treated separately in Chapter 2.3.

2.2.2 Impact in originating country

In 2014, Sweden and Denmark produced 11 and 9.3 TWh, respectively, from onshore wind (IRENA 2016). This electricity production covers 8% and 25% of the domestic demand in Sweden and Denmark, respectively. These are the most recent official statistics, but Sweden has likely seen continued growth since 2014. For the share of technical potential realized, see the following section.

Denmark and Sweden also generate power from offshore wind, which is analysed as a separate solution.

2.2.3 *Scale-up method*

Onshore wind power is becoming a relatively cheap technology, even compared to generation from fossil fuels. We thus assume that onshore wind can be built worldwide, even in low-income countries. We scale up to the global abatement potential in 2030 by estimating what share of the technical potential for onshore wind Sweden and Denmark have utilized. We then take the average of the shares achieved by these two countries, and require all other countries to achieve that average share of their respective potentials by 2030. For 2025, we assume a linear increase in power production until 2030. The reason for taking the average of Sweden and Denmark's achieved share is that neither country is representative of most countries in important respects, but represent outliers in opposite directions. Sweden is a large country with a very high technical potential relative to its total electricity demand, while Denmark is a small country where a significant part of the potential is already used. An average therefore is more realistic. As a few countries have large windy areas and low population densities, we sanity-check our estimated wind production: We assume that onshore wind can only cover 40% of the electricity mix in a single country. This leads to a reduction in the production potentials in Canada and Australia.[21]

Note that, although the term "technical potential" is often poorly defined, and although different sources tend to arrive at different numbers, our calculation is not affected by variation in the *absolute* value of the potential. We assess the *share* of technical potential achieved in the originating countries, and then scale that share up to the corresponding share of the global potential. As long as the global and local technical potentials are consistently defined, only the *ratio* between them matters for our results. Any over- or underestimate of the absolute potentials in the original sources does not affect our result, as long as both the Nordics and the global potential are over- or underestimated consistently.

We do several scalings based on different sources. According to a Greenpeace report (Greenpeace EREC, 2011), which reviewed the available literature, the technical potential of onshore wind is estimated to be 510 TWh for Sweden and 100,000 TWh for the world in 2020. For Denmark, we scaled the potential based on estimates given in a report by the European Environment Agency (EEA, 2009), by dividing with the ratio of

---

[21] Other countries may in principle also see a reduction in their total potential, but Canada and Australia are the only ones that are likely to have a significant impact on the global potential. Due to small potential and lack of detailed data, we do not perform the check for all smaller countries. The one country that might matter and for which we do not have sufficient data on the technical potential, is Kazakhstan. We assume that Kazakhstan would have or be able to build enough transmission capacity to Russia that this would not be an issue. The total electricity demand in Russia is large enough to absorb the potential wind generation in the former Soviet Union as a whole if sufficient transmission capacity is built.

the potentials given for Sweden in that report and in Greenpeace EREC (2011), in order to make the technical potential for Denmark consistent with the one we use for Sweden and for the world. We estimate the potential to be 80 TWh.

The built out potential is therefore 2.1% in Sweden, 11% in Denmark, and 6.8% in average. If we assume similar production shares globally in 2030, the global onshore wind production is 5,000 TWh in 2025 and 6,800 TWh in 2030. As we only accept a 40% share of wind in the electricity mix in individual countries, these potentials are reduced by 1,400 TWh in 2025 and 2,000 TWh in 2030, due to too high shares in Canada and Australia. The production potentials are then 3,600 TWh in 2025 and 4,800 TWh in 2030.

2.2.4 Baseline

We use the 4DS scenario of IEA's "Energy Technology Perspectives 2016" (IEA, 2016a) as our baseline, since the published data for the New Policies Scenario does not disaggregate onshore and offshore wind. In the 4DS, the global onshore wind production is 1,900 TWh and 2,400 TWh in 2025 and 2030, respectively.

2.2.5 Net abatement potential

Our estimated onshore wind potential above the baseline is 1,700 TWh in 2025 and 2,400 TWh in 2030.

We assume an electricity mix with a CO_2 intensity of 330 g CO_2/kWh in 2025 and 290 g CO_2/kWh in 2030, based on the New Policies Scenario in IEA's "World Energy Outlook 2015" (IEA, 2015).

The net abatement potential is given in Table 3. This estimate varies depending on the assumptions made, with a net potential near zero only based on the Sweden case and an enormous potential based on the Danish numbers. As the electricity generation from onshore wind is growing rapidly, especially in Sweden, the global potential would be larger with newer numbers.

Table 3: The global abatement potential in 2025 and 2030

Abatement potential ($MtCO_2$)	2025	2030
Based on average of Sweden and Denmark	580	690

2.2.6 Abatement cost

We use the weighted average of low- and high-penetration wind in McKinsey's cost curve (McKinsey, 2009). McKinsey's cost curve assumes a capital cost and learning rate, which is almost the same as IEA's data from 2014 and projections for 2030, at around 1,500-1,600 USD/kW, after adjusting for exchange rate and inflation. We therefore assume that cost levels in their analysis are still valid.

The abatement cost in McKinsey's cost curve is given to be 23.9 USD (in 2012 terms) per tonne CO_2 in 2025 and 24.3 USD/tCO_2 in 2030. Note that the cost is actually somewhat lower in 2025 than in 2030. This is because wind reaches a higher penetration in 2030, and that increases the integration costs.

The unit abatement cost, although low, implies an assumption that onshore wind power will on average still be slightly more expensive than fossil alternatives in 2030,[22] although only on the order of 1 US cent per kWh or less. This illustrates that the abatement cost is highly sensitive to the relative cost of onshore wind and baseline fossil power. If the cost difference were to improve by only 1 cent or so in favour of wind – which is not an unlikely possibility – the abatement cost would in fact become negative.

The total abatement costs using McKinsey's unit costs are given in Table 4.

Table 4: The abatement cost for onshore wind in 2025 and 2030

Abatement cost (in 2012 USD)	2025	2030
Unit abatement cost (USD/tCO_2)	23.9	24.3
Total, based on average of Sweden and Denmark (Bn. USD)	14	17

Note: Prices are based on 2012 US dollars.

2.2.7 Important enablers

Wind turbines need to be built where there are both good wind resources and sufficient suitable land area, which means that they are often built further from major centres of electricity demand than is typical for fossil plants. This means that transmission grids in most cases need to be expanded in concert with wind deployment, preferably in a coordinated fashion to minimize the time required to connect new wind farms.

---

[22] This applies after extra costs of integrating a variable power source like wind into existing electricity systems are included, not necessarily when comparing only per-kWh levelized generation costs. McKinsey includes a relatively modest estimate of integration costs (0.2–0.5 US cents per kWh, depending on penetration levels), although there is low consensus on the size of these costs.

Further, wind is a variable power source, and therefore requires a good deal of specialized knowledge to plan dispatching schedules according to both daily and ideally sub-hourly weather forecasts, as well as a dispatching system which is set up to adjust generation at shorter time intervals than is customary in systems based purely on thermal power and hydroelectricity. Onshore wind could also be combined with offshore wind, as the latter tends to have more stable wind speeds and hence more stable electricity output. Another important enabler in the future is energy storage, such as storage of surplus power production in batteries or hydrogen produced from electrolysis.

Finally, the variable nature of wind power requires it to be combined with other, dispatchable power sources, and it therefore benefits from a large coordinated electricity market. This is especially true of markets with a high share of flexible hydropower, such as the common Nordic electricity market. Indeed, one can argue that it would be difficult or impossible for Denmark to achieve its current record share of wind power (both onshore and offshore) in its electricity mix without good interconnections with its Scandinavian neighbours, enabling it to sell surplus electricity in the relatively frequent instances when its wind power generation exceeds total domestic electricity demand, and to draw on plentiful reserves of hydropower and other dispatchable sources in Norway and Sweden when domestic wind generation is low.

Furthermore, if wind farms are built in widely separated locations in a grid which covers a large geographical area, it reduces the correlation in output between the different wind farms (since the wind speeds in widely separated locations are less correlated), which reduces the requirements for backup power and the likelihood of incidents with very low output from all wind farms simultaneously.

2.2.8 Possible barriers

Wind turbines are only economical in areas with reasonable wind speeds throughout most of the year, which excludes large land areas. As more wind power is built out, the wind turbines may become less economical as the turbines tend to produce when other turbines are producing and, thus, producing when electricity prices are low.

Further, wind turbines are known to pose risks to birdlife, which can potentially be an environmental issue that may make block development of wind farms near important conservation areas, and has attracted resistance from some environmental and conservationist groups.

Wind power may also be unsuitable in relatively small and isolated areas such as isolated islands, unless combined with large-scale battery storage. Since wind speeds in a small area are highly correlated, the smaller the area the higher the probability of incidents where most or all of the area experiences quiet conditions and zero wind power output at the same time. This means that, unlike the case for larger, less correlated areas, small and isolated areas without interconnections to other areas would require full backup capacity from a non-variable source (unless there is sufficient battery storage to last through any low-wind period), which would drastically increase the effective cost of wind power.

2.2.9 *Major co-benefits*

Due to the merit order effect, where power sources with low marginal cost are usually prioritized before higher marginal cost sources, wind power almost always replaces other power production modes. This means that in some circumstances it can be more effective at replacing coal power than, e.g., biomass or natural gas, which may not always be prioritized ahead of coal power.

The reduction in fossil fuel-based (in particular coal-based) electricity production due to wind power generation will also reduce air pollution.

2.2.10 *Current situation in other countries*

Other Nordic countries are also installing wind power, but we have focused on Denmark and Sweden as the leaders. The top producing countries of onshore wind power is China, United States, Spain, and Germany. The yearly global production has grown rapidly over an extensive period of time.

2.3 Offshore wind power

2.3.1 *Description of the solution*

Denmark is an early mover on offshore wind. Denmark has a long history of subsidizing wind power, which earlier has also boosted construction of onshore wind power. It currently produces more than 40% of its electricity from wind power, of which approximately 40% again comes from offshore wind. The offshore share is growing. Other Nordic countries are also constructing offshore wind power, but have not reached as high a share as Denmark.

Onshore wind was treated separately in Chapter 2.2. Although onshore and offshore wind share the same energy source and basic technology, offshore wind has many features that set it apart. The technical requirements and more challenging conditions for equipment, installation and maintenance make offshore wind substantially more expensive than onshore wind, but costs have been coming down steadily. Further, offshore wind has two major benefits relative to onshore wind: Wind speeds offshore are usually both higher and less variable than onshore, which leads to higher utilization of total capacity (higher capacity factor), and lower requirements for backup and balancing power. Further, placing wind parks offshore reduces demand for usually more economically valuable land areas onshore, and can also make it economically viable to build wind parks closer to densely populated areas, where competition for land and real estate prices onshore are too high.

We define the solution here as replacing fossil electricity generation by electricity produced from offshore wind, and the degree of implementation as the ratio of electricity generation from offshore wind to the total technical potential for offshore wind in a country. The technical potential is large for most countries with long coastlines.

2.3.2 Impact in originating country

In 2014, Denmark produced 5.2 TWh from offshore wind (IRENA 2016). This electricity production covers 14% of the domestic demand in Denmark. For the share of the technical potential realized, see the following section.

Denmark also generates substantial amounts of electricity from onshore wind, which is analysed as a separate solution.

2.3.3 Scale-up method

We scale up Denmark's implementation of offshore wind to certain regions of the world in 2030 as described below. For 2025, we interpolate based on a linear increase in power production until 2030. The scaling is based on technical potentials listed in several sources, as we have not found a single source that reports a technical potential directly for both Denmark and all of our selected regions. The approach is the same as used for scaling up the onshore wind power solution from Denmark and Sweden (see Section 2.2.3).

Offshore wind has historically been an expensive technology, but costs have been decreasing. Most construction of offshore wind is expected to occur in high-income and upper middle-income countries. We thus select regions with known technical potentials, which together cover most of the OECD, but which also include a few other parts of the world. We assume that the solution can be replicated in North America, Oceania (mostly Australia) and Asia, as well as OECD Europe. All existing offshore wind capacity is covered by these regions. Our scaling is based on the offshore wind potential in Denmark and globally, taken from the reports "The Advanced Energy [R]evolution. A sustainable energy outlook for Sweden" (Greenpeace EREC, 2011) and "Europe's onshore and offshore wind energy potential" (EEA, 2009). We take the technical potential for each individual region from numbers given by the Ecofys report "Global potential of renewable energy sources: A literature assessment" (Hoogwijk & Graus, 2008), scaled to be consistent with Greenpeace EREC (2011) based on the ratio of global technical potentials in the two reports.

In 2014, offshore wind generation in Denmark was 5.0% of the estimated technical potential. Our calculations show that that share would result in an electricity production from offshore wind in OECD Europe, North America, Oceania, and Asia of 210 TWh in 2025 and 290 TWh in 2030.

2.3.4 Baseline

We use as our baseline the 4DS scenario of IEA's "Energy Technology Perspectives 2016" (IEA, 2016a), since the data published for the New Policies Scenario do not disaggregate onshore and offshore wind. We further use as our baseline the *global* offshore wind production, which is 150 TWh and 220 TWh in 2025 and 2030, respectively. The selected regions represent 100% of existing offshore wind generation, although it is possible that some capacity will be built in other regions by 2025 or 2030. Unfortunately, we have not found reports that estimate the offshore wind production in 2025 and 2030 for the selected regions specifically, or that allow us to project generation outside of the regions. Our baseline may therefore be an overestimate, which could reduce our calculated net abatement potential somewhat, but the selected regions would still be expected to comprise most of the baseline.

2.3.5 Net abatement potential

The net increase in offshore wind production globally based on the method outlined above is 64 TWh above the baseline in 2025 and 72 TWh in 2030.

We have calculated electricity mixes in the different regions based on the New Policies Scenario in World Energy Outlook (IEA, 2015). The CO_2 content decreases in all regions from 2025 to 2030. In 2025, the electricity mix contains between 270 and 460 g CO_2/kWh in the different regions, compared to 220 to 430 g CO_2/kWh in 2030. We have calculated the CO_2 emissions for each region and the net abatement potential is based on the sum.

The net abatement potential is *22 $MtCO_2$ in both 2025 and 2030*.[23] The abatement potential is much smaller than for onshore wind. This is partly because the baseline is already quite ambitious, at 70%–75% of the scale-up based on the Danish case. The gross potential, before subtracting the baseline, would in other words be 3-4 times larger. We should bear in mind that this somewhat positive baseline still needs to be implemented. Hence, the total number of offshore wind turbines constructed under the scale-up of the Danish case will be large despite the small net abatement potential.

A difference in the total global technical potential also contributes to the gap between the onshore and offshore wind power solutions. In the main source we use for scaling up, global technical potential for offshore wind is almost an order of magnitude smaller than for onshore wind (Hoogwijk & Graus, 2008). Although the theoretical potential for wind power over all of the Earth's oceans is vast, and far greater than the potential over land, practical considerations limit offshore wind farms to be built close to shore (Hoogwijk and Graus (2008) assume <40 km, which may be somewhat conservative). Although wind speeds are more stable and higher than over land, the surface area of this strip of sea close to suitable coastlines is small compared to windy areas onshore and in continental interiors.

2.3.6 Abatement cost

McKinsey's cost curve does not contain any cost estimates for offshore wind. Instead, we scale the abatement cost for offshore wind according to onshore and offshore cost data in IEA's New Policies Scenario as follows:

We calculate the levelized cost per MWh of electricity from both onshore and offshore wind using IEA data and New Policies projections from 2014 (IEA, 2015), for capital and O&M costs as well as average capacity factors. We then assume that the number of tonnes of CO_2 abated is the same per MWh of onshore and offshore wind, and scale the abatement cost using the ratio between the levelized cost of each wind type.

The resulting abatement cost is 40 USD/tCO_2 (in 2012 currency) in 2025 and 37 USD/tCO_2 in 2030.

The total abatement costs are given in Table 5.

---

[23] They are not identically the same in both years, but are rounded to the same integer number of megatonnes.

Table 5: The abatement cost for offshore wind in 2025 and 2030

Abatement cost (2012 USD)	2025	2030
Unit abatement cost (USD/tCO_2)	40	37
Total, based on average of Sweden and Denmark (Million USD)	890	840

2.3.7 *Important enablers*

Offshore wind is a somewhat volatile power source, but much less so than onshore wind. These two solutions may sound similar; however, they are very different and should be addressed individually. Offshore wind demands less balancing power than onshore wind. However, given its offshore location, constructing sufficient transmission capacity may be even more challenging than for onshore wind. Otherwise, enablers are much the same as for onshore wind.

2.3.8 *Possible barriers*

Offshore wind power has until recently been one of the most expensive mainstream renewable power technologies, hence, incentives may be needed for the construction phase. However, given the current rapid learning rate, costs may come down quite fast. Otherwise, barriers are similar to onshore wind, except that wind speeds are generally more stable offshore, and therefore some of the variability-related challenges of onshore wind are less severe for offshore wind.

2.3.9 *Major co-benefits*

The co-benefits of offshore wind are much the same as other renewable, non-combustible power sources. In particular, if offshore wind replaces fossil power sources or even biomass, this will reduce air pollution from electricity production.

The more stable wind speeds offshore provides an added bonus in countries which already have large shares of onshore wind, which may pose technical challenges to grid stability and require balancing and backup power: In many areas (including Denmark), power generation from offshore installations can be stable enough that they not only pose less severe technical challenges to the grid than onshore installations, but can even help provide balancing power for their onshore counterparts.

2.3.10 Current situation in other countries

Offshore wind has a much smaller global footprint than onshore wind, with a much smaller number of countries pursuing it. Before the last 10 years, the global scene was dominated by only Denmark and the UK. The UK and Denmark are still in the lead, with 54% and 21% of global generation (24.9 TWh) between them, respectively, as of 2014. In the last 10 years, however, a significant number of other EU countries have rapidly started and expanded offshore wind generation. Belgium, Germany, the Netherlands and Sweden now generate electricity from offshore wind at a level comparable to or above the level of the UK and Denmark 10 years ago. China has also been expanding rapidly, and passed the Netherlands in 2014, but its generation of 0.9 TWh is still negligible relative to its vast total electricity supply of more than 5,500 TWh, most of it based on coal (IRENA 2016).

2.4 Geothermal power

2.4.1 Description of the solution

The geological location of Iceland makes it very suited for use of geothermal energy. In 2014, geothermal energy supplied 29% of the electricity production (Orkustofnun, 2015). In addition, most of the heating demand is met by geothermal heating.

Iceland has traditionally met most of its electricity needs through hydropower, but during the 2000s it expanded electricity generation using geothermal energy on a large scale. Until then, geothermal energy had been used mainly for heating.

Although no other country has the combination of vast geothermal resources and a small population found in Iceland, most regions in the world have significant geothermal potential (indeed, 93% of the world's geothermal power is generated outside of Iceland). The speed of Iceland's expansion of geothermal power can therefore serve as a model. We take the solution as expanding geothermal power at the same rate as in Iceland during the 12-year period 2001-2013, and using this to displace other power sources (either existing generation or growth).

Note that we do not consider geothermal heating in this solution. Iceland's special conditions combined with the fact that geothermal heat generation in Iceland has grown very slowly for the past 20 years while still representing 80-90% of the global total for most of that period, make it difficult to construct a meaningful scaling of Iceland's geothermal heating use (see further discussion in Section 2.4.3).

2.4.2 Impact in originating country

Iceland has a high geothermal potential relative to its population (323,000 in 2013). Geothermal electricity generation in 2013 was 5.3 TWh, while it is estimated that 10-30 TWh could be generated sustainably with current technology (Orkustofnun, 2011). Although the population is small, Iceland has used its plentiful renewable electricity to expand industry, which currently represents approximately 75% of electricity demand.

In 2013, Iceland produced 7.3% of the global generation of geothermal electricity, and 75% of the geothermal delivered heat (IEA, 2016b). The growth rate of geothermal electricity in Iceland has been above the global growth rate, at 11% on average in the period 2001-2013. For geothermal heat, however, the Icelandic growth rate is well below the average growth rate in the rest of the world, which is to be expected given that geothermal heat already supplies most of the building heat in Iceland, and total demand is long since saturated.

Almost all of the electricity not generated from geothermal power (approximately 70%) comes from hydropower, and there are still considerable hydropower resources available for expansion. As a result, geothermal electricity generation does not lead to any significant CO_2 emissions abatement inside Iceland, but can have a significant abatement potential when scaled up to regions with higher carbon intensity of electricity generation.

2.4.3 Scale-up method

Scaling up the geothermal energy production in Iceland to the world is not straightforward. Iceland is a country with large geothermal resources relative to its population size and surface area, and with a relatively small total energy demand per surface area despite high industrial energy demand. We have therefore based our calculations on the annual growth rate in Iceland, which could potentially be reproduced worldwide.

In the scale-up, we require the rest of the world to have the same average annual growth rate for geothermal electricity production from 2018 to 2030 as Iceland did during the 12 years 2001-2013 (11.3%). This contrasts with the average 2.4% global growth rate between 2001 and 2013.

While geothermal heat could be an important part of the solution, Iceland is seeing smaller growth rates than the rest of the world does. This reflects saturation in Iceland, which experienced higher growth more than 20 years ago. But it also reflects a very low current base and rapid growth in the rest of the world. Currently the rest of the world combined produces only one-third as much geothermal heat as Iceland (it was less than one-twentieth until 2000), but is growing at more than 20% per year (IEA, 2016b). This makes applying a growth rate questionable, and also makes it difficult to construct a reliable baseline.[24] As a result, we only scale up the electric potential.

2.4.4 Baseline

We take the New Policies Scenario by IEA (2015) as the baseline scenario. The global geothermal electricity generation according to the baseline is 160 TWh in 2025 and 230 TWh in 2030 (compared to 72 TWh in 2013), with an average growth rate of 7.1% (IEA, 2016b).

2.4.5 Net abatement potential

The electricity production above the baseline is 60 TWh in 2025 and 151 TWh in 2030.

We assume an electricity mix of 330 gCO_2/kWh in 2025 and 290 gCO_2/kWh for baseline electricity generation in 2030 globally, based on the New Policies Scenario in IEA's "World Energy Outlook 2015" (IEA, 2015).

Although geothermal energy does not release CO_2 from combustion of fossil fuels, geothermal power generation often does cause the release of some geological CO_2 as well as possibly methane and other gases (Ármannsson, Fridriksson, & Kristjánsson, 2005). This venting of geologically stored gases will usually be faster or even in addition to what would have occurred naturally, and may therefore be considered an anthropogenic addition to the stock of greenhouse gases in the atmosphere. The amount of CO_2 can vary by orders of magnitude, depending on local conditions and the type of technology used. We here employ an average value of 122 gCO_2/kWh cited by the 2011 IPCC special report on renewable energy as the upper value of a range (Goldstein *et al.*, 2011). However, several measures can be taken to limit or nearly eliminate these emissions, e.g., by prioritizing sites where extracted hot water has little CO_2 content, using closed-loop binary cycle plants (Goldstein *et al.*, 2011), or even using a form of CCS under development in Iceland to sequester the CO_2 in basaltic rocks close to the power plant if available (see Chapter 3.1). We therefore use a range of 0-122 gCO_2/kWh for the carbon intensity of the extra geothermal power, and use the midpoint (61 gCO_2/kWh) as the central value.

The net abatement potential after including CO_2 emissions from geothermal power and subtracting the baseline is *24 (20-27)* $MtCO_2$ *in 2025* and *55 (46-64)* $MtCO_2$ *in 2030.*

---

[24] Our standard baseline scenarios do not contain projections for geothermal heat generation, only geothermal electricity generation.

2.4.6 *Abatement cost*

We apply the unit abatement cost found in the McKinsey Global Greenhouse Gas Abatement Cost Curve v2.0 for geothermal electricity (McKinsey, 2009). As they provide estimates for 2020 and 2030, we interpolate to find the abatement cost in 2025. The unit abatement cost is set to *7.6 and 5.5 USD (in 2012 currency) per ton* CO_2 *in 2025 and 2030*, respectively.

The total abatement costs are *182 (154-210) million USD in 2025* and *304 (253-355) million USD in 2030.*

2.4.7 *Important enablers*

Geothermal power is usually not a very high-cost energy source, but still requires significant investments, and can provide relatively stable power for a long time. It would therefore benefit from predictable power-purchasing arrangements such as power purchasing agreements (PPAs).

In jurisdictions where laws about ownership of underground resources are not clear or where above-ground landowners have effective veto power, geothermal power plants can face legal obstacles if they rely on heat gathered from a large area.

2.4.8 *Possible barriers*

Geothermal electricity is economically most attractive in areas that are geologically active, such as in Iceland and other areas close to tectonic plate boundaries or hot spots. While most areas of the world in principle can produce electricity from geothermal heat by drilling deep enough wells, the technology for drilling wells several kilometres deep and using them for power generation is not mature, and may not necessarily ever become economically attractive.

Further, although geothermal energy is in principle renewable (over human, not astronomical timescales), the speed of regeneration depends on the local heat flux through the Earth's crust and through the ground water or other fluid that is extracted in order to transport the heat to the surface. If the fluid is extracted too quickly, the power generation potential may decline and can take decades to recover.

Finally, the amount of geothermal energy in a geothermal field and the rate at which it can be sustainably extracted cannot be known with certainty before wells are drilled. This creates uncertainty and risks for investors, not unlike that associated with oil and gas exploration.

2.4.9 Major co-benefits

Geothermal heat in most cases provides stable power for a long time, unlike variable renewable sources such as solar and wind. It can therefore act as a good renewable baseload complement to variable renewables.

It also requires much less above-ground land area than practically any other renewable energy source, and in most cases does not have a significant impact on ecosystems.

2.4.10 Current situation in other countries

Other countries that produce geothermal power today, as well as having a large geothermal potential, are the U.S., Philippines, Indonesia, Mexico, New Zealand, Italy and Japan. Costa Rica, El Salvador and Nicaragua also have significant capacity relative to their sizes, and Turkey and Kenya have also expanded geothermal power generation greatly in the last few years (IRENA 2016).

3. Industrial sector solutions

3.1 Carbon Capture and Storage for vented CO_2 in oil and gas production

3.1.1 *Description of the solution*

Carbon capture and storage (CCS) – the process of capturing CO_2 from an emitting process and storing it permanently, usually in a geological reservoir – is a central part of most published integrated assessment modelling scenarios which keep the average global temperature increase below 2C (or even 3C) above pre-industrial levels.

Testing and implementation of CCS in most sectors have not come as far as they need to according to most of those scenarios. There is currently only one large-scale project operating in the power sector, in Canada (the Boundary Dam plant), and two more in the United States which were scheduled to come online in 2016 (Global CCS Institute, 2016a). In other industries, only a handful of projects currently operate. Most are in natural gas extraction and processing, where two Norwegian projects stand out.

Oil and natural gas reservoirs contain varying but often significant amounts of geological CO_2. This CO_2, which is classified as one type of "fugitive" CO_2 when emitted, is often released to the atmosphere both intentionally and unintentionally, either through leakages or venting during the extraction process itself, or during on-site or downstream processing of extracted natural gas. The statistics vary, especially on the former, but are in principle reported by all countries who report annual greenhouse gas emissions to the UNFCCC secretariat (Annex I countries). The reported emissions in the countries for which data are available amounted to approximately 54 $MtCO_2$ in 2014 (UNFCCC, 2016).[25]

Statoil operates two oil and natural gas fields on the Norwegian continental shelf that capture and sequester fugitive CO_2 from natural gas extraction: Sleipner in the North Sea, and Snøhvit in the Barents Sea. The CO_2 is injected into sedimentary rocks

---

[25] The countries in question accounted for 71% of global combined oil and natural gas production (in energy terms) in 2014 (IEA, 2016b). See the UNFCCC website for the complete list of countries (UNFCCC, 2016).

approximately 1,000 metres under the sea floor, overlain by impermeable cap rock, for permanent storage.

Seven other projects to capture CO_2 from natural gas processing, with a capture capacity of more than 100 ktCO_2 per year, are currently in operation, in the United States, Australia, Brazil, and Saudi Arabia. Three more projects – in the United States, Australia, and China – are currently in various stages of planning or construction, with anticipated start of operations in or before 2020 (Global CCS Institute, 2016a). However, the Sleipner and Snøhvit projects are currently the only ones in which CO_2 is injected specifically for permanent storage. All other operating projects use the CO_2 for enhanced oil recovery (EOR),[26] in order to recover costs. While CO_2 injected for EOR may well stay below ground permanently, this is not necessarily the case, and CO_2 injected for EOR is not considered permanently stored in the UNFCCC national inventory reporting system.

We define the solution in this section to be CCS for geological CO_2 from oil and gas wells, i.e., capturing the CO_2 that comes to the surface with the extracted oil or gas, and injecting it back into the ground into a formation suitable for permanent storage. The available UNFCCC national inventory statistics do not allow us to differentiate fully between CO_2 that is released from on-site natural gas processing as in Sleipner and Snøhvit, and CO_2 from other production-related processes or from natural gas processing at a downstream processing facility. Since parts of the latter may be a mix of processes that are analogous to the capture of admixed CO_2 which is done at Sleipner and Snøhvit, and processes that are not, we calculate four different scaled abatement potentials based on different assumptions about which UNFCCC figures to include, and on whether to include both oil and gas production or gas production only.

In addition to CCS in natural gas extraction and processing, Norway currently has three CCS pilot projects running in three other industries: in ammonia production (by the fertilizer producer Yara), in cement production (by the cement company Norcem), and in municipal waste incineration (by the City of Oslo). All are still at the testing stage and not operating at a significant scale. All three would potentially transport the CO_2 to the North Sea for injection and storage in the continental shelf, but the potential maximum volumes are not considered large enough to construct a pipeline, instead necessitating transport of compressed gas by ship. They are nevertheless significant for CCS development in their respective industries: The Norcem project is important for being one of the first in cement production, which cannot be made CO_2-free because the main

---

[26] Using CO_2 for EOR means that the CO_2 is injected into an existing oil reservoir, and the pressure is used to push oil towards a well where it is extracted. This increases the recovery rate beyond what would be possible if relying only on the natural pressure in the reservoir.

raw material (calcium carbonate) releases CO_2 as it is converted to calcium oxide during the manufacturing process. CCS is therefore a necessity to achieve a pathway compatible with the 2 °C target in this industry. Further, the waste incineration CCS project in Oslo is notable since a large part of the waste comes from biological sources, and storing the CO_2 from incineration can hence lead to net negative emissions. This is in practice a form of BECCS (Bioenergy with CCS), which is essential in most climate mitigation scenarios, but still hardly developed at all.

Iceland has also made a notable contribution to the field of CCS in general. Although Iceland's power sector is practically free of fossil fuels, geothermal energy extraction causes the release of almost 200 kt per year of geological CO_2. Iceland's basaltic bedrock is not suitable for the most common types of CCS, where CO_2 is stored in sedimentary rocks and trapped under an impermeable cap rock layer. But the project CarbFix has developed a method where the CO_2 is first dissolved in water and then injected into basaltic rocks in order to react chemically with the rock and form solid carbonate minerals. The water solution both slows the escape of the gas and speeds up the chemical reaction. The project began to inject part of the CO_2 from the Hellisheiði geothermal power plant in 2012, and has found that over 95% of the CO_2 is mineralized already after 2 years (CarbFix, 2016).

The method is cheaper than most other forms of CCS, at around 30 USD/tCO_2, and the rapid mineralization can make the risk of accidental release and the monitoring requirements lower than for other forms. A drawback is that the method requires basaltic rocks with relatively high concentrations of calcium, magnesium and iron, and with sufficient porosity to capture the CO_2. These are primarily found in young basalts near oceanic rift zones. Apart from Iceland and a number of usually small volcanic islands, such rift zones are usually located in deep ocean, which makes transporting and injecting the CO_2 a challenge. The storage potential is nevertheless estimated to be as high as 100,000-250,000 GtCO_2, with anywhere from 60 to 7,000 GtCO_2 available close to Iceland (Snæbjörnsdóttir & Gislason, 2016).

3.1.2 Impact in originating country

Sleipner began capturing CO_2 from natural gas processing at an offshore facility in 1996, motivated mainly by a tax on CO_2 emissions imposed on several sectors by the Norwegian government since 1991, and by the need to separate CO_2 from the gas to meet a European cap of 2.5% on the CO_2 content of natural gas (Global CCS Institute, 2016b). Snøhvit has been capturing CO_2 from natural gas processing at an onshore processing site since its start in 2008, motivated not only by the Norwegian CO_2 tax, but also by the Norwegian government requiring CCS as a condition for receiving a license to operate (Global CCS Institute, 2016b).

Sleipner has a capacity of approximately 850 ktCO_2 per year, and Snøhvit 700 ktCO_2 per year (Global CCS Institute, 2016a). The total amount of CO_2 actually captured and stored for both projects combined has been between 1.1 Mt and 1.3 Mt since the first full year of operations at Snøhvit (2008) (UNFCCC, 2016). A total of 16.2 Mt has been captured at Sleipner and close to 3 Mt at Snøhvit since the start of operations.

Thanks in part to the CO_2 tax, and due to relatively low CO_2-content in most other Norwegian gas and oil fields, the vented and other non-flaring-related fugitive CO_2 emissions at other Norwegian oil and gas production sites are quite low. Total reported emissions from upstream vented CO_2 and from fugitive emissions from natural gas processing were between 90 and 170 ktCO_2 each year since 2007, with even lower emissions before then.[27]

The average ratio of emissions captured at Sleipner and Snøhvit to total vented CO_2 from all Norwegian oil and gas fields, per year from 2008 through 2014, was 90%. We adopt this as the degree of implementation, which we will require other countries to achieve by 2030 (although the base to which the percentage is applied varies depending on assumptions, see below).

3.1.3 Scale-up method

The technology used to capture and store CO_2 at Sleipner and Snøhvit is mature and well understood. The type of geological formations used for storage is also usually found where oil and gas are found, so availability of storage is not likely to be a significant limitation. The economic incentive to implement CCS is the major obstacle, but we assume that all governments of Annex I countries of the UNFCCC, will have the financial and organizational muscle to implement the incentives needed (see section 3.1.7).

We therefore assume that all countries that report annual emission inventories to the UNFCCC will implement the solution to the extent achieved in Norway by 2030. In addition, this form of CCS is relatively simple and low-cost, given that it involves a fairly pure stream of CO_2 that needs to be separated from the extracted natural gas during extraction and processing in any case, and storage is readily available close to the production sites in most cases. We therefore consider that most middle-income gas- and

---

[27] It should be noted that some gas is transported through pipelines directly to continental European markets, and some CO_2 may be separated there, in which case any associated emissions would not be reported as part of Norway's inventory.

oil-producing countries will be able to implement the solution. We thus additionally include all countries in the Middle East with significant oil- and gas-related vented CO_2 emissions,[28] as well as China, India, Indonesia, Malaysia, Brunei, and Argentina.

The type of emissions most directly equivalent to what is captured at Sleipner and Snøhvit, are on-site vented CO_2 from gas production (reported under "Venting" in section 1.B.2.c "Venting and flaring" in the Common Reporting Format (CRF) used for national inventories reported to the UNFCCC). As reported, these amounted to only 7.0 $MtCO_2$ in 2013 (6.9 $MtCO_2$ when excluding Norway). We will henceforth refer to estimates based on only these emissions as "restrictive".

However, the same type of emissions may also be reported under fugitive emissions associated with natural gas production (1.B.2.b.2). In many cases, the CO_2 may be transported with the gas to a downstream processing facility and separated and released there (1.B.2.b.3). When these fields are included, total emissions in the reporting countries rise to 48.7 Mt in 2013. In the following, we will call estimates based on this scope of emissions as "inclusive".

Finally, venting of CO_2 may also occur from wells that produce only oil, even when no natural gas is extracted. Although such CO_2 is not captured at Sleipner or Snøhvit, similar capture and storage techniques may be used. If we therefore also include vented CO_2 emissions from upstream oil production (1.B.2.a.2), total emissions in 2013 amounted to 52.4 Mt.

We report scaled abatement potentials both for the most restrictive and for the most inclusive definitions of relevant vented emissions, as well as for gas and combined oil/gas production only, and for all production types including oil-only (four different potentials in total).

No data on these detailed emissions types are available for the standard baseline scenarios we use. Instead, for Annex I countries, we project emissions to 2030 by their reported 2014 emissions proportionally to projected growth in gas or total oil+gas production to 2030 in the New Policies Scenario of the IEA's World Energy Outlook 2015 (IEA, 2015). For 2025, we make a linear interpolation. For countries where the World Energy Outlook does not make a specific projection, we assume the same growth rate as in the "rest of" the relevant region (i.e., projected total production in the region – such as "OECD Europe" in the case of the UK – minus the projected production in the countries for which the World Energy Outlook does report an individual projection).

For non-Annex I countries, we estimate emissions by multiplying their gas or oil+gas production with the average emission intensity of gas or oil+gas production in

---

[28] The Middle Eastern countries included are (in order of decreasing oil and gas production) Saudi Arabia, Iran, Qatar, the United Arab Emirates, Kuwait, Iraq, Egypt, Oman, and Bahrain.

the reporting countries (the relevant included emissions, divided by total gas or oil+gas production). We use this average to calculate central values for the emissions, and apply a range of plus/minus two production-weighted standard deviations centred on the central values.

The resulting total emissions in 2025 and 2030 for each case is shown in Table 6.

Table 6: Projected emissions for selected countries

Scope of emissions	2025	2030
Restrictive, gas and combined oil/gas production only	19 (13-42)	22 (15-47)
Restrictive, all production (including also oil-only)	24 (14-54)	27 (16-60)
Inclusive, gas and combined oil/gas production only	101 (65-113)	109 (60-121)
Inclusive, all production (including also oil-only)	129 (71-145)	137 (72-155)

Note: All numbers in $MtCO_2$, central value followed by range in parentheses, as described in main text. The numbers do not include Norway's own emissions.

3.1.4 Baseline

The World Energy Outlook does not report any disaggregated numbers for future deployment of the specific types of CCS that make up our solution. Instead, we use data on relevant planned and currently operating CCS projects within natural gas processing, and assume that these represent the baseline for both 2025 and for 2030 (all currently planned projects are projected to start operations by 2020).

The available data lists capacity for each project, but not actual activity (actual tonnes of CO_2 injected). Since the full capacity is not likely to be utilized, we multiply the projected emissions by the reported average ratio of captured CO_2 to total capacity for Sleipner and Snøhvit from 2008 to 2014 (75.9%).

In table 7, we report baselines using both restrictive and inclusive definitions of relevant emissions, and including only projects for permanent geological storage, or also including projects using EOR.

Table 7: Baseline carbon capture volume in 2025 and 2030

Scope of emissions	Storage only (excl. EOR)	All types (incl. EOR)
Restrictive scope	2.8	3.6
Inclusive scope	2.8	19.8

Note: All numbers in $MtCO_2$. The same baseline is assumed in both 2025 and in 2030, due to all planned relevant projects being planned for 2020 or earlier. The capacity of each project is scaled according to the average capacity utilization at Sleipner and Snøhvit 2008-2014.

Source: (Global CCS Institute, 2016a).

3.1.5 Net abatement potential

We require that the target countries reach the Norwegian share of capturing 75.9% of the relevant CO_2 by 2030. In order to calculate the net abatement potential, we subtract the baseline in Table 7 *excluding* EOR-based projects, since CO_2 used for EOR is not guaranteed to be permanently sequestered.

The result for the 4 different cases (restrictive/inclusive and gas+combined oil/gas vs. all production) is shown in Table 8. As our central value for the solution as a whole, we assume the average of the four central values, and we take the range to be from the lowest low value to the highest high value of the 4 cases. We thus obtain *36 (5-79) MtCO₂* for 2025 and *63 (11-137) MtCO₂* for 2030.

Table 8: Net abatement potentials

Scope of emissions base	2025	2030
Restrictive, gas and combined oil/gas production only	8 (5-22)	17 (11-40)
Restrictive, all production (including also oil-only)	11 (6-29)	21 (11-52)
Inclusive, gas and combined oil/gas production only	54 (32-61)	95 (57-107)
Inclusive, all production (including also oil-only)	69 (35-79)	120 (62-137)
Main values	*36 (5-79)*	*63 (11-137)*

Note: All numbers are in $MtCO_2$. The baseline only includes projects that use permanent geological storage, not EOR.

3.1.6 Abatement cost

There is little solid data available on the likely cost of CCS in upstream gas and oil production or in natural gas processing, and the actual costs will vary depending on the context, in particular how much infrastructure needs (e.g., extra pipelines) need to be built relative to what is already in place. The McKinsey GHG abatement cost curve does include a cost estimate for CCS in the upstream oil and gas sector, but this is CCS for CO_2 from energy production (mainly gas turbines used to produce energy for operations), which is very different from CCS for fugitive geological CO_2. We here use measures of cost for the Sleipner project as an estimate.

The current cost of injection at Sleipner has been estimated at 17 US dollars per tonne CO_2. This however is a marginal cost, so we adopt this as the lower end of the cost range. As the upper end of the range, we use the Norwegian CO_2 tax, which was a sufficient incentive for Statoil to decide on implementing CCS at Sleipner. At the time of construction (1996), the tax was approximately 35 USD/tCO_2 (2010 NOK/tCO_2). Converted to 2012 US dollars, this becomes 48 USD/tCO_2 (World Bank, 2016). We thus adopt a cost range of *17-48 USD/tCO_2*, and adopt the middle (*33 USD/tCO_2*) as the central value.

Applying these unit costs to the main values adopted for the net abatement potential, we get a total cost of *1.2 (0.09-3.9) billion USD/tCO_2* in 2025, and *2.1 (0.18-6.7) billion USD/tCO_2 in 2030*.

3.1.7 Important enablers

The most important enabler for CCS of any kind, is to establish a financial incentive. Unlike many other forms of mitigation, CCS usually has little commercial value beyond reducing climate change risks. As a result, government incentives or mandates are almost always needed. There is a commercial value for some uses of CO_2 – notably EOR – but permanent storage of the CO_2 is then not guaranteed. More or less permanent storage is a possibility for some uses (e.g., EOR and use in construction materials). But most other uses, such as for carbonated beverages in the food industry or enhanced growth in greenhouses, lead to all or most of the CO_2 eventually being released to the atmosphere.

In Norway, the CO_2 tax (as well as a direct licensing requirement in the case of Snøhvit) was the main incentive for CCS in the petroleum sector. It was 210 NOK in 1996 (approximately 35 USD at 1996 exchange rates) at the time operations began at Sleipner, and has since been gradually increased to the current level of 540 NOK (approximately 65 USD) (Global CCS Institute, 2016b).

Various legal aspects of CCS are also poorly developed in some regions, notably safety requirement and requirements for long-term monitoring of stored CO_2. Ensuring consistent and complete regulations and legal frameworks for all aspects of CCS would help improve predictability for investors, and thus expedite investment decisions once financial incentives are in place.

3.1.8 Possible barriers

Public resistance or indifference towards CCS is currently a significant obstacle for greater efforts in developing and deploying CCS. Fears about leakage (whether justified or not), misunderstandings about the safety of CCS (e.g., fears that the underground "gas" could explode), general NIMBYism and concerns that it provides an "excuse" for continuing use of fossil fuels indefinitely, have all led to CCS being an unpopular solution among large parts of the public and many environmental organizations. Only the last concern is likely to be a significant factor for CCS in oil and gas fields, in particular offshore ones. The negative attitudes may also be changing somewhat as people become aware of the central role CCS plays in almost all scenarios for limiting global warming, but more effort on the educational and public relations front is still needed.

All commonly used and most commonly explored methods of geological CO_2 storage require specific types of sedimentary rocks formations. In particular, traditional CCS is not possible in locations with igneous rocks such as basalt or volcanic rocks. This is a concern for some parts of the world with large volcanic provinces, such as Japan, large parts of India, eastern Africa and parts of China. It is not a major concern for upstream oil and gas production, except possibly in the case of gas processing plants located far from extraction sites, since oil and gas fields are usually associated with the type of sedimentary formations needed. However, where needed for other industries, the new method developed in Iceland to incorporate injected CO_2 into basaltic rocks shows great promise, and is thought to be even cheaper than more traditional options.

3.1.9 Major co-benefits

There are few if any co-benefits from capturing and storing CO_2 permanently, except for EOR and a few other use cases, for which there is concern that the CO_2 could be released to the atmosphere again. For most use cases apart from EOR, most of the CO_2 is practically guaranteed to be released over the short or medium term.

As with any new technology, however, CCS can bring benefits in terms of developing new technologies and techniques that may be transferrable to other areas. Innovative, large-scale CCS projects may also help attract talent to the country or municipality hosting them, and may help growth in the local economy.

3.1.10 Current situation in other countries

Nine other CCS projects are already operating or scheduled to begin operations soon in the oil and gas industry or in natural gas processing, with a combined capture capacity of almost 20 $MtCO_2$ per year. Five are located in the United States, with one more in each of Brazil, Saudi Arabia, Australia, and China. In addition, there is one project in the power sector currently operating in Canada, and several in various stages of planning or construction in the United States, China, the United Kingdom, South Korea, and the Netherlands. The United States, China, Canada and Australia also operate or are planning several projects in chemical industries or in fertilizer production, and the first phase of the world's only project in the steel industry is in the final stages of construction in the United Arab Emirates.

3.2 Reduced methane emissions in oil and gas production

3.2.1 *Description of the solution*

Methane is the main component of natural gas, and is also usually present together with heavier hydrocarbons in petroleum reservoirs. It is also a potent greenhouse gas, with a global warming potential 30-36 times that of carbon dioxide over a 100-year period (See table 8.7 of Myhre *et al.* (2013)).[29]

Methane is released both intentionally and unintentionally as part of oil and gas extraction, as so-called fugitive emissions. Unintentional releases include leakages from wellheads and pipes at the production site, as well as from midstream pipelines when transporting the gas to a processing facility. Intentional releases happen primarily for safety reasons if needed to vent pressure, or during start-up or wind-down of production. Most intentionally released methane is burnt on release (flaring) and converted to CO_2, usually because the production site is too far away from a major demand centre to make transporting and selling the gas unattractive. Large but poorly quantified amounts of methane also escape through leakage from downstream distribution networks, as well as from refineries and various methane-consuming industries.

In this solution, we will discuss reducing release of methane in the upstream petroleum sector, not methane converted to CO_2 through flaring or downstream leakage. A similar solution based on U.S. measures to reduce methane emissions was discussed in the global Green to Scale report (Afanador *et al.*, 2015). We here look at the results obtained in Norwegian oil and gas production, and scale those up globally as described below.

There is considerable uncertainty about the amount of fugitive methane emissions at all stages of the value chain. Some countries have launched major efforts to measure the emissions, notably the US Environmental Protection Agency (see, e.g., US EPA (2016b)) and, in a Nordic context, the Norwegian Environment Agency (Husdal, Osenbroch, Yetkinoglu, & Østebrøt, 2016). However, reported methane emissions are often based on production volumes and standard emission factors (in large part derived from US EPA work) (IEA, 2013).

---

[29] After being released to the atmosphere and exposed to oxygen, methane is gradually oxidized and converted to carbon dioxide, with a mean lifetime of approximately 12 years. The climate effect therefore varies greatly over different time scales. The 100–year global warming potential cited here is most commonly used, but in scenarios where climate change impacts become severe already in the near term, one could argue that a higher value / shorter time scale should be used.

Norwegian oil and gas production is reported to have the lowest methane intensity of any major oil- or gas-producing country,[30] [31] and has seen a steady decline in methane intensity over the past decade greater than the global average rate of improvement (see below). According to the industry itself, this is not primarily the result of a specific focus on reducing methane leakages, but rather due to strict safety regulations and high-quality equipment (Statoil, 2013). All oil and gas production in Norway also takes place offshore, which requires greater attention to pipe sealing and equipment durability than onshore production.

Due to the favourable circumstances in Norway, to the likely prohibitive cost of replicating every part of the solution in Norway by essentially reconstructing much existing infrastructure using higher quality materials and equipment, and to the great differences between the characteristics of different oil and gas fields, it would be unrealistic to expect many other countries to achieve Norway's low absolute methane intensity. We do estimate what the impact of this would be, but do not use it as the main scaled abatement potential for this solution. Instead, we require the target countries to achieve the same annual rate of reduction from 2018 to 2030 as the average achieved by Norway in the 10-year period 2000-2010 (–2.3%).[32]

3.2.2 *Impact in originating country*

In 2000, Norwegian oil and gas production had a methane intensity of only 3.5 kg of methane (kgCH_4) per TJ of oil and gas production. By 2010, this had gone down to 2.8 kgCH_4/TJ, an average reduction of 2.3% per year. By comparison, most other oil and gas producing countries had intensities of several hundred kgCH_4 per TJ, with intensities typically *increasing* over the same period or going down by only fractions of a percent per year. No country had a lower methane intensity, and only two countries included in our analysis had higher rate of reduction (Egypt and Vietnam).[33]

---

[30] We here define methane intensity as average number of tonnes of methane emitted per unit energy of oil or gas extracted.

[31] Estimated by combining methane emission estimates as described later in this chapter with production statistics from IEA (2016b).

[32] This period is selected primarily for data reasons, but also has the advantage of not having seen a startup of very many new oil and gas fields (which is often associated with significant startup emissions), while still seeing some new construction take place, as well as significant wind-down of some older fields, so that the reduction in methane intensity is representative of a shift from older to newer equipment and standards.

[33] We combine estimates of methane emissions from the US Environmental Protection Agency (see Data Annex of (US EPA, 2012)) with oil and gas production statistics from IEA (IEA, 2016b). While more recent methane emission estimates are available from other sources for a few individual countries, we use the EPA data set to have a consistent source that covers most countries in the world.

Total oil and gas production in Norway decreased by 9% from 2000 to 2010 (measured in energy terms), but methane emissions from oil and gas production decreased by 28%. If Norway's production had stayed constant, the reduction in methane intensity would have implied a reduction in methane emissions of 176 ktCO_2eq using a 100-year global warming potential of 30, which is very modest in absolute terms due to Norway's already low methane intensity, but still represents a 21% reduction in relative terms. In a country with more typical methane intensity, the same relative reduction would have been several tens of megatonnes of CO_2 equivalents.

3.2.3 Scale-up method

We require that the countries we scale up to achieve the same rate of reduction in methane intensity in their oil and gas production as Norway did from 2000 to 2010 (–2.3% per year), for the period 2018-2030. For comparison, we also estimate the abatement that would result if the same countries by 2030 also achieved the very low methane intensity that Norway had in 2010 (2.8 kgCH_4/TJ, or 84 kgCO_2eq/TJ), but do not view this as a realistic potential.

We interpolate between the most recent year of data for oil and gas methane emissions and US EPA projections for 2020 to set the initial emission levels in 2018. We then use projections for oil and gas production from the IEA's New Policies Scenario (IEA, 2015) in 2020, 2025 and 2030 to interpolate the production level in 2018, and to set the production levels that we multiply by the resulting emission intensities in 2025 and 2030 to find methane emissions in those years given that the solution is implemented.

The available data for the New Policies Scenario in the World Energy Outlook do not give projections for all the countries we include. For other countries, we calculate the production growth in the rest of the region in which the country is located (the total for the region minus all the countries for which the World Energy Outlook contains an individual projection), and assume the same growth rate for the country in question.

Also note that the US EPA data does not separate between emissions in the upstream oil and gas sector (associated with extraction at oil and gas fields), and downstream emissions from processing and distribution. No global data set makes this distinction, but our solution only concerns the former. However, an IEA analysis estimates that the upstream industry accounts for approximately 50% of the emissions globally (IEA, 2013). For each country, we therefore scale the methane emissions estimated by the US EPA by the ratio between oil and gas production in the country divided by total production plus consumption.

Although achieving Norway’s low methane intensity would probably be prohibitively expensive for most countries, the relatively high intensities in most countries suggest that achieving the same reduction rate as Norway should be considerably less challenging and costly. Combined with the relative wealth of most oil and gas-producing countries, we therefore assume that all oil and gas producing countries with a level of economic development at or above that of an oil- or gas-producing Middle Eastern or former Soviet country can implement the solution.

In addition, to include a country in the analysis, we require that total oil- and gas-related methane emissions be considerable (more than 2 $MtCO_2eq$ in 2010), and that oil and gas production be at least twice the size of domestic consumption, in order to reduce the uncertainty in the relative share of upstream and downstream emissions. We also exclude countries which are known to have initiated major efforts that are likely to reduce methane emissions much more than our imposed growth rate but which may not have shown up in the 2000-2010 data, excluding notably the US and Canada.

We then end up with the countries listed in Table 9. In addition, four more countries meet the inclusion criteria (Argentina, Azerbaijan, Oman, and Turkmenistan), but are excluded because the US EPA and IEA projections imply a rate of methane intensity reduction of more than 2.3% per year.

Table 9: Countries included in the scaled abatement potential

Europe/Central Eurasia	Middle East	Asia Pacific	Americas
Russia	Egypt	Brunei	Colombia
	Iran	Indonesia	Mexico
	Iraq	Malaysia	Venezuela
	Kuwait	Vietnam	
	Saudi Arabia		
	UAE		

Note: See main text for the selection criteria used. Argentina, Azerbaijan, Oman and Turkmenistan would also be included if their baseline annual methane intensity reduction were not projected to be greater than that of Norway during 2000-2010. Syria is also excluded due to the ongoing turmoil in the country.

3.2.4 Baseline

For our baseline, we use the upstream oil and gas-related methane emissions in 2025 and 2030, calculated from US EPA projections as described in the previous section. The estimated baseline emissions in the selected countries are 1.10 $GtCO_2eq$ (36.8 $MtCH_4$) in 2025 and 1.18 $GtCO_2eq$ (39.2 $MtCH_4$) in 2030.

3.2.5 Net abatement potential

By imposing the growth rate described in section 2.1.3, we obtain absolute upstream oil- and gas-related emissions in the target countries of 905 $MtCO_2eq$ (31.2 $MtCH_4$) in 2025, and 845 $MtCO_2eq$ (28.2 $MtCH_4$) in 2030, when using a 100-year GWP of 30. However, to account for the uncertainty in GWP values related to climate feedbacks over time, we use a range of GWPs from 30 to 36 to calculate the net abatement potential (cf. Table 8.7 of Myhre *et al.* (2013), and discussion in Section 1.5). The net abatement is then *216 (200-233)* $MtCO_2eq$ *(6.66* $MtCH_4$*) in 2025* and *357 (329-384)* $MtCO_2eq$ *(10.0* $MtCH_4$*) in 2030*.

If we impose the probably unrealistic requirement that each target country achieves Norway's actual methane intensity for 2010 by 2030, the abatement becomes rather staggeringly high at 1.10 $GtCO_2eq$ (36.4 $MtCH_4$) in 2025 and 1.16 $GtCO_2eq$ (38.7 $MtCH_4$) in 2030, using a GWP of 30, a rather extreme 98.9% reduction relative to the baseline in both years.

3.2.6 Abatement cost

There are no estimates available on the cost difference of specific measures that Norway has taken to reduce methane emissions. Further, because of the great variations between onsite conditions, individual countries must be able to use a variety of country-specific measures to achieve the targeted reduction rates. We therefore base our cost estimate on the most comprehensive assessment of global methane abatement opportunities to date, the US EPA 2013 report on Global Mitigation of Non-CO_2 Greenhouse gases (US EPA, 2013). In so doing, we are strictly speaking assuming that each target country will not take exactly the same measures as in Norway, but rather that they will implement the measures that are most cost-effective for their individual circumstances in order to reach the same rate of reduction in methane intensity of oil and gas production as Norway.

The US EPA analysis provides marginal abatement cost curves for both the world in total, major regions, and for a few selected individual countries. We estimate the abatement cost by assuming that the mitigation options in the US EPA cost curve are implemented in order of increasing cost, starting with the options with the lowest cost / greatest savings.

Unfortunately, the published numbers do not in general disaggregate upstream and downstream oil and natural gas systems as we require for our analysis, but this disaggregation is available for the United States alone.

In the U.S., upstream and downstream measures are distributed relatively evenly along the cost curve, and upstream measures account for approximately 63% of the total abatement potential (in the US EPA analysis, restricted to the U.S. alone). Further, the net abatement potentials in our analysis amount to 17% of the global potential identified by the US EPA in 2025, and 27% in 2030. Assuming that upstream and downstream measures are distributed similarly in our target countries, we estimate that we would need to go up to 27% of the global potential along the cost curve in 2025 and to 43% in 2030, in order to capture 17% and 27%, respectively, from upstream measures alone.

The average cost of the measures thus included, using the global cost curve, is –27 USD/tCO$_2$eq in 2025 and -24 USD/tCO$_2$eq in 2030. However, the EPA cost curve for some significant regions, notably Russia, has higher costs relative both to the US and to the global cost curve. We therefore adopt a range of costs between the global cost curve and the highest-cost large country (Russia), leading to a range *from -27 to -7 USD/tCO$_2$eq in 2025* and *-24 to -7 tCO$_2$eq in 2030*, using a GWP of 30. We adopt the averages (–17 and -15 USD/tCO$_2$) as central values. The total cost (i.e., savings) is then -*5.3 to -1.4 billion USD in 2025*, and *-8.0 to -2.1 billion USD in 2030* (central values -3.3 and -5.1 billion USD).[34]

Note that the costs quoted here are average costs. The marginal costs are higher, and average costs would increase if a higher level of abatement is sought, as this would require implementing measures further and further up the US EPA cost curve.

3.2.7 Important enablers

Until recently, there has been a relatively low focus on reducing methane leakage, even though a majority of the measures needed to reduce them would result in net savings after taking the value of the fugitive gas into account (US EPA, 2013). Government programmes to spread information about cost-effective technologies and operational procedures can help increase awareness and implementation. The most prominent (and

---

[34] We give here the unit costs for a GWP of 30 only, in order not to mix the range due to uncertainty about the unit cost, and the range due to uncertainty about the GWP value. The unit costs are then multiplied by the abatement potential at a GWP of 30 to obtain the total costs, which only depend on the amount of methane abated and are not affected by the choice of GWP.

arguably most impactful) example of this is the Natural Gas STAR programme administered by the US EPA (see Section 3.2.10).

In the cases where financial incentives are not sufficient or even not present (e.g., due to only relatively expensive options being available, or a low return rate relative to what the producing companies normally require), direct requirements, rewards or penalties from regulators may be required.

3.2.8 Possible barriers

Even though most abatement of oil- and gas-related methane emissions have negative cost when accounting for the value of the recovered gas, that value is not always applicable. If an oil field is not in a suitable location relative to potential customers to sell any associated gas, the gas has no intrinsic value and is usually disposed of through flaring. In such cases, there is no financial incentive to reduce methane emissions. This can be remedied by building pipelines or infrastructure for gas liquefaction and transport, but the capital requirements are likely to be too high to make sense in most cases. This could be an issue for eastern Russian oil fields in particular.

Even when abatement measures do result in savings or increased profit, most actors in the oil and gas industry are used to high return rates, and the relatively low returns on methane abatement measures may not be attractive enough.

3.2.9 Major co-benefits

The benefits from reducing methane leakages and other oil- and gas-related methane loss are mainly financial, through the additional sales value of the recovered gas. But the focus on better designs and materials, increased maintenance and inspection required to implement the solution, is likely to also lead to better safety levels, less downtime and more efficient operations, and probably also health benefits from reduced emissions of reduced emissions of volatile organic compounds and other air pollutants associated with oil and natural gas extraction as well.

3.2.10 Current situation in other countries

The United States, under the governance of the US EPA, has been one of the most active countries in taking steps to quantify and reduce methane emissions. The most prominent abatement programme is the Natural Gas STAR programme (US EPA, 2016a), a voluntary partnership, in which the participants both receive and share information about cost-effective technologies and solutions, and can voluntarily have their achievements recorded in a public registry. The EPA has also expanded this programme to international partners, and has recently also initiated the Natural Gas STAR Methane Challenge programme, in which partners make public measurable commitments in return for having their commitments and eventual achievements showcased.

Russia has also been somewhat proactive in reducing methane emissions, by setting targets to reduce methane flaring and coupling the targets to preferential market access or penalties for companies. They have achieved methane intensity reductions of more than 1% per year since the early 2000s, although their absolute methane intensities are still nearly 3 times as high as the United States.

3.3 Low-carbon industrial energy use

3.3.1 Description of the solution

The Nordic countries have relatively large share of energy-intensive industries, in particular when compared to other small- to medium-sized advanced economies, most of which have reduced their activity in such industries considerably as their economies developed (IEA / NCM, 2016). In the Nordic countries, in particular Sweden, Norway, Iceland, and – in the case of the paper and pulp industry – Finland, these industries enjoy particular benefits from natural resources and plentiful, relatively cheap and clean electricity.

Nordic industries have shown a decent though not exceptional reduction in energy intensity this decade. However, several Nordic industries stand out more clearly for their low carbon intensity (CO_2 per unit energy use),

For most industries, the main reasons behind the low carbon intensity cannot be easily transferred to other regions: Most industries benefit from the low-carbon electricity mix in the Nordic region, which cannot be replicated in other regions without major efforts in the power sector, and in some cases not at all by 2030 due to resource constraints. The metallurgical industries, in particular the steel industry, rely on high recycling rates, which make possible both lower energy use and a higher share of electricity in the energy mix. Most industries also have a higher share of electricity in their energy mix thanks to relatively low electricity prices (thanks to large hydropower capacity and other renewable resources, and relatively low populations, which leads to less pressure from household demand). And several sectors can have so much internal structural variability between different countries (e.g., the chemical and petrochemical industry, the non-metallic minerals industry and the non-ferrous metals industry) that comparison with other countries becomes unhelpful without a more detailed sub-industry analysis than we can undertake in this analysis.

The only industry for which the carbon intensity in the Nordic countries stands out *and* where the drivers are likely to be mostly transferrable to other countries, is the pulp and paper industry, which is dominated almost equally by Sweden and Finland, plus smaller volumes in Norway. Although the absolute carbon intensity in each country has varied considerably, it has typically been less than two-thirds of the OECD average, and one-third to one-half of the world average.

The pulp and paper industry in many countries derive a high share of their final energy from biomass by using wastes and residues from their main raw material – wood – and by reusing waste products from part of the pulping process (e.g., "black liquor"), which can contain as much as 50% of the energy from the original wood input. The rate of using this resource varies greatly between countries, and the Nordic countries – Sweden in particular – have excelled at it. On average over the period 2003-2013, the pulp and paper industry in Finland and Norway derived 76% and 72%, respectively, of their non-electricity final energy consumption from bioenergy, and Sweden as much as 89%. By comparison, the OECD average for 2013 was only 54%, the world average 39%, and the average in non-OECD countries as low as 16% (IEA, 2016b).

In the following, we will take the solution to be that the pulp and paper industry in the target countries achieves either a carbon intensity or a reduction in carbon intensity that matches either Finland or Sweden (see below). We base the solution on Finland and Sweden because their pulp and paper industries are much larger than Norway's, and because the Norwegian pulp and paper industry has an unusually high share of electricity in its energy mix,[35] which may make it less suitable for international comparison.

The reduction would primarily be done by increasing the share of bioenergy in the energy mix. In most cases, this should be possible using mostly wood-derived wastes and residues, but we acknowledge that in some countries these may not be as plentiful as in Sweden or Finland, and therefore adopt growth rates rather than absolute intensities where appropriate.

Note that this solution may seem to overlap with the use of CHP in industry (including the pulp and paper industry) in Chapter 2.1. In that solution, heat generated directly from combustible fuels – including both biomass and fossil fuels – is replaced with waste heat from electricity-generating units. A large part of the present solution is instead to replace much of the heat generated from fossil fuels with a higher share of bioenergy, mainly derived from wood residues. Heat production replaced in one solution is strictly speaking not available to be replaced in the other. However, a hybrid solution, in which

---

[35] Presumably due to high hydropower capacity and generally low electricity prices.

the total abatement could be approximately equal to the sum of both solutions individually, would be to implement the CHP solution as before, but require that a suitable proportion of the CHP use bioenergy rather than fossil fuels. In the original CHP solution, there was no such requirement, and it was instead assumed that fuel input to CHP on average had the same carbon intensity as the local average fuel input to electricity generation.

3.3.2 Impact in originating country

As mentioned, both Finland and Sweden have among the world's highest shares of bioenergy use in their pulp and paper industry, and their low carbon intensities reflect this. The global average direct carbon intensity in this industry was 34.7 tCO_2/TJ,[36] with 22.1 tCO_2/TJ for the OECD countries and 54.6 tCO_2/TJ for non-OECD countries. Finland meanwhile had a carbon intensity of only 14.4 tCO_2/TJ, while Sweden was in a class of its own at 4.3 tCO_2/TJ (IEA, 2016b).

In the scale-up (see next section), we will use the average carbon intensities in Finland for the period 2001-2013, to have the same length as the implementation period 2018-2030 for the target countries. We will present numbers for both Finland and Sweden, but in the final scale-up we will use Finnish implementation levels only, as the Swedish numbers look too ambitious.

In the 2001-2013 period, average pulp and paper industry carbon intensities were 17.6 tCO_2/TJ in Finland and 8.6 tCO_2/TJ in Sweden, while the average growth (reduction) rate for the carbon intensities were -3.1 and -7.4 percent per year, respectively. The low carbon intensities saved 0.7 $MtCO_2$ (21%) in Finland and 2.1 $MtCO_2$ (49%) in Sweden per year relative to OECD average, or 2.8 $MtCO_2$ (61%) and 4.2 $MtCO_2$ (75%) relative to the world average.

3.3.3 Scale-up method

We assume that all countries with a significant pulp and paper industry can take steps to reduce the carbon intensity, even in non-OECD countries, where the currently quite high carbon intensity and low share of bioenergy use indicate significant potential for

---

[36] By "direct" carbon intensity, we mean CO_2 emitted directly from the industry itself (not including CO_2 emitted to generate the electricity or the delivered heat it consumes) divided by total final energy use excluding electricity and delivered heat. This should in most cases be equal to the average emission factor of all fuels combusted directly by the industry itself, weighted by energy content. Unless otherwise noted, we mean "direct" carbon intensity wherever the term "carbon intensity" is used for this solution.

improvement. However, because of the extremely low carbon intensity / high bioenergy share in Sweden, and the generally high availability of wood residues in both countries, we need to be careful about what figures we seek to scale up.

For OECD countries, the already relatively low carbon intensity makes it not completely unrealistic that they could achieve Finland's average absolute carbon intensity for 2001-2013 (17.6 tCO_2/TJ, approximately 20% below the OECD average), by 2030. Sweden's even lower intensity (8.6 tCO_2/TJ, almost 60% below the OECD average), however, looks out of reach. The picture for growth rates is similar; Finland's 2001–2013 annual CO_2 intensity reduction rate of -3.1% would result in just over 30% reduction by 2030, while Sweden's rate of -7.4% per year would again imply a less realistic-looking 60% reduction by 2030. We therefore scale the solution up to OECD countries by applying a range from an absolute carbon intensity of 17.6 tCO_2/TJ by 2030, to a reduction rate in carbon intensity of -3.1% per year.

For non-OECD countries, applying either Finland's *or* Sweden's absolute intensities would require a questionable 68% and 84% reduction relative to 2013 levels, respectively. Applying growth rates give the same relative reductions as for OECD countries. For non-OECD countries, we use only Finland's 2001-2013 reduction rate of -3.1% per year.

3.3.4 Baseline

The published details of the New Policies Scenario of the IEA do not contain enough details on the pulp and paper industry to construct a baseline. We instead use the 4DS scenario of the IEA's Energy Technology Perspectives 2016 (IEA, 2016a), which contains breakdowns of energy use and CO_2 emissions for selected energy-intensive industries, including the pulp and paper industry.

In the 4DS, carbon intensity in the pulp and paper industry decline by only 0.4% per year on average in OECD countries and 0.6% per year outside the OECD, reaching 20.5 tCO_2/TJ and 49.2 rCO_2/TJ, respectively, in 2030. Total emissions reach 226 $MtCO_2$ in 2025 and 231 $MtCO_2$ in 2030, with approximately one-third in the OECD countries.

3.3.5 Net abatement potential

Using the scale-up as described in Section 2.1.3 and subtracting the baseline described in Section 2.1.4, we get a total net abatement potential of *34 (31-37)* $MtCO_2$ *in 2025*, and *57 (52-63)* $MtCO_2$ *in 2030*. The breakdown for OECD and non-OECD countries is shown in Table 10.

Table 10: Net abatement potentials

Region	2025	2030
OECD	9 (6–12)	16 (11–21)
Non-OECD	24	41
World total	*34 (31 –37)*	*57 (52–63)*

Note: All numbers are in $MtCo_2$.

3.3.6 *Abatement cost*

The cost for implementing this solution will likely vary greatly depending on local circumstances, and the pulp and paper industry is not included in McKinsey's global abatement cost curve. The cost curve does however include a measure for replacing coal by biomass in several processes in the chemical industry, which is likely to capture much of what is needed for the current solution. The cost may in fact be a good deal less since more of the biomass used in the pulp and paper industry will be waste, but we use the McKinsey cost here as a conservative estimate.

The cost there is *23 USD/tCO_2*, after converting from 2005 euros to 2012 US dollars. This includes a blend of new build and retrofit costs. The total cost then becomes *762 (694-830) million USD in 2025*, and *1.31 (1.19-1.42) billion USD in 2030*.

3.3.7 *Important enablers*

The most important enabler for this solution is sufficient waste wood residues or other biomass sources. The carbon intensity can of course be reduced by supplying biomass from other sources as well, but this would both increase cost and raise more questions about sustainability.

3.3.8 *Possible barriers*

Biomass supply from wood wastes may be considerably lower in countries which do not have a large forestry industry of their own and which need to import pulp. High recycling rates could paradoxically also make high biomass use more challenging by reducing the amount of wood wastes available per unit of produced paper, but the net effect is not clear, since using recycled paper also reduces the total energy demand.

There are also concerns about the impact of bioenergy use on ecosystems and food production in general (which should not be a major issue for this solution) and whether bioenergy is truly carbon neutral, i.e., does not cause a net increase in average atmospheric CO_2 concentrations (which is only an issue if the solution leads to extra biomass extraction rather than using existing residues). See discussion of these issues in Section 1.6.

3.3.9 Major co-benefits

Increasing the share of bioenergy in the pulp and paper industry, particularly in non-OECD countries where the utilization rate is still low, is a good way of increasing bioenergy use without encroaching on agricultural land or increasing the total rate of bioenergy extraction from ecosystems. Also, in some cases the energy made available can be enough to also provide some energy to other sectors.

4. Transport sector solutions

4.1 Electric vehicles

4.1.1 Description of the solution

Norway is a world leader in replacing conventional cars with electric vehicles (EVs). Owners of EVs have had numerous benefits over a long period of time (Fridstrøm, 2013), which has resulted in a large increase in the sales of EVs, especially since 2011. There is a high registration tax on conventional cars, based partly on CO_2 and NO_x emissions. EVs are exempt both from these taxes and from VAT. In addition, owners of EVs enjoy a number of benefits. The annual registration fee is heavily reduced for EVs. Further, EVs are exempt from road tolls and parking fees in public parking spaces, and may use public transportation lanes. Charging stations have also been built to cover most urban areas, as well as between the largest cities.

From 2015, the vehicle tax based on CO_2 emission was changed, to also reduce the tax for plug-in hybrid-electric vehicles (PHEVs). This change has resulted in a large increase in the sale of PHEVs.

4.1.2 Impact in originating country

EVs in Norway are by many seen as zero emission cars, as the electricity mix in Norway contains almost no fossil fuels. In countries with a greyer electricity mix – i.e., most countries – the abatement impact will be smaller. For regions with a high share of coal in their electricity mix, the mitigation benefit can even be cancelled out. However, we see a general trend towards decarbonisation of power production in most markets, which will increase the abatement potential for EVs over time.

At the end of 2015, 2.6% (69,100 cars) of the private vehicle fleet in Norway were EVs (SSB, 2016b). In addition, PHEVs had a 0.5% share (EV Norway), which gives a total 3.1% share for EVs and PHEVs. As sales of these cars have exploded in the last five years, these shares are expected to grow further. Due to a car lifetime of about 17 years in Norway, it takes time to replace conventional cars with EVs and PHEVs.

The share for newly registered cars is much higher. In 2015, 17% of the newly registered cars were EVs and 5.3% PHEVs (OFVAS, 2016). In total, low and zero emission cars had a share of 22%.

The abatement impact of these low emission vehicles depends on how they are used, in particular to what extent they replace conventional cars or simply come in addition. In our estimates, we assume that EVs and PHEVs replace conventional cars. Recent findings show that EVs are driven the same annual distance as an average car (12 987 km versus 12 387 km for an average personal car in 2015) (SSB, 2016a).

4.1.3 Scale-up method

We assume that EV incentives are most relevant for high-income and upper middle-income countries, and therefore base our calculations on having the OECD region, Brazil, and China copy the development in Norway by 2030. We assume an exponential growth towards 2030, and use this growth curve to interpolate the abatement potential for 2025.

We use two different main cases. The first, low-range case is based on other countries achieving Norway's 2015 share of EVs in their car fleet by 2030. The second, higher-range case is based on them having Norway's 2015 share of EVs in new *sales* from 2018 to 2030, given that the explosion of EV sales in Norway is relatively recent, and therefore has not had time to effect a major shift in the total vehicle fleet yet. In each of these cases, we make one calculation for only EVs and one calculation with both EVs and PHEVs (in the same proportion as in Norway in 2015).

Our analysis is based on how much gasoline and diesel conventional internal combustion engine (ICE) cars use, as well as the electricity consumption of EV and PHEV cars. The greenhouse gas emissions of these sets of technologies are compared based on the distances these vehicles in total are driven. The details and scaling applied follow in the next two paragraphs.

We assume an average consumption of 0.2 kWh/km for an average EV, as EPA find that Nissan Leaf and smaller EVs typically have fuel economy slightly better than this, while larger EVs such as Tesla Model S have larger consumption. For PHEVs, we assume that 66% of the distances they are driven is on electric power, based on assumptions in McKinsey Global Greenhouse Gas Abatement Cost Curve v2.0 (McKinsey, 2009). For simplicity, we assume the same gasoline consumption for PHEVs as for gasoline cars when the PHEVs are not on electric power.

We estimate the electricity demand for EVs in Norway in 2015 to be 180 GWh, increased to 200 GWh when PHEVs are included. This estimate is based on an average annual driving distance of 13,000 km and an average consumption of 0.2 kWh/km. We scale these numbers to the OECD, Brazil, and China by comparing the gasoline and diesel demand in Norway today with the expected demand in the OECD, Brazil, and China in 2030. In Norway, transportation consumed 130 PJ from gas/diesel oil excluding biofuel (in 2013, the most recent year available from IEA's energy statistics) (IEA, 2016b). To scale this to OECD, China and Brazil in 2030, we use the 4 Degree Scenario (4DS) of the IEA Energy Technology Perspectives 2016 (IEA, 2016a). That scenario foresees a demand for conventional gasoline/diesel of 56 EJ in 2025 and 55 EJ in 2030 for the OECD region, China, and Brazil altogether.

4.1.4 Baseline

More than 1.5 million EVs have been sold worldwide, and the sales of these cars are expected to grow with current policies. The World Energy Outlook expects with the current policies that the electricity demand from electric vehicles in 2040 will be 240 TWh following an annual growth of 18.2% (IEA, 2015). Our baseline is therefore that EVs and PHEVs demand 22 TWH in 2025 and 51 TWH in 2030. Unfortunately, this baseline is global, while we only estimate the EV and PHEV demand in OECD countries, Brazil, and China. However, we believe most of the global demand will occur in these regions, partly based on current EV fleet. They currently cover more than 95% of global EV sales, and virtually all of the current global stock (US DoE, 2016).

We do not consider the potential overlap between electrifying the car fleet and replacing conventional fuel with biofuel, which today is most relevant for Brazil. The net abatement potential of these two solutions will be somewhat less than the sum of the individual solutions.

In our calculations, we assume electric vehicles to be 70% more energy efficient than conventional cars. This ratio is based on a consumption of 0.2 kWh/km for EVs and 0.07 litres of gasoline per km for gasoline cars.

4.1.5 Net abatement potential

In our first case (assume current fleet), the total energy demand from EVs (EVs and PHEVs in parentheses) in the OECD countries, Brazil, and China is 33 (37) TWh in 2025 and 77 (86) TWh in 2030 given the assumptions of vehicle efficiency and distance travelled above. If we subtract the energy demand in the baseline, the net additional electricity demand from EVs (EVs and PHEVs) is 11 (16) TWh in 2025 and 26 (36) TWh in 2030.

In our second case, the car fleet will consist of 4.6% EVs (1.4% PHEVs) in 2025 and 5.4% EVs (1.7% PHEVs) in 2030 if we assume that the car fleet is renewed in 17 years, as it is in Norway (Fridstrøm & Alfsen, 2014). The Nordic average age of the current car park is among the highest in Europe; hence, replacement rate may be faster for some regions. This estimated car fleet translates to an energy demand for EVs (EVs and PHEVs) of 140 (170) TWh in 2025 and 160 (190) TWh in 2030, which is 120 (140) TWh and 110 (130) TWh above the baseline, respectively.

Additional demand of electricity will increase the emissions from electricity production. Our calculation is based on the electricity mix in the New Policies Scenario in the World Energy Outlook 2015 (IEA, 2015). For the OECD region, the electricity mix contains 330 g CO_2/kWh in 2025 and 290 g CO_2/kWh in 2030. China has the greyest electricity mix, with 580 and 540 g CO_2/kWh in 2025 and 2030, respectively. Brazil has a much cleaner electricity mix, 62 and 59 g CO_2/kWh in 2025 and 2030, respectively.

The net mitigation potential is given in Table 11. The abatement potential varies from 17 to 83 MT CO_2-eq. in 2030, and we adopt the midpoint as the central value. As current sales of EVs and PHEVs are much higher than their share of the car fleet, the largest potential is seen based on current sales. The sales of EVs and PHEVs are expected to grow regardless of new policies, although their shares of the existing car park in Norway in 2015 was low, which explains the low abatement potential based on the Norwegian 2015 fleet. Most of the potential is from the EVs, while PHEVs can contribute about 20% of the potential. As we have only looked at the OECD region, China, and Brazil, the potential may be even larger if successful policies are also introduced in other regions.

It is also notable that we find an abatement potential for EVs that is an order of magnitude lower than that for biofuels in transport (Chapter 4.2). This does not necessarily reflect a lower total potential or lower importance for decarbonizing the global transport sector. Rather, the main reasons are that the degree of implementation for biofuels (biofuel share of total fuel in Sweden and Finland) is almost five times higher than the degree of implementation for EVs and PHEVs in Norway (share of electricity in total energy use in road transport), and that the biofuel solution is scaled up to all road transport globally, while EVs are only scaled up to personal vehicles in a smaller geographical region.

Table 11: The abatement potential for the OECD region, Brazil, and China in 2025 and 2030

Abatement potential ($MtCO_2$)	2025	2030
Based on 2015 fleet	6.8-9.3	17-23
Based on sales in 2015	70-84	69-83
Main values (central value and range)	*46 (7-84)*	*50 (17-83)*

Note: The lower value indicate the potential when only focusing on EVs, while the upper value includes PHEVs.

The net abatement potential is not high, but can be increased by reducing the share of fossil fuels (in particular coal) in the electricity mix. Other solutions analysed in this report (Onshore wind power, offshore wind power, and geothermal energy) do reduce the overall carbon intensity of electricity generation moderately, and would lead to a modest increase in the abatement potential for electric vehicles. However, to illustrate the full potential for electric vehicles to further reduce emissions in a world with a lower-carbon electricity system, we redid our calculations with the electricity mix given in the 450 scenario from IEA's World Energy Outlook (IEA, 2015), broadly compatible with a 2-degree target. In this case, the abatement potential increases significantly, especially in 2030, but still not dramatically (see Table 12).

Table 12: The abatement potential with a cleaner electricity mix, based on the 450 scenario

Abatement potential (MtCO_2.)	2025	2030
Based on 2015 fleet	7.9-11	21-29
Based on sales in 2015	81-97	86-104

4.1.6 Abatement cost

We apply the McKinsey Global Greenhouse Gas Abatement Cost Curve v2.0 for EVs and PHEVs (McKinsey, 2009). We estimate EVs and PHEVs to have abatement costs of 135 and 28 USD (in 2012 terms) per ton CO_2. The abatement cost per ton CO_2 is likely to decrease with larger sales or potential technology breakthroughs.

Unfortunately, we were not able to isolate the assumptions made by McKinsey for battery costs so that we could compare these to current industry projections. The cost curve does assume a dramatic reduction of almost 80% in the additional cost of an EV relative to an internal combustion engine vehicle (from 26,336 euros to 5,764 euros per vehicle, in 2005 currency), although the additional cost is still significant.

It should be noted that the abatement cost does not include the capital costs of widespread charging infrastructure, which is likely to be substantial, but will vary greatly depending on local circumstances. The total abatement costs are given in Table 13. The central value and range for the weighted average unit abatement cost are *120 (117-135) USD/tCO_2*. Note that the upper range of the cost interval corresponds to the *lower* range of the abatement potential and vice-versa, since the upper range of the abatement potential contains more PHEVs, which have a lower unit abatement cost than pure EVs.

Table 13: The abatement cost for the OECD region, Brazil, and China in 2025 and 2030

Abatement cost (Billion USD 2012)	2025	2030
Based on 2015 fleet	0.92-0.99	2.2-2.4
Based on sales in 2015	9.5-9.9	9.3-9.7
Main values (central value and range)	5.4 (0.92-9.9)	6.0 (2.2-9.7)

Note: The lower values indicate the potential when only focusing on EVs, while the upper values include PHEVs.

4.1.7 Important enablers

Effective abatement based on introducing EVs (as well as several of the other solutions analysed) requires several enablers that are present in the Nordic region. First, it can be argued that the integrated Nordic electricity market has incentivized both high inter-connector capacity and expansion of hydroelectric capacity in Norway and Sweden.

These factors are important for flexible, clean and reasonably priced electricity, which is a crucial to ensure that EVs have relatively low "fuel" costs and that emissions from the additional electricity production does not offset too much of the emission reductions from displaced gasoline and diesel use. Secondly, a high pre-existing tax level for conventional vehicles has made it easier to incentivize EV and PHEV purchases by simply forgoing tax revenue rather than actively subsidizing sales. Finally, Nordic income levels are relatively high, and new technologies tend to be adopted relatively quickly, which has made it easier to bear the high costs of early EV models (although this may be a less important enabler as costs come down).

The introduction of EVs in more countries as well as expansion in the Nordics depends on charging infrastructure. Although battery capacity and range of EVs are continuously improving, charging still takes significantly longer than refilling a fuel tank, and it is therefore important to install chargers in parking spots and other convenient locations where cars can be charged while drivers go about other business, while minimizing the need to make detours to visit special charging locations. Another enabler is a well-functioning local grid that can handle the large demand during peak charging.

4.1.8 Possible barriers

The technology shift can be capital intensive. Charging infrastructure is expensive to build and are likely not profitable in the early stages. Further, for consumers, buying a car is the most expensive part of being a driver, and the currently higher upfront cost for EVs is therefore a significant barrier, although this barrier is likely to be steadily lowered as batteries become cheaper.

Norway has a high tax on vehicle purchases and on fuels. Countries with less tax to cut might have fewer options to choose from to incentivize EVs or other low-emission vehicles, and may have to use different, less politically convenient policies and measures.

4.1.9 *Major co-benefits*

The most important co-benefit of electric vehicles, especially in urban areas, is drastically reduced air pollution levels and associated health benefits. Although electric vehicles still generate particulates from friction between tires and the road, they do not emit NO_x, volatile organic compounds or other pollutants associated with combustion engines, thus removing major categories of pollutants that can damage human airways and cause smog formation.

As EVs are more efficient that conventional cars, and the efficiency difference is typically greater than the energy loss in most reasonably efficient power plants, the total energy demand is reduced when converting from internal combustion engines to EVs. Noise levels along busy roads are also reduced.

4.1.10 *Current situation in other countries*

Several of the other Nordic countries are also among the countries in the world with the largest EV and PHEV sales, as well the Netherlands. In Finland, the sales are low because of nearly complete lack of targeted incentives. A range of countries has introduced government incentives for plug-in electric vehicles, such as a purchase discount of 4,000 EUR for most EVs and 3,000 EUR for most PHEVs introduced by the German government in 2016.

4.2 Biofuels in transport

4.2.1 *Description of the solution*

Finland and Sweden have reached relatively high shares of biofuels in road transport, due to blending obligations and taxation. The two countries have focused on different fuels: Finland on biodiesel, Sweden on bioethanol. Other Nordic countries also have blending obligations, but we focus on Finland and Sweden as the leading nations in the Nordic region in this field.

This solution has the potential to overlap with the solution of introducing electric vehicles (Chapter 4.1). However, these two solutions can be combined to target different segments of transportation, and the present solution will be formulated in a way that avoids overlap (in terms of shares of biofuels in total energy for transport rather than just liquid fuels). But if electric vehicles reach a very high share (higher than required in Chapter 4.1), the reduction in gasoline and/or diesel demand would make it more challenging to reach the absolute reduction in emissions foreseen in this chapter from substituting biofuels for fossil fuels in the transport sector. See also Section 1.4 for discussion of overlaps in general.

We define the solution as replacing fossil fuel in transportation with biofuels worldwide, and take the degree of implementation to be the share of energy from biofuels in total final energy consumption for transport. We give two estimates, one based on the Swedish case, the other on the Finnish case.

4.2.2 Impact in originating country

In Sweden, the total consumption of biofuels in all sectors in 2014 is 117 TWh, of which 12 TWh went to transportation (Swedish Energy Agency, 2016a). The share of biofuel in energy for road transport and all transport is given in Table 14. The scaling between road transport and all transport is based on numbers from Finland, as we assume the relative shares are comparable for Sweden and Finland.

Table 14: Biofuel share for transportation in Sweden in 2014

Share of energy content in transport fuel in Sweden	Share in road transport	Share of all transport
Ethanol	1,70%	1,4%
FAME (Fatty acid methyl ester, biodiesel mainly from vegetable oils)	4,30%	3,5%
Biogas	1,30%	1,0%
HVO (hydrotreated vegetable oil, alternative type of biodiesel)	7,50%	6,1%
Sum	*14,8%*	*11,9%*

The biofuel share for transportation in Finland is given in Table 15 and based on (Statistics Finland, 2016a). 9.3% of the energy needed in Finnish transportation comes from biofuels.

Table 15: Biofuel share for transportation in Finland in 2014

Share of energy content in transport fuel in Finland	Share of all transport
Biogas	0,027%
Biogasoline	1,4%
Biodiesel	7,9%
Sum	*9,3%*

4.2.3 *Scale-up method*

In the scale-up, we require the global transportation sector to achieve a share of biofuels in total energy use in 2030 somewhere between that achieved by Sweden and by Finland in 2014. Since biomass and various other biofuel feedstocks in most cases are relatively cheap and available globally, and the processing into biofuels in most cases is not overly complex or expensive, we do not impose any limits on which countries to include in the analysis. The estimates for 2025 are based on an exponential growth until 2030. For the scale-up in 2030, we use the total energy consumption by the transport sector in the 4DS scenario of IEA's Energy Technology Perspectives 2016 (IEA, 2016a).

While the mix of the transportation sector varies between countries, we assume a similar share of energy consumption for biofuels in all countries. For simplicity, we assume the biofuel needed is available and that countries are able to import biofuel if needed. Our estimates are in the same order of magnitude as current consumption of "modern bioenergy" for all sectors. In reality, physical constraints and in particular sustainability concerns can limit the biofuel supply. We find that the potential we arrive at in Section 4.2.5 can most likely be achieved sustainably (see Section 4.2.8, as well as 1.6), but may require moderate advances in second-generation biofuels. We also acknowledge that competition from other sectors for limited bioenergy resources could pose a challenge.

4.2.4 *Baseline*

Our baseline is taken from the 4DS scenario of IEA's Energy Technology Perspectives 2016 (IEA, 2016a), which sees a biofuel share in transportation of 3.6% in 2025 and 4.0% in 2030. In 2013, the biofuel share was 2.5%.

4.2.5 Net abatement potential

As Sweden had a higher biofuel share in 2014, the abatement potential is largest based on the Swedish numbers. This case gives a global biofuel energy consumption of 9.1 EJ (15 EJ) in 2025 (2030). These numbers are similar to current "modern bioenergy" consumption by all sectors and compare to 3.1 EJ/yr for current biofuel consumption by transportation (Chum *et al.*, 2011). Our second case (based on Finland) gives a global biofuel energy consumption of 7.6 EJ (12 EJ) in 2025 (2030). In comparison, the baseline has a biofuel energy demand of 4.3 EJ in 2025 and 5.1 EJ in 2030.

The net abatement effect of replacing liquid fossil fuels with biofuels is highly debated, due to sometimes high consumption of fossil fuels in vehicles and machinery employed in growing, harvesting and processing, and due to possible emissions from associated land use change. The effect of combusting large amounts of bioenergy on average CO_2 content in the atmosphere (whether it in fact stays unchanged) is also highly controversial.

For the net abatement effect of replacing fossil fuels with biofuels, we apply the range proposed by IPCC (Sims *et al.*, 2014). They give a best estimate of 60% when replacing conventional fuels with biofuels, and we use this figure in our calculations (they give a range of 30-90%). This includes fossil fuels used in producing biofuels, but does not take into account possible emissions from land use change, which would be highly variable and difficult to assess. We acknowledge that some specific biofuels from certain locations may be better or worse, even leading to increased CO_2 emissions. Sustainability issues, arising from competition for land with food production and/or from possible ecosystem disruptions, are also a significant concern, though probably not insurmountable for the implementation levels we arrive at in our analysis (see also Section 4.2.8, "Possible barriers" as well as 1.6).

The net abatement potential based on Sweden is 236 (118-354) $MtCO_2$ in 2025 and 506 (253-760) $MtCO_2$ in 2030. The Finnish case give a smaller potential, 164 (82-246) $MtCO_2$ in 2025 and 340 (170-511) $MtCO_2$ in 2030. As main values, we adopt the average of the central values for Sweden and Finland, and the combined ranges for both countries. We thus get a net abatement potential of *200 (100-300) $MtCO_2$ in 2025* and *423 (212-635) $MtCO_2$ in 2030*.

4.2.6 Abatement cost

We apply the McKinsey Global Greenhouse Gas Abatement Cost Curve v2.0 for biofuels (McKinsey, 2009). A weighted average of biofuels gives an abatement cost of *1.9 USD* *(in 2012 terms) per tonne CO_2*. First-generation biofuels have a slightly negative abatement cost per ton (i.e., slight net savings), while 2nd generation biofuels have a slightly larger, but positive abatement cost (i.e., net actual costs).

The total abatement cost (in 2012 USD) is then *376 (188-564) million USD in 2025* and *796 (398-1,194) million USD in 2030*.

4.2.7 Important enablers

This solution is based on a large increase in biofuel worldwide. This increase is likely to depend on technology improvements, especially for second and third generation biofuel, which do not necessarily require arable land to be grown and hence do not compete with food production, but which in most cases have *not* yet achieved commercial-scale production.

4.2.8 Possible barriers

Biofuel is limited, in terms of both technical potential and what part of this potential is sustainable. The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) states an enormous range in the technical potential, from less than 50 EJ to over 5,000 EJ per year (Chum *et al.*, 2011). Hoogwijk, Faaij, Eickhout, Vries, and Turkenburg (2005); Hoogwijk, Faaij, Vries, and Turkenburg (2009) have estimates of about 300 EJ/yr, while Dornburg *et al.* (2008); Dornburg *et al.* (2010) indicate a technical potential up to 500 EJ/yr.

Chum *et al.* (2011) review the potential deployment levels of biomass for energy by 2050 and conclude that it could be in the range of 100 to 300 EJ, after taking into account various sustainability concerns. In 2008, "traditional biomass" made up the bulk of primary energy demand from bioenergy (37-43 EJ/yr). Total "modern bioenergy" consumption was 11.3 EJ/yr, of which 3.1 EJ/yr went to road transport fuels (Chum et al., 2011).

These numbers suggest that the levels of total biofuel consumption for transport that our analysis yields (12-15 EJ in 2030) are considerable, at more than total current consumption of modern bioenergy sources, and 4-5 times current use of biofuels for transport. Such production levels could be difficult to achieve sustainably if done with first-generation biofuels, made from feedstock grown on dedicated agricultural land that is then made unavailable for food crops. But with the development of second-generation biofuels such as biomass-derived diesels (BTL diesel) and lingo-cellulosic ethanol, this level of biofuel production could be achieved without appropriating any extra productive land resources, but would require using the equivalent of 30%–37% of all residues from current agricultural and forestry residues (IEA, 2010).

Given these numbers, we do not think that sustainability concerns would be a challenge but not an insurmountable barrier for the target level of implementation we set for 2025 or 2030. However, they could become an issue with greater deployment beyond that timeframe. See also Section 1.6 for further discussions about bioenergy and sustainability in general.

Further, many climate scenarios consistent with the 2C goal also foresee large-scale bioenergy use in other sectors. Although many other sectors are more flexible in their fuel choices and could to some extent use biomass sourced from other sources, it is likely that such competition would place further constraints on the amount of biofuels available for the transportation sector.

As the biofuels are limited, certain sectors may be given priority. As the car fleet can be electrified and thus does not strictly speaking need this solution, it may be that aviation, heavy transport and non-transport sectors are prioritized, reducing the room for implementing the solution in the manner described in this section.

4.2.9 Major co-benefits

Biofuels reduce the dependency on fossil fuels, while limiting the need for new technology. If the car fleet is to be electrified, all cars have to be replaced. The biofuel solution is to some degree compatible with the internal combustion engine in current vehicles, as most ICEs can tolerate a share of biofuels in the range of 10-20% in their fuel mix, while many modern cars can tolerate much higher shares.

4.2.10 Current situation in other countries

Biofuel is also mixed into the gasoline or diesel mix in other countries, even in other Nordic countries. Many countries, including prominently much debated mandates for mixing biofuels into the gasoline supply in the US. Biofuels have also been approved for blending into aviation fuel as of 2011, but are currently not widely deployed, and are mainly used for test purposes.

4.3 Biking in cities

4.3.1 *Description of the solution*

Denmark is one of the countries in the world with the highest shares of biking in personal transportation. This solution describes biking in urban areas, which is a solution based on behaviour change, but depends on infrastructure and policies that encourage cycling. In Denmark, policies have focused on urban planning, transportation policies that favour biking, and bike parking facilities.

4.3.2 *Impact in originating country*

In 2015, Mason, Fulton, and McDonald (2015) estimated that Danes living in urban areas cycled 2.8 km per day. This cycling is expected to increase further. Cycling trips replaces a mix of trips with car, public transport, and walking.

4.3.3 *Scale-up method*

We initially scale up by assuming that people in all urban areas of the world in 2030 will bike the same average distance per person as Danes did in 2015 (although in practice, most of the resulting potential is reduced by a "sanity check", see below). For 2025, we take an interpolation between 2015 and 2030. As several regions and countries have very low level of biking in 2015, we do not expect that all regions can replicate Denmark by 2030. This is especially the case in regions like North America, where the infrastructure-related and cultural factors at the root of the low biking share also would make rapid gains difficult. We therefore include a sanity check, which is a maximum growth rate of 30% from 2015 to 2030. This relative increase is roughly the largest increase expected for the regions or countries with the largest growth between 2015 and 2030 in our baseline scenario (Mason *et al.*, 2015). This limitation kicks in for most countries and regions, and reduces the potential by 80%–95% in most regions outside of Europe and East Asia.

4.3.4 *Baseline*

The New Policies scenario does not contain sufficient published information about bike use to construct a baseline. We therefore use the report by Mason *et al.* (2015) as a baseline, which is based on the 4DS scenario of IEA's "Energy Technology Perspectives 2016" (IEA, 2016a). In that analysis, the world is separated into 21 countries and regions.

Both high levels and further growth is typically seen for OECD Europe, while low levels and decreasing levels is seen for most of the world. The number of people living in urban areas in 2025 and 2030 has been estimated by UN (2014).

4.3.5 *Net abatement potential*

We estimate that 4.8 and 5.2 bn. people will live in urban areas globally in 2025 and 2030, respectively (UN, 2014). People will bike more in our scenario than in the baseline for most regions. The weighted average is 0.14 km/day more in 2025 and 0.21 km/day more in 2030. We assume that this biking replaces travel by bus (42%), car (32%) and walking (26%) (Blondel, Mispelon, & Ferguson, 2011). This gives an emission reduction of 94 g CO_2-eqv. per km.

The total abatement potential is *23 MtCO_2 in 2025* and *37 MtCO_2 in 2030*.

4.3.6 *Abatement cost*

As the main component of this solution is a change in behaviour, which entails many subjective and hard-to-quantify costs such as changes in comfort level and time use, setting an abatement cost is difficult. The McKinsey Global Greenhouse Gas Abatement Cost Curve v2.0 does not include any solutions similar to this one (McKinsey, 2009). We provide an estimate based on the costs from the infrastructure (cycle paths) and maintenance as well as the reduced costs due to reduced gasoline consumption. The net cost is the difference between these two costs. Other costs and savings may also apply, but for simplicity, we focus on these two parameters. The infrastructure and maintenance costs are estimated based on costs for biking highways in Denmark (Herby & Friis, 2013), 0.020 USD per km (converted from DKK and scaled using the ratio of Denmark's purchasing power parity (PPP) GDP and market exchange rate (MER) GDP, to adjust for high cost levels in Denmark). The cost of gasoline is based on crude oil price estimates for 2025 (100 USD) and 2030 (113 USD) in the World Energy Outlook by IEA (2015). We assume an additional cost of 50% from refining, distribution, and sales. As 32% of the new biking trips replace car trips, we find a negative cost of 0.021 USD per km in 2025 and 0.024 USD per km in 2030. As the cost and negative cost are similar in magnitude, the net cost is quite sensitive to the assumptions, such as crude oil prices, exchange rate between DKK and USD, and cost levels in each target country.

The unit abatement cost we estimate is *-14 USD/tCO_2 (in 2012 currency) in 2025* and *-42 USD/tCO_2 in 2030*. The total abatement cost is then *-308 million USD in 2025* and *-1,553 million USD in 2030*.

4.3.7 Important enablers

This solution is mostly a behavioural solution that depends on enablers, such as a city infrastructure suitable for biking. The distances, as well as the commuting times, must be short enough for making biking a realistic option for daily travel.

Bicycles must also be affordable enough relative to average income levels that most people can afford one. Further, public campaigns may be needed to portray biking as an aspirational mode of transportation based on health, fitness, convenience, contributing to better air quality or other reasons, in particular in many developing countries where owning and using a car is often a status symbol, while biking is something many people are aspiring to move away from.

4.3.8 Possible barriers

Biking may be limited by weather, such as snow and cold in regions with cold winters, and hot and humid climate, which may make cycling unpleasant in the Tropics. Steep inclines or other challenging topographical features may also discourage biking in cities that are not situated in a flat area. Some of these limitations can levied by e-bikes.

Lack of separation between cyclists and motorists in traffic, especially if coupled with aggressive driving and a poor attitude towards bikes in traffic, can also be a major roadblock.

4.3.9 Major co-benefits

Biking has health benefits, with the exception of biking in very polluted areas. Bikes also take up considerably less space than cars in traffic and hence can reduce congestion when replacing car use. In the long run, parking spaces could potentially also be freed up, freeing up real estate in high-value central urban areas.

5. Solutions for buildings and households

5.1 Energy efficiency in buildings

5.1.1 *Description of the solution*

The cold climate in the Nordic countries means that buildings are generally better insulated and consume less energy for a given indoor/outdoor temperature difference than most buildings in the world, even though absolute levels of heating energy consumption are high. Short days with a significant number of working hours before sunrise and after sunset in the winter also increases lighting requirements, and although cooling needs are lower than in many other parts of the world, energy use for ventilation purposes in commercial and office buildings is still considerable. Further, the populations in the Nordic countries tend to be early adopters of new consumer technologies, and the demand for energy services from new gadgets and household appliances has grown considerably in the past few decades.

Governments and the construction sector in all Nordic countries have for some time paid much attention to improving energy efficiency in buildings, and there has recently been a trend towards designing and building very low- or even net-zero energy buildings. As in many other advanced economies, there is also a trend towards improving and setting standards for energy efficiency for lighting and household appliances, so that the energy requirements from some appliance groups like refrigerators/freezers and washers have gone down despite increased use, while the energy demand from others (like driers and TVs) have increased far less than they otherwise would have.

Average total energy consumption per square metre has fluctuated over the last two decades, but shown a downwards trend in all Nordic countries in the last decade. Nevertheless, moderate growth in home sizes and the number of individual households, considerable expansions of total commercial floor space and an explosion in electronic appliances have still led to a steady growth in total energy consumption in buildings of close to 1% per year (IEA / NCM, 2016). The only exception to this trend is Sweden, where even absolute energy consumption has gone down by close to 1% per year, despite moderate growth in economic output, population and building mass.

Sweden has a policy of organizing technology procurement groups, in which actors in certain segments cooperate on procurement of energy efficiency technologies and exchange experiences. 20% of all commercial space and 70% of all apartment buildings are estimated to be covered by such groups (Swedish Energy Agency, 2015). Energy efficiency requirements in building codes have also been ramped up, and information about opportunities for energy efficiency improvements is actively distributed through municipal climate and energy advisors and the Swedish Energy Agency.

Since Sweden has had the clearest results in improving building energy efficiency in the Nordic countries, we take the solution to be implementing building energy efficiency measures as those found in Sweden, for both existing and new buildings, and achieving a similar rate of energy efficiency improvement as Sweden during the period 2002-2013 (chosen for reasons of data availability and length close to the span 2018-2030). We include all forms of energy use in buildings, including both heating/cooling, ventilation, lighting, and electric appliances.

5.1.2 Impact in originating country

We estimate total energy use per square metre (direct heating, delivered heat, and non-heating electricity use) in buildings in Sweden over the period 2002-2013 using statistics from the Swedish Energy Agency.

We estimate total floor area for each main building type in Swedish statistics (single houses, apartment buildings, and non-residential buildings) by using reported temperature-corrected total energy use per square metre for each building type (Swedish Energy Agency, 2016b), together with a separate data set for total energy use for the same building types (Swedish Energy Agency, 2016b). We then use these total floor areas and the reported energy consumption per square metre for each building type to estimate average energy use per square metre for all buildings combined. This somewhat circuitous calculation was necessary because no complete time series could be found that satisfied our needs for either floor area per building type or total energy use per square metre in all buildings.

We find an average reduction in energy use per square metre of 1.9% per year from 2002 to 2013. Reductions vary across energy uses and building types, but both heating energy and non-heating electricity use per square metre declined in all three main building types.

5.1.3 Scale-up method

Many regions in the world already have much lower energy use per square metre in buildings (for economic reasons) than Sweden, and have a reasonably good downwards trajectory (China, ASEAN, Latin America). For several other regions, economic and/or climatic conditions are so different from Sweden as to make comparisons unreasonable (Africa, the Middle East, India). For these and for reasons of data availability, we scale up the solution to the rest of the EU, the United States, and Japan. These regions all have levels of economic development not too different from Sweden, and climatic conditions that require significant space heating for a significant part of the region for at least part of the year. They also currently have similar levels of energy use per square metre as Sweden, but have not shown as rapid improvement as Sweden since the early 2000s.

Since climatic conditions and customary building standards vary widely in different countries, and Sweden is not representative in terms of either, it would not be meaningful to apply Swedish absolute energy use per square metre to other geographies. We instead require the target countries to achieve the same annual reduction in energy use per square metre as Sweden did in the period 2002-2013.

5.1.4 Baseline

Our standard baseline scenarios do not include a published level of energy consumption per square metre. However, each of the target regions have shown a relatively steady but modest rate of decline for the period 2002-2013 (0.5% p.a. for the US, 0.8% p.a. for the EU, and 1.1% p.a. for Japan) (IEA, 2016a).[37] We therefore take as our baseline that these rates of improvement continue through the period 2018-2030.

We assume that the CO_2 intensity of electricity generation and of direct final energy consumption in buildings will be equal to that of the New Policies scenario in 2025 and 2030, both in the baseline and in the abatement case.

5.1.5 Net abatement potential

For each region, we calculate the ratio of building energy use per square metre in 2025 and 2030 for a Swedish growth rate (–1.9% p.a., from 2018 to 2030) relative to the baseline growth rates. We do not assume any difference in total floor areas between the two

---

[37] The resulting energy use in 2013 was 197 kWh/m^2 in the US, 191 kWh/m^2 in the EU, and 185 kWh/m^2 in Japan, compared to a global average of 161 kWh/m^2, and our estimate of 195 kWh/m^2 in Sweden

cases, so the resulting ratios also apply to total building energy use, and allow us to calculate the net reduction in energy use.

For simplicity, we also assume that consumption of all energy types are reduced by the same ratio and that there are no changes in CO_2 intensities. This allows us to apply the same reduction ratio to total CO_2 emissions from building energy use.

We calculate total CO_2 emissions for buildings in each geography in 2025 and 2030 using final energy and final energy CO_2 emissions in (or CO_2 emissions of power generation in the case of electricity) the New Policies scenario to find the effective emission factor of each energy type.[38] We then apply that to projected final energy use in buildings to find total direct and indirect CO_2 emissions from all final energy use in buildings.

The resulting total savings after applying the estimated reduction ratio are shown in Table 16.

Table 16: CO_2 emission reductions from energy use in buildings, in each target region and total

Region	2025	2030
USA	170	266
EU	86	126
Japan	23	38
Total	*280*	*430*

Note: All numbers in million tonnes of CO_2 ($MtCO_2$).

5.1.6 Abatement cost

Apart from policies and information, the actual engineering measures taken to improve energy efficiency in Swedish buildings are various, and difficult to pin down relative to a counterfactual scenario. They do however include numerous small-scale improvements of insulation of windows, doors, walls and other improvements of building envelope, as well as heat-conserving ventilation technologies, and a host of improvements in appliances and lighting.

These measures overlap with a broad section of items relating to building and appliance energy efficiency improvements in the McKinsey cost curve. It is not feasible to estimate exactly which and how much of each would be implemented in the target regions.

---

[38] The data do not allow us to calculate CO_2 intensity of district heating or other forms of delivered heat. We instead assume that the CO_2 intensity of heat is the same as the average of other energy types after excluding electricity. Electricity and natural gas dominate total emissions in all three regions, so the assumption has relatively small impact on total emissions.

The relevant measures are quite diverse, and many are a difference between two large numbers (e.g., capital costs for building retrofits, minus considerable energy savings). The unit costs therefore vary greatly, and range anywhere from more than 70 USD/tCO_2 to less than (savings of more than) -130 USD/tCO_2 (McKinsey, 2009). However, the bulk are concentrated between approximately *0 and -40 USD/tCO_2*. We therefore apply this range to the estimated net abatement in both 2025 and 2030, and estimate a total abatement cost as shown in table 17.

Table 17: Total abatement cost in 2025 and 2030

	2025	2030
Upper range	0.0	0.0
Central value	*–5.6*	*–8.6*
Lower range	–11.2	–17.2

Note: All numbers in billion US dollars (2012).

5.1.7 Important enablers

Awareness levels of energy efficiency in buildings are often low among developers, landlords, and especially consumers. Information and awareness campaigns are therefore important, and explicit regulatory requirements will also help to raise awareness and to signal that energy efficiency is a priority area. This is especially an issue for measures related to building envelopes or HVAC systems, which typically require large investments and have long lifetimes.

Energy efficiency in lighting and in other appliances – especially for consumer use – also suffer from a lack of awareness, as well as, paradoxically, from *low* costs: The day-to-day cost of less energy efficient appliances to individual consumers can often be low enough that there is little incentive to switch from a familiar technology or pay more up-front for a new one. Both information campaigns and explicit regulation is therefore often needed, as exemplified by the EU ban on incandescent light bulbs, and promotion of efficient alternatives such as fluorescent lights and LEDs.

Energy efficiency improvements to building envelopes and technical installations often produce net savings. But the payback time can be long and – even more importantly – the savings often accrue to tenants rather than to the decision makers (developers and landlords). The higher building standard may not result in a sufficiently higher sales price or rent to cover the investment. Policy makers therefore need to put in place both explicit requirements such as building codes, and possibly also financial incentives such as low-interest rate or otherwise favourable loans, or tax credits or other favourable tax policies. Low-interest government-backed loans for energy efficiency improvements can also help.

5.1.8 *Possible barriers*

As mentioned above, savings from energy efficiency improvements may not accrue to the people making the decisions, and this is a critical barrier to overcome.

In areas with low electricity prices and/or prices for gas or other principal energy sources in buildings, there will be little incentive to care about energy efficiency measures. The relatively high capital cost of building envelope improvements and more efficient technical installations can also lead to very long payback times in parts of the target regions where heating demand is low, and hence can make improvements economically unattractive.

5.1.9 *Major co-benefits*

In cases where oil, coal or – to a lesser extent – natural gas is combusted in buildings to provide heat,[39] reducing heating energy consumption will also help to improve air quality in the local environment (although in the case of biomass, the net CO_2 savings will be small). Reducing electricity consumption from appliances can likewise do the same in areas where a significant portion of the electricity is generated by local coal-fired power plants.

If LEDs are used to reduce energy consumption from lighting, an added benefit will be increased lifetime of the light bulbs, reduced need to change them, and in many cases reduced lifetime cost, although the initial cost can be significantly higher than for other types of lighting.

5.1.10 *Situation in other countries*

Although Sweden has shown a markedly better rate of improvement in energy efficiency in buildings than the EU as a whole and than the other target countries, it is not alone in proactive measures for improved building energy efficiency.

In an EU context, Germany stands out as having implemented extensive measures and incentive schemes. In particular, new buildings that exceed a certain relatively high

---

[39] The measure potentially also reduces the demand for biomass for heating purposes. Although reductions in biomass use is not the focus here since it contributes little to reduced CO_2 emissions, burning biomass can create significant local air pollution, and reducing its use therefore leads to similar air quality benefits as reducing the use of fossil fuels.

minimum efficiency standard are eligible for funding through low-interest loans from the state-owned bank Kreditanstalt für Wiederaufbau (KfW), and receive bonuses towards their repayments depending on the achieved standard. Similar loans and also grants are available for retrofit projects.

5.2 Residential heat pumps

5.2.1 Description of the solution

Heat pumps allow for more efficient heating by taking some heat energy from the (colder) outside air or an underground reservoir of slightly-less-cold ground water or rock, and with the help of electrical work "pumping" that energy into a warmer indoor area as heat, effectively acting as a refrigerator in reverse. It can thus potentially save energy by releasing more energy than is put in (although the net benefit will depend on the efficiency electricity generation in power plants, since the input energy is in the form of electricity).

Unlike district heating, heat pumps do not require major infrastructure construction, and are not dependent upon high population density to be economical. They can hence be a complement to district heating in lower-density areas, and for individual homes where district heating not an option.

Most of the Nordic countries are leading in installing heat pumps for residential heating, especially Sweden, Finland, and Norway. As Sweden is the frontrunner, we focus on Sweden. Sweden has stimulated innovation of heat pumps and has given investment subsidies to buyers. The solution is scaled up to most other EU countries (see below) in 2030. The selection of countries is mainly driven by data availability, but the selected region is significant both for climatic reasons (relatively high heating demand) and due to the purchasing power of consumers (since heat pump equipment and installation are not cheap).

5.2.2 Impact in originating country

In 2014, Swedish heat pumps delivered 14 TWh (EHPA, 2015). This translates to 20% of the total space and water heating demand (Swedish Energy Agency, 2016a). The yearly growth since 2005 has been 8.4%.

5.2.3 Scale-up method

Scaling-up is challenging, as we have not found datasets for current installed stock of heat pumps globally that include necessary information on capacity or energy use. The best available dataset we found covers heat pump energy use in the EU21 countries (EU countries that were also OECD members as of 2014) (EHPA, 2015), and we have scaled up to these countries. The countries in question are (sorted according to heat output in 2014): France, Sweden, Germany, Italy, Norway, Finland, Switzerland, Austria, Holland, United Kingdom, Portugal, Spain, Belarus, Denmark, Poland, Estonia, Czech Republic, Ireland, Hungary, Lithuania, and Slovakia.[40] We believe that a significant part of heat pump installation will take place there, although significant potential most likely also exists in the US, Canada, and Russia and possibly northeast Asia (though possibly limited by high carbon-intensity of power generation for the latter two).

We scale-up by assuming that the target countries in 2030 can replicate Sweden's 2014 share of heat pumps in total energy use for space and water heating (9.3%). As heat pumps are small units that are easy to install, our estimate for 2025 is based on exponential growth between 2014 and 2030.

5.2.4 Baseline

Observ'ER (2015) estimates that heat pumps deliver 8614 ktoe of heat the EU in 2015. This increases to 12657 ktoe in 2020. The increase implies an average annual growth rate of 10%. In the baseline, we assume that this trend continues until 2030 and is representative for the 21 selected European countries. For the Nordic region, we assume a growth identical to the scenario growth (which effectively means that the Nordic countries themselves do not contribute to the extra abatement potential).

5.2.5 Net abatement potential

In our solution scenario, heat pumps produce 118 TWh more heat than in the baseline in 2025 and 397 TWh more in 2030, in the selected countries.

The emission reduction is then the sum of reduced emissions due to heat replaced and the increased emissions from the electric consumption by the heat pumps. We assume that for each 1 TWh electricity input, heat pumps deliver 2-4 TWh of heat

---

[40] Note that while the Nordic countries are included in this list – including Sweden itself – our choice of baseline effectively means that we do not include them in the abatement potential (see section 5.1.4).

output (based on typical real-life performance coefficients), and calculate a corresponding range for saved baseline heating energy and corresponding increase in electricity consumption.

As (non-electric) heat and electricity are generated using different input energy mixes, we find the CO$_2$ intensity for each. Due to data availability, we use the CO$_2$ emissions per unit heat and electricity for all EU countries as reported in IEA (2016a). The largest countries and countries with large amount of coal power are represented in both groups; hence, the difference in region definitions is small. For the electricity mix, we have a CO$_2$ intensity of 300 g CO$_2$/kWh in 2025 and 240 g CO$_2$/kWh in 2030. For heating, the CO$_2$ intensity is 250 g CO$_2$/kWh in 2025 and 230 g CO$_2$/kWh in 2030. Note that this reflects the average energy mix for electricity and heat generation over one year in the target countries. As heat pumps are generally used more in the winter, when electricity demand is generally higher than average in many of the target countries, the relevant CO$_2$ intensity of *marginal* electricity generation may be somewhat different, but we have not considered this effect in our analysis.

The net abatement potential is estimated to be *19 (12-22) MtCO$_2$ in 2025* and *64 (47-72) MtCO$_2$ in 2030*. The abatement potential would likely be larger if further regions were to be included. Further, expected baseline growth implies that the target countries on average reach a share of heat pump use in 2030 that is four-fifths of the current share in Sweden, which significantly reduces the net potential.

5.2.6 Abatement cost

We apply the McKinsey Global Greenhouse Gas Abatement Cost Curve v2.0 for retrofit HVAC (electric resistance heating to electric heat pump), residential (McKinsey, 2009). We set the abatement cost to *-52 USD/tCO$_2$* (in 2012 currency) for both 2025 and 2030.

This net-negative unit abatement cost gives a net total abatement cost of *-0.90 (–1.1--0.60) billion USD in 2025* and *-3.2 (2.3 – -3.6) billion USD in 2030*.

5.2.7 Important enablers

Installing a heat pump is inexpensive compared to many major energy efficiency measures in a home. It is, nevertheless, a considerable expense compared to most consumer purchases, even though energy savings may lead to a net saving over time. Since up-front cost typically weigh more heavily than net cost over time for individual consumers, some form of subsidy or tax incentive may help to drive adoption, especially in markets with low energy prices where the payback time will be long.

5.2.8 Possible barriers

Heat pumps may have a long payback time, and hence be economically unattractive in regions where heating demand is not high.

Further, as for CHP and district heating, the abatement potential and economic savings for heat pumps are reduced by any measure that reduces heat loss and hence total heating demand in a building, such as improved insulation. It also competes directly with district heating where that is available.

In climates that experience seasonal high temperatures, the net abatement from heat pumps may be reduced by the fact that many heat pump models can also function as air conditioning units and be used for cooling (heat pumps are essentially air conditioning units run in reverse, and vice-versa). When used for cooling heat pumps can save some energy relative to regular air conditioning units if they use bedrock or another underground reservoir colder than the outside air temperature as their cold reservoir. However, they save no energy if installed in (usually cheaper to install) air-to-air mode. Further, in both cases they cause *increased* energy use if the baseline is not to install anything at all. In that case, incentivizing heat pump installation will also make air conditioning more available and create an incentive for higher electricity consumption and higher associated emissions during the summer months.

5.2.9 Major co-benefits

If heat pumps replace electric heating, the electricity demand is reduced due to efficiency improvements. Some of this reduction may, however, be limited, as people tend to warm their houses more after installing heat pumps.

The reduced demand for burning fossil fuels or biomass for heat can reduce air pollution, both locally in the case of heating oil, coal or gas burnt locally in individual buildings, and some distance away in the case of district heating. Where heat pumps replace electric heating, the increased efficiency and reduced electricity demand may also reduce air pollution if the electricity is generated from fossil fuels or biomass.

5.3 Bioenergy for heating in buildings

5.3.1 *Description of the solution*

Cold climates combined with widespread forests and large forestry industries makes biomass in the form of wood residues a natural source of energy for heating in Finland. The same is also true of Sweden and Norway, but we here use Finland as an example due to its larger forestry sector relative to population size and even higher share of bioenergy in heating than in the other countries.

Biomass has a large and growing share in many parts of the Finnish energy system. Biomass (mostly in the form of wood residues or pellets) accounted for 20% of total final energy consumption in the country in 2013, as well as 10% of electricity production, and over 40% of commercial heat generation (e.g., district heating networks, and sold industrial heat) (IEA, 2016b). Biomass has a particularly high share of the energy used for heating (see next section).

One important factor in the high share of biomass use for heating in Finland is the motivation of forestry companies to find ways to turn as much as possible of their waste into profit-making products. There are also three different subsidies for biomass use in general: A feed-in tariff for electricity from wood chips dependent on the EU-ETS allowance price; a separate feed-in tariff for small wood-burning CHP plants; and an energy subsidy for small-diameter wood from young forests (Finland Ministry of Employment and the Economy, 2012).

We take the solution in this section to be using biomass for heating buildings, at the same share as that achieved in Finland. The solution is only scaled up to three selected countries with similarly high heating demand and availability of forestry residues as Finland (see below).

This solution, with Finland as the originating country, was originally part of the global Green to Scale report (Afanador *et al.*, 2015; Sitra, 2015), and was analysed by Ecofys. The solution presented here is identical to the analysis and quantitative results from that report.

5.3.2 *Impact in originating country*

In the building sector in Finland, direct use of wood and other biomass accounted for 28% of final energy use other than electricity, while delivered heat – itself more than 40% biomass-based as mentioned above – accounted for a further 55%. The balance was made up by an even mix of natural gas, peat and coal, as well as some incineration of non-renewable wastes, heating oil, and small amounts from other sources (IEA, 2016b).

In total, bioenergy use in Finland is estimated to save approximately 6.8 $MtCO_2$ of emissions annually (Afanador *et al.*, 2015).

5.3.3 Scale-up method

In order for the solution to be economic and sustainable, a country must have both sufficient heating demand and available biomass. The solution is therefore scaled up only to countries that have more than 3,000 heating degree days (HDDs) per year,[41] and produce at least 80% as much wood residue per capita as Finland (Afanador *et al.*, 2015).

Only Russia, Canada and Mongolia fulfil these criteria. The energy balance of each country is used to calculate the share of bioenergy in non-electricity consumption in buildings (direct final consumption plus delivered heat from heat plants, and the share of bioenergy in each). The difference to Finland's bioenergy share is calculated, and multiplied by the total baseline non-electricity energy consumption in buildings in 2030 (see next section for baseline estimation) to calculate the amount of energy converted to bioenergy. This energy is then multiplied by the emission factor of natural gas, which is assumed to be the main alternative heating source (Afanador *et al.*, 2015).

5.3.4 Baseline

The New Policies Scenario of the World Energy Outlook is used to calculate the total baseline non-electricity consumption in buildings in 2030 in the target regions (Afanador *et al.*, 2015).

5.3.5 Net abatement potential

Following the procedure above gives a net abatement potential of *187 (159-215)* $MtCO_2$ *in 2025*, and *193 (164-222)* $MtCO_2$ *in 2030* (Afanador *et al.*, 2015).

5.3.6 Abatement cost

To estimate the abatement cost, McKinsey's abatement cost curve for Russia is used to set an upper end of the cost range. The cost there is 80 USD/tCO_2 for usage of biomass.

---

[41] A heating degree day is defined as the outside temperature being on average 1 degree Celsius below a reference temperature – at which no heating is necessary to maintain a given indoor comfort temperature – for one day. It is used as a measure of weather-dependent heating requirements for a given location. The reference temperature may vary by country.

As a lower bound, it is assumed that the solution can be implemented cost-effectively in the target countries, i.e., 0 USD/tCO_2. The midpoint is used as the central value

The unit cost adopted is thus *40 (0-80) USD/tCO_2* in both 2025 and 2030. The total abatement cost then becomes *7.5 (0-15) billion USD* for both 2025 and 2030.

5.3.7 Important enablers

As in Finland, direct subsidies may help to increase the uptake of biomass. However, in most cases forestry companies will have a large financial incentive to market their waste wood to consumers or heating plant operators. The main enabler may therefore be to ensure that market conditions and infrastructure conditions are right to be able to accept large amounts of biomass into the heating systems, both district heating systems and local heating. Constructing district heating will be an important enabler where possible, since this allows for more flexible use of fuels than local burners in each home.

5.3.8 Possible barriers

As discussed in Section 1.6, large increases in bioenergy use in general can have adverse impacts on ecosystems that are disrupted by land use change required to grow the biomass, or on food production if agricultural land is converted to grow energy crops. In the current solution, however, the target countries are required to have similar amounts of wood residue per capita as Finland, and it should therefore in principle be possible to reach Finland's level of bioenergy use in heating without any additional biomass extraction. If the required biomass is already being used for other purposes, however, tradeoffs with the alternative uses may be necessary, although we do not foresee this being a major issue in any of the three target countries.

Also note that the estimated abatement potential assumes that biomass use is net carbon neutral, even though it is quite likely that biomass combustion would lead to a net positive increase in atmospheric CO_2 due to imbalances between biomass combustion and regrowth, as well as production- and transport-related emissions. See discussion in Section 1.6.

The most economic use of biomass for heating is through district heating (Afanador *et al.*, 2015). District heating would also avoid the local air pollution that could result from distributed burning of biomass in residential areas. District heating requires significant effort and expense to build the necessary infrastructure. In major cities in Russia, district heating is already widespread. However, the low population density in large parts of all three target countries may make district heating uneconomical. Smaller-scale local heating systems may still be an option in low-density areas, and are widely used in smaller communities in Finland.

5.3.9 Major co-benefits

Using bioenergy for heating has few co-benefits other than reduced greenhouse gas emissions and reduced dependence on natural gas and other possibly imported fossil fuels. However, the extra revenue and activity in the forestry sector can make more jobs available. Jobs in the forest fuel supply chain and supply of associated machinery in Finland are expected to have increased five times relative to 2010 levels by 2020 (Afanador *et al.*, 2015).

5.3.10 Current situation in other countries

Although Finland and to some extent Sweden stand out for their bioenergy use in heating, Austria provides another example of successful bioenergy heating solutions. Austria has built district heating plants and distribution grids even in some rural areas, and subsidizes private biomass heating plants. 85% of woody biomass produced in the country goes to heating, and a further 15% to electricity generation (Afanador *et al.*, 2015).

6. Agriculture and forestry sector solutions

6.1 Reforestation and land restoration

6.1.1 Description of the solution

Large shares of the three largest Nordic countries, Sweden, Norway and Finland, are covered by dense boreal forests that support large forestry sectors. While most of Denmark's forests were replaced by fields and pastures centuries ago, and land erosion is a significant problem in many coastal areas, much of the country is covered by rich and productive soils. Iceland, by contrast, has very little forest cover, and large parts of the country are sparsely vegetated. Nevertheless, research has shown that 28%–31% (30-36 thousand square kilometres) of the country was covered by natural woodlands when the country was settled in the late 9th century A.D., but most of it disappeared within the first two centuries of human habitation (Government of Iceland / UNFCCC, 2014). Similarly, as much as 40% of the land is believed to have been degraded by wind erosion and soil and vegetation loss after settlement (Davíðsdottir *et al.*, 2009).

Iceland has conducted systematic reforestation efforts since after the Second World War, and the efforts were ramped up with 4-5 times as many seedlings planted per year in the 1990s and early 2000s. The rate of afforestation decreased considerably after the 2008 financial crisis, but was still significantly higher than before the 1990s. Most reforestation has taken place through state support for afforestation on farms and other privately owned land (Government of Iceland / UNFCCC, 2014). Current Icelandic regulations aim for afforestation on at least 5% of land below 400 metres above sea level in various regional projects (Government of Iceland / UNFCCC, 2016).

Iceland also has an extensive program to battle soil erosion and desertification, and reclaiming and restoring thus degraded land. The Soil Conservation Service of Iceland was founded for this purpose, and a land restoration training programme under the auspices of the United Nations University was launched in 2007.

In addition, there is increasing focus on restoring wetlands that have previously been drained for pasture and agriculture. Intact wetlands can absorb and permanently sequester large amounts of CO_2 (currently approximately one tonne of CO_2 per hectare in Iceland), while drained wetlands conversely can release more than 20 tonnes of CO_2 per hectare (Hellsing *et al.*, 2016). Drained wetlands are one of the largest sources of CO_2 emissions from land use change at present, and restoring drained wetlands conversely holds some of the greatest potential for abatement from land restoration in Iceland. At present, however, this effort has not come very far, and we will therefore not use it for scale-up to a global potential.

We define the solution in this section to be reforestation and restoring degraded lands in temperate climates. We will define a degree of implementation for reforestation and for restoration of eroded land (revegetation) in Iceland, and use this to scale up to a global abatement potential (see Section 2.1.3).

Mountain birch makes up almost all of the naturally occurring woodland in Iceland, although some imported species occur in plantations. Both native and imported tree species generally do not grow to great heights, and the amount of sequestered carbon per square metre may be lower than for reforestation in regions with better growing conditions. For this reason, we use the surface area of reforested and restored land to measure degree of implementation in Iceland (see below), and apply that to total mitigation potential measured in abated greenhouse gas emissions in the target countries.

6.1.2 Impact in originating country

Iceland's 2016 National Inventory Report to the UNFCCC finds that 47 kha of non-forested land had been converted to forest according to UNFCCC definitions by 2014.[42] The carbon sink represented by this added forest land is estimated to be 265 $ktCO_2$ per year (Hellsing *et al.*, 2016). This constitutes 1.4% (1.3%–1.6%) of the 3,000-3,600 kha estimated to have been covered by woodland before settlement, as stated in the previous section. We therefore take this percentage range to be the degree of implementation for reforestation in Iceland.

268 kha were estimated to have been revegetated by 2014, providing a carbon sink of 560 $ktCO_2$ per year. If we take revegetation of the estimated 40% of Iceland's surface (41,200 kha) affected by wind erosion (see previous section) to represent the technical potential for restoration, the currently revegetated area represents a 0.65% degree of implementation.

---

[42] kha = kilohectare, or 10 km^2.

6.1.3 Scale-up method

It is challenging to find suitable global analogues from published global technical mitigation potentials for scaling up the reforestation and land restoration effort in Iceland. Most published potentials cover many different measures and very varied biome types, so scaling up the exact types of measures and policies adopted in Iceland is not possible. Instead, we adopt a rather broad potential, by looking at the potentials for afforestation and for land restoration presented by Working Group III in the IPCCC's 4th Assessment Report and reiterated in the 5th Assessment Report (see Table 9.3 of Nabuurs *et al.* (2007), and Figure 11.17 of Smith *et al.* (2014)).

Much of reforestation and afforestation potential is located in the tropics, and which are likely to constitute a particularly unsuitable analogue for Iceland's efforts, both in terms of climate and biome types and in terms of the types of measures employed. Fortunately, there is significant potential for both afforestation and for restoration of degraded lands in the mostly temperate OECD–1990 and "Economies in Transition" (EIT, corresponding to former Eastern Bloc countries) regions used in IPCC reports. We therefore limit our scale-up to these regions, as most of the other IPCC regions would contain a large share of land that may be poor analogues for Icelandic land.

The measures covered by Restoration of degraded lands in the IPCC sources will cover more than just revegetation and restoration of eroded soils. Also, the potentials reported are not strictly speaking technical potentials, but rather economic potentials at a carbon price of up to 100 USD/tCO_2. These two issues introduce opposite biases. Further, since the total scaled-up potential from land restoration is small (see Section 2.1.5), we do not modify it. All in all, with the carbon price limitation on the IPCC potentials we use, as well as the fact that using total pre-settlement forested and vegetated area as the technical potential for Iceland may make its degree of implementation too small, our resulting abatement potential is likely to be quite conservative.

For the scale-up, we will multiply the global potentials with the degree of implementation in Iceland for each measure, as found in the previous section.

6.1.4 Baseline

The New Policies Scenario contains no details on reforestation, land restoration or other not energy-related land-use measures, and the IPCC sources do not include a single baseline scenario or much detail on any of the scenarios that are presented as business-as-usual scenarios. The ones that are presented do not include enough detail to be able to say how much of the total land-use use change in those scenarios corresponds to the measures we treat here.

Two of three scenarios presented as "Baseline" scenarios in Smith *et al.* (2014) include either decreases or negligible increases for forest cover or lands typically included in land restoration in the OECD and EIT areas. We therefore take our baseline to be no change, i.e., we take the net abatement potential to be the same as the gross scaled-up potential.

6.1.5 Net abatement potential

The total abatement potential for afforestation in the target regions as defined above is 1.22 $GtCO_2eq$ in 2030, while the potential for restoration of degraded lands is 554 $MtCO_2eq$. Multiplying this by the Icelandic degrees of implementation (1.42% (1.30%–1.56%) and 0.65%, respectively), we get total potentials of 17 (16-19) $MtCO_2eq$ and 3.6 $MtCO_2eq$.

We then add up, and find the potential for 2025 through interpolation. We then get total abatement potentials of *12 (11-13)* $MtCO_2eq$ *for 2025* and *21 (20-23)* $MtCO_2eq$ *for 2030*.

6.1.6 Abatement cost

The IPCC 5th Assessment Report does not contain precise abatement costs for the measures included there, but rather only includes broad ranges (total abatement potential available at a cost of less than either 20, 50 or 100 USD/tCO_2). We instead use the abatement cost for the measures "Degraded forest reforestation" and "Degraded land restoration" of the McKinsey abatement cost curve (see Exhibits 8.9.1 and 8.10.1, respectively, of McKinsey (2009)).

After converting McKinsey's 2005 Euro costs to 2005 US dollars and then applying a deflator to convert to 2012 US dollars, we obtain abatement costs of 17.0 USD/tCO_2 for reforestation, and 12.4 USD/tCO_2 for degraded land restoration. This is consistent with the cost ranges in the IPCC figures, as the abatement potentials we find fit into the total potentials at "less than 20 USD" per tonne CO_2 from the IPCC reports.

After multiplying, the total abatement cost becomes *198 (183-215) million USD in 2025* and *339 (315-369) million USD in 2030*. The weighted average unit cost is *16.2 USD/*tCO_2.

6.1.7 Important enablers

Necessary enablers will vary considerably between different countries, depending on land ownership and political systems, as well as local land use circumstances. In most of the target countries, we do not expect that large-scale illegal logging or other contravention of government land policies will be a major problem. But legal and political resistance from landowners may be.

Since reducing soil erosion is likely to benefit local landowners in the medium and long-term in most cases, information campaigns may be important. Further, economic compensation for reforestation and payments based on the amount of standing biomass will help where landowners do not already have a financial incentive to plant trees or vegetation.

6.1.8 *Possible barriers*

The greatest barriers are likely to be alternative land uses with higher perceived economic value. In particular, any measure that requires encroaching on cropland or pastures, may face opposition by landowners, and may also be opposed by political groups who are concerned with any measures that reduce domestic food production capacity. This is unlikely to be an issue for restoration of degraded lands, which typically have little economic value in their current state, but afforestation on land that has been deforested for a long time is more likely to be problematic.

6.1.9 *Major co-benefits*

Restoring degraded lands can lay the basis for increased sustainable farming in the future. By forming a barrier against further erosion and by having a greater capacity to absorb moisture, it can also help to protect valuable property from flooding or further land loss.

Both land restoration and re-/afforestation are also likely to help (re-)increase biodiversity, and will in many cases have recreational value.

6.2 Manure management

6.2.1 *Description of the solution*

Emissions of nitrous dioxide (N_2O) in Denmark have declined over an extensive time period due to strict regulations on fertiliser and manure management. These regulations are not due to climate concerns, but environmental issues, especially regarding the aquatic environment. The main driver has been the EU Nitrate Directive. This solution is complex and consists of a number of policies (Antman *et al.*, 2015).

One part of the solution is to control how and when manure spreading is allowed. Animal manure must be tilled into the soil within six hours. Fertiliser is not allowed to spread into drains and streams. Application onto black soil and permanent grass must be done by injection or pre-treated slurry. The total amount of manure that can be used is limited to an amount corresponding to manure from 2.3 livestock units per hectare.

The second part of requirements is on storage and use. Slurry containers cannot be located less than 100 m from the nearest stream or lake, must be made of durable materials, and must be covered.

Finally, various crops have nitrogen standards on how much fertilizer can be applied.

Similar improvements can likely be made worldwide, and we scale up by assuming similar trends in emission reductions.

The global warming potential for N_2O varies between sources. As discussed in Section 1.5, we use a range of 265-298, reflecting uncertainty in the effect of climate feedbacks. Unless otherwise noted, if we report a single CO_2-equivalent without a range, we are using the midpoint GWP (282).

6.2.2 *Impact in originating country*

In Denmark, N_2O emissions from agriculture have decreased by almost 30% between 1990 and 2014, with most of the improvement seen in the first half of the period (Institut for miljøvidenskab, 2016). The reduction is observed for both manure management and agriculture soils. In the same period, agricultural area has decreased by approximately 4% (Antman *et al.*, 2015). We therefore see an N_2O efficiency improvement of 28% in 24 years (i.e., a -28% change in N_2O emissions per unit surface area of agricultural land), or an annual compound average improvement rate of 1.5% per year.

6.2.3 *Scale-up method*

This solution is complex, and we have not analysed the details of how it would be implemented in individual countries. For scaling up, we assume that the historical yearly decline in N_2O emissions in Denmark can be reached worldwide for the 2018-2030 period. FAOSTAT (2015) estimates that global N_2O emissions from agricultural soils, manure management, manure applied to soils and left on pasture will be 3.5 $GtCO_2eq$ in 2025 and 3.3 $GtCO_2eq$ in 2030, compared to 2.9 $GtCO_2eq$ in 2014. By imposing the historical Danish improvement rate found in the previous section, this emission level would be reduced to 2.9 $GtCO_2eq$ in 2025 and 2.8 $GtCO_2eq$ in 2030.

6.2.4 Baseline

We believe that the measures done in Denmark are not likely to be copied worldwide unless policies force these measures, as new infrastructure and machinery will be costly for the farmers and they are unlikely to harvest direct benefits from these measures. In reality, a reduction of fertilizer consumption may reduce the cost for farmers, but we do not consider the incentive level or savings associated with this for lack of data. Our baseline follows the emission estimates from FAOSTAT (2015), which gives 3.3 GtCO_2eq in 2030.

6.2.5 Net abatement potential

This solution does not reduce emissions of CO_2, but of N_2O. In our calculations, we estimate the N_2O reduction in CO_2-equivalents, using a global warming potential range of 265-298 (see Table 8.7 of Myhre *et al.* (2013), and discussion in Section 1.5). The net abatement potential (difference between emissions with the solution and in the baseline case) is *269 (253-284) MtCO_2eq in 2025* and *478 (450-506) MtCO_2eq in 2030*.

6.2.6 Abatement cost

Manure management is not covered by the McKinsey abatement cost curve, and we have not been able to obtain sufficient information about the associated costs in Denmark to construct a unit abatement cost based on the Danish case directly. However, an estimate is available for the cost of implementing similar measures in Iceland (see Section 4.6.5 of Davíðsdottir *et al.* (2009)). The cost there is estimated at 550 ISK/tCO_2eq, in August 2008 currency.

We convert to 2008 US dollars and adjust for purchasing power differences by dividing by a PPP conversion factor for Iceland in 2008 from the World Bank, and apply GDP deflators for the United States to convert to 2012 US dollars. We then obtain a unit cost of *5.0 USD/tCO_2eq*. which we apply for both 2025 and 2030.

The total abatement cost is then *1.33 (1.26-1.41) billion USD for 2025*, and *2.37 (2.23-2.51) billion USD for 2030*.

6.2.7 Important enablers

This solution is a policy-driven solution, as seen in Denmark. Stringent requirements regarding other issues than climate change, in particular water quality regulations, may be the main drivers.

6.2.8 Possible barriers

The solution requires substantial policy interventions into farming practices, which may be politically difficult in some countries. Monitoring compliance with the regulations on how quickly manure must be tilled into the soil may not be feasible in many cases.

6.2.9 Major co-benefits

A stricter regulation on manure will lead to less leaching of nitrogen to the environment, and will improve water quality if done properly. Some financial benefit in terms of less manure used may also occur.

7. References

Afanador, A., Begermann, E., Bourgault, C., Krabbe, O., & Wouters, K. (2015). *The potential of scaling up proven low-carbon solutions – Final report*. Retrieved from

Antman, A., Brubæk, S., Andersen, B. H., Lindqvist, K., Markus-Johansson, M., Sørensen, J., & Teerikangas, J. (2015). *Nordic agriculture air and climate – Baseline and system analysis report*. Retrieved from http://dx.doi.org/10.6027/TN2015-570

Ármannsson, H., Fridriksson, T., & Kristjánsson, B. R. (2005). CO_2 emissions from geothermal power plants and natural geothermal activity in Iceland. *Geothermics, 34*(3), 286-296. doi:http://dx.doi.org/10.1016/j.geothermics.2004.11.005

Blondel, B., Mispelon, C., & Ferguson, J. (2011). *Cycle more often 2 cool down the planet!* Retrieved from https://ecf.com/files/wp-content/uploads/ECF_CO2_WEB.pdf

CarbFix. (2016). The CarbFix project. Retrieved from https://www.or.is/english/carbfix-project

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H.,… Pingoud, K. (2011). Bioenergy. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, & C. v. Stechow (Eds.), *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Danish Energy Agency. (2016a). Basic facts on Heat Supply in Denmark. Retrieved from http://www.ens.dk/en/supply/heat-supply-denmark/basic-facts-heat-supply-denmark

Danish Energy Agency. (2016b). Heat supply in Denmark. Retrieved from http://www.ens.dk/en/supply/heat-supply-denmark

Davíðsdottir, B., Loftsdóttir, Á., Hallsdóttir, B., Skúladóttir, B., Kristófersson, D. M., Rúnarsson, G.,… Sigfússon, Þ. I. (2009). *Möguleikar til að draga úr nettóútstreymi gróðurhúsalofttegunda á Íslandi (Options to reduce net emissions of greenhouse gases in Iceland)*. Retrieved from https://ust.is/library/Skrar/Atvinnulif/Loftslagsbreytingar/serfraedinganefnd_umhvraduneyti_draga_ur_losun_ghl.pdf

Dornburg, V., Faaij, A., Verweij, P., Langeveld, H., Ven, G. v. d., Wester, F.,… Egmond, S. v. (2008). *Assessment of Global Biomass Potentials and their Links to Food, Water, Biodiversity, Energy Demand and Economy* (WAB 500102 012). Retrieved from Bilthoven, The Netherlands:

Dornburg, V., Vuuren, D. v., Ven, G. v. d., Langeveld, H., Meeusen, M., Banse, M.,… Faaij, A. (2010). Bioenergy revisited: Key factors in global potentials of bioenergy. *Energy & Environmental Science, 3*, 258-267.

EEA. (2009). *Europe's onshore and offshore wind energy potential* (6/2009). Retrieved from http://www.eea.europa.eu/publications/europes-onshore-and-offshore-wind-energy-potential

EHPA. (2015). *European heat pump market and statistics report 2015*. Retrieved from http://www.ehpa.org/fileadmin/red/07._Market_Data/2014/EHPA_European_Heat_Pump_Market_and_Statistics_Report_2015_-_executive_Summary.pdf

EV Norway. Norwegian EV market. Retrieved from www.evnorway.no

FAOSTAT. (2015). *Emissions – agriculture*. Retrieved from: http://faostat3.fao.org/download/G1/*/E

Finland Ministry of Employment and the Economy. (2012). *Energy policy in Finland – how we will reach the RES targets*. Retrieved from http://www.feed-in-cooperation.org/wDefault_7/download-files/9th-workshop/presentations/session-3/RES-Finland.pdf

Fridstrøm, L. (2013). *Norwegian transport towards the two-degree target: Two scenarios, 1286/2013*. Retrieved from Institute of Transport Economics: https://www.toi.no/getfile.php?mmfileid=34417

Fridstrøm, L., & Alfsen, K. H. (2014). *Vegen mot klimavennlig transport [Norway's path to sustainable transport]* (1321-2014). Retrieved from Institute of Transport Economics: https://www.toi.no/getfile.php?mmfileid=36652

GEA. (2012). *Global Energy Assessment – Toward a Sustainable Future*. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Global CCS Institute. (2016a). *Large scale CCS projects*. Retrieved from: https://www.globalccsinstitute.com/projects/large-scale-ccs-projects

Global CCS Institute. (2016b, 2016-09-20). Snøhvit CO_2 storage project. Retrieved from https://www.globalccsinstitute.com/projects/sn%C3%B8hvit-co2-storage-project

Goldstein, B., Hiriart, G., Bertani, R., Bromley, C., Gutiérrez-Negrín, L., Huenges, E.,… Zui, V. (2011). Geothermal energy. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, & C. v. Stechow (Eds.), *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Government of Iceland / UNFCCC. (2014). *Iceland's sixth national communication and first biennial report under the United Nations Framework Convention on Climate Change*. Retrieved from https://unfccc.int/files/national_reports/annex_i_natcom/submitted_natcom/application/pdf/nc6_br1_isl.pdf

Government of Iceland / UNFCCC. (2016). *Iceland's second biennial report to the UNFCCC*. Retrieved from https://unfccc.int/files/national_reports/biennial_reports_and_iar/submitted_biennial_reports/application/pdf/iceland_biennial_report_2nd.pdf

Greenpeace EREC. (2011). *The advanced energy [r]evolution – a sustainable energy outlook for Sweden*. Retrieved from http://www.greenpeace.org/sweden/Global/sweden/klimat/dokument/2011/energy-revolution-sweden.pdf

Hellsing, V. Ú. L., Ragnarsdóttir, A. S., Jónsson, K., Andrésson, K., Jóhannsson, Þ., Guðmundsson, J.,… Þórsson, J. (2016). *National Inventory Report 2016. Emissions of greenhouse gases in Iceland from 1990 to 2014. Submitted under the UNFCCC and the Kyoto Protocol.* Retrieved from https://ust.is/library/Skrar/Einstaklingar/Loftgaedi/Iceland%20NIR%202016_Version%205(20160415).pdf

Herby, J., & Friis, A. (2013). *Samfundsøkonomiske analyser af cykelsuperstierne*. Retrieved from http://incentive.dk/wp-content/uploads/2013/01/Samfunds%C3%B8konomiske-analyser-af-cykelsuperstierne.pdf

Hoogwijk, M., Faaij, A., Eickhout, B., Vries, B. d., & Turkenburg, W. (2005). Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. *Biomass and Bioenergy, 29*(4), 225–257.

Hoogwijk, M., Faaij, A., Vries, B. d., & Turkenburg, W. (2009). Exploration of regional and global cost-supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. *Biomass and Bioenergy, 33*(1), 26-43.

Hoogwijk, M., & Graus, W. (2008). *Global potential of renewable energy sources: A literature assessment*. Retrieved from http://www.ecofys.com/files/files/report_global_potential_of_renewable_energy_sources_a_literature_assessment.pdf

Husdal, G., Osenbroch, L., Yetkinoglu, Ö., & Østebrøt, A. (2016). *Kaldventilering og diffuse utslipp fra petroleumsvirksomheten på norsk sokkel (Cold venting and diffuse emissions from the petroleum activity on the Norwegian continental shelf)*. Retrieved from http://www.miljodirektoratet.no/Documents/publikasjoner/M509/M509.pdf

IEA. (2008a). *CHP / DHC country Scorecard: Denmark*. Retrieved from http://www.iea.org/media/files/chp/profiles/denmark.pdf

IEA. (2008b). *CHP / DHC Country Scorecard: Finland*. Retrieved from Paris: http://www.iea.org/media/files/chp/profiles/Finland.pdf

IEA. (2010). *Sustainable production of second-generation biofuels: Potential and perspectives in major economies and developing countries*. Retrieved from https://www.iea.org/publications/freepublications/publication/second_generation_biofuels.pdf

IEA. (2013). *Redrawing the energy-climate map*. Retrieved from Paris: http://www.iea.org/publications/freepublications/publication/weo-2013-special-report---redrawing-the-energy-climate-map.html

IEA. (2014). *Linking Heat and Electricity Systems*. Retrieved from Paris: https://www.iea.org/publications/freepublications/publication/LinkingHeatandElectricitySystems.pdf

IEA. (2015). *World Energy Outlook 2015*. Paris, France: IEA Publications.

IEA. (2016a). *Energy Technology Perspectives 2016*. Paris: IEA Publications.

IEA. (2016b). *IEA World energy statistics and balances* [Online database].

IEA / NCM. (2016). *Nordic Energy Technology Perspectives 2016*: IEA Publications.

Institut for miljøvidenskab. (2016). Nitrous oxide. Retrieved from http://envs.au.dk/videnudveksling/luft/emissioner/greenhouse-gases/nitrous-oxide/

IRENA (2016). *Renewable energy statistics 2016*. Abu Dhabi.

Mason, J., Fulton, L., & McDonald, Z. (2015). *A global high shift cycling scenario*. Retrieved from https://www.itdp.org/wp-content/uploads/2015/11/A-Global-High-Shift-Cycling-Scenario-_-Nov-12-2015.pdf

McKinsey. (2009). *Pathways to a low-carbon economy: Version 2 of the global greenhouse gas abatement cost curve*. Retrieved from http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/pathways-to-a-low-carbon-economy

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J.,… Zhang, H. (2013). Anthropogenic and Natural Radiative Forcing. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 659-740). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Nabuurs, G. J., Masera, O., Andrasko, K., Benitez-Ponce, P., Boer, R., Dutschke, M.,... Zhang, X. (2007). Forestry. In B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, & L. A. Meyer (Eds.), *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.

Observ'ER. (2015). *The state of renewable energies in Europe*. Retrieved from

OFVAS. (2016). Bilsalget i 2015 [The car sale in 2015]. Retrieved from http://www.ofvas.no/aktuelt-1/bilsalget-i-2015-article553-385.html

Orkustofnun. (2011). *Orkustefna fyrir Ísland (Energy policy for Iceland)*. Retrieved from http://www.nea.is/media/gagnasofn/Orkustefna-fyrir-Island.pdf

Orkustofnun. (2015). *Electricity generation per month by energy source type 2012-2014*.

Pales, A. F. (2013). *CHP / DHC Country Scorecard: Finland (2013)*. Retrieved from Paris: https://www.iea.org/publications/insights/insightpublications/the-iea-chp-and-dhc-collaborative-finland---chpdhc-country-scorecard-finland.html

Sims, R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D'Agosto, M., Dimitriu, D.,... Tiwari, G. (2014). Transport. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. v. Stechow, T. Zwickel, & J. C. Minx (Eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Sitra. (2015). *Green to Scale -- Low-carbon success stories to inspire the world* (978-951-563-946-2). Retrieved from http://www.sitra.fi/julkaisut/Selvityksi%C3%A4-sarja/Selvityksia105.pdf

Smith, P., Bustamente, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A.,... Tubiello, F. (2014). Agriculture, forestry and other land use (AFOLU). In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. v. Stechow, T. Zwickel, & J. C. Minx (Eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Snæbjörnsdóttir, S. Ó., & Gislason, S. R. (2016). CO_2 Storage Potential of Basaltic Rocks Offshore Iceland. *Energy Procedia, 86*, 371-380. doi:http://dx.doi.org/10.1016/j.egypro.2016.01.038

SSB. (2016a). Kjørelengder, 2015 [Driving distances, 2015]. Retrieved from https://www.ssb.no/transport-og-reiseliv/statistikker/klreg/

SSB. (2016b). Registrerte kjøretøy, 2015 [Registered vehicles, 2015]. Retrieved from https://www.ssb.no/transport-og-reiseliv/statistikker/bilreg/aar/2016-03-30

Statistics Finland. (2016a). Official Statistics of Finland: Energy supply and consumption.

Statistics Finland (2016b, August 2016). [Private communication. Estimate of CHP-derived heat and electricity consumption in individual Finnish industries, based on unpublished industry statistics.].

Statoil. (2013). *The Norwegian oil industry history and climate challenges*. Retrieved from https://www.globalmethane.org/expo-docs/posters/OilnGas/OG_NO_Success_Statoil_FINAL.pdf

Swedish Energy Agency. (2015). *Energy efficiency trends and policies in Sweden*. Retrieved from http://www.odyssee-mure.eu/publications/national-reports/energy-efficiency-sweden.pdf

Swedish Energy Agency. (2016a). *Energy in Sweden – Facts and figures 2016*. Retrieved from: http://www.energimyndigheten.se/globalassets/statistik/overgripande-rapporter/energy-in-sweden-2016_160218.xlsx

Swedish Energy Agency. (2016b). *Summary of energy statistics for dwellings and non-residential premises 2015 (Energistatistik för småhus, flerbostadshus och lokaler 2015)*. Retrieved from http://www.energimyndigheten.se/globalassets/ny-statistik/bostader/energistatistik-for-smahus-flerbostadshus-och-lokaler-2015.xlsx

UN. (2014). *World urbanization prospects: The 2014 revision*.

UNEP. (2015). *District Energy in Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy*. Retrieved from http://www.unep.org/energy/portals/50177/DES_District_Energy_Report_full_02_d.pdf

UNFCCC. (2016). *National Inventory Submissions 2016*. Retrieved from: http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/9492.php

US DoE. (2016). Fact #918: March 28, 2016 Global plug-in light vehicle sales increased by about 80% in 2015. Retrieved from http://energy.gov/eere/vehicles/fact-918-march-28-2016-global-plug-light-vehicle-sales-increased-about-80-2015

US EPA. (2012). *Global anthropogenic non-*CO_2 *greenhouse gas emissions: 1990-2030*. Retrieved from https://www.epa.gov/global-mitigation-non-co2-ghg-report/non-co2-greenhouse-gases-international-emissions-and

US EPA. (2013). *Global mitigation of non-*CO_2 *greenhouse gases: 2010-2030*. Retrieved from https://www3.epa.gov/climatechange/Downloads/EPAactivities/MAC_Report_2013.pdf

US EPA. (2016a). EPA's voluntary methane programs for the oil and gas industry. Retrieved from https://www.epa.gov/natural-gas-star-program

US EPA. (2016b). *Inventory of U.S. greenhouse gas emissions and sinks: 1990-2014*. Retrieved from Washington, D.C.: https://www.epa.gov/sites/production/files/2016-04/documents/us-ghg-inventory-2016-main-text.pdf

World Bank. (2016). *World Bank Databank*. Retrieved from: http://data.worldbank.org/indicator/NY.GDP.DEFL.ZS?end=2012&name_desc=false&start=1996

Sammendrag

Klimaavtalen i Paris i 2015 fastsatte et utfordrende mål om å holde den globale gjennomsnittstemperaturen til "godt under" 2°C over førindustrielt nivå, og å "forfølge tiltak" for å begrense oppvarmingen til 1,5°C. I årene som kommer håper man at alle land vil øke de relativt beskjedne ambisjonene som ble framsatt i hvert lands Tiltenkte Nasjonalt Bestemte Bidrag (INDC), og at de til slutt vil nå et nivå som er konsistent med temperaturmålet i avtalen.

De nordiske landene kan spille en viktig rolle i denne prosessen på flere måter, inkludert å levere eksempler på tiltak som allerede har bidratt til å redusere utslipp i de nordiske landene selv. Sitra, sammen med Ecofys og flere internasjonale partnere, utgav rapporten "Green to Scale" i 2015, hvor de analyserte effekten av å implementere globalt 17 løsninger som hadde ført til reduksjoner i diverse enkeltland i ulike deler av verden. I denne rapporten anslår vi hvor mye globale utslipp kan reduseres innen 2030 ved å skalere opp 15 løsninger som kommer spesifikt fra de nordiske landene. Vi anslår også de direkte nettokostnadene av å implementere løsningene, og gir en oversikt over de viktigste tilleggsfordelene med og barrierene mot implementering. Vi følger hovedsakelig metodologien som Ecofys utviklet for den globale "Green to Scale"-rapporten.

Rapporten fokuserer på den graden av gjennomføring som allerede har skjedd i de nordiske landene. Vi anslår derfor ikke hvor mye globale utslipp i prinsippet kan reduseres hvis hver løsning implementeres i størst mulig grad i andre land. I stedet tar vi utgangspunkt i den graden av implementasjon som faktisk har funnet sted i de nordiske landene til nå, og anslår reduksjon i globale utslipp ved at andre land oppnår den samme graden av implementasjon.

De 15 løsningene, skalert opp globalt eller til egnede grupper av ikke-nordiske land, kan føre til en reduksjon i globale drivhusgassutslipp på 4.1 milliarder tonn CO_2-ekvivalenter (CO_2e) i 2030, med et spenn fra 3.7 til 4.6 milliarder tonn. Overlapp mellom de ulike løsningene vil sannsynligvis gjøre reduksjonen ca. 140 millioner tonn lavere, avhengig av hvordan løsningene implementeres i detalj.

Kostandene varierer mye avhengig av spesifikke antakelser. Vi finner et beste anslag på 13 milliarder USD totalt, og en gjennomsnittlig kostnad på 3 USD/tCO_2e, når både direkte kostnader og direkte besparelser (f.eks. som følge av lavere energiforbruk) tas med. Men anslaget har et spenn fra -40 til +70 milliarder USD totalt, og -12 til +15 USD/tCO_2e i snitt.

De nordiske landene er lite representative for resten av verden når det gjelder økonomisk utvikling, utdanningsnivå og politiske institusjoner, og har også større lett utnyttbare fornybare energiressurser i forhold til folketallet enn mange andre regioner. Men disse ressursene finnes også i mindre relativ skala mange andre steder i verden, og flere nordiske land har også hatt stort hell med tekniske løsninger som ikke er knyttet til spesielle naturressurser, som for eksempel kombinert strøm- og varmeproduksjon (CHP), fjernvarme, optimal gjødselhåndtering, og diverse energieffektiviseringstiltak.

Vi velger ut løsningene slik at de ideelt sett kan implementeres enten globalt eller i en utvalgt gruppe ikke-nordiske land, selv uten de spesielle forholdene som er til stede i Norden. Vi justerer resultatene for eventuelle forskjeller i CO_2-utslipp fra strømproduksjon for de løsningene som innebærer endring i strømforbruk. I de tilfellene hvor løsninger krever store kapitalinvesteringer som kan være vanskelige for mange land å realisere innen 2030, begrenser vi oppskaleringen til land med tilstrekkelig høy økonomisk utviklingsgrad, i de fleste tilfeller OECD-landene eller OECD-landene pluss utvalgte mellominntektsland.

Utslippsreduksjonene som vi anslår i denne rapporten er på noen måter et ideelt scenario, hvor mange land gjør en stor innsats for å implementere de foreslåtte løsningene. Men på mange andre måter er det et konservativt anslag. Vi antar kun at andre land vil oppnå i 2030 det som nordiske land allerede har oppnådd, selv om nødvendige teknologier i mange tilfeller er blitt billigere og bedre, og det er mer erfaring å bygge på fra teknisk implementering og fra relevante politiske prosesser. I tillegg er vi i mange tilfeller konservative med hvilke land vi skalerer hver løsning opp til. På kostnadssiden har vi dessuten kun tatt med direkte kostnader og besparelser, selv om indirekte besparelser som reduserte helseskader fra luftforurensing og reduserte miljøskader sannsynligvis vil gjøre totalkostnaden vesentlig lavere.

Nordic Council of Ministers
Ved Stranden 18
DK-1061 Copenhagen K
www.norden.org

Technical report: Nordic Green to Scale

This technical analysis for the Nordic Green to Scale report was commissioned to CICERO (Center for International Climate and Environmental Research – Oslo), which is Norway's foremost institute for interdisciplinary climate research. The report illustrates the scaling potential of 15 proven Nordic low-carbon solutions and presents an analysis of the greenhouse gas emissions reductions of these solutions and their scalability internationally.

TemaNord 2016:545
ISBN 978-92-893-4720-4 (PRINT)
ISBN 978-92-893-4721-1 (PDF)
ISBN 978-92-893-4722-8 (EPUB)
ISSN 0908-6692

9 789289 347204