Nordic Green to Scale for Cities and Communities

How far could we go simply by scaling up already proven climate solutions?

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PREFACE:

Learning to act faster

The fight against the climate crisis has reached new levels of urgency. The special report by the Intergovernmental Panel on Climate Change (IPCC) brought home the fact that allowing global heating to go beyond 1.5 degrees would bring unacceptable harm and risks.

The report also showed how keeping climate change at tolerable levels would require transformative action on an unprecedented scale. We now need to essentially halve global emissions every decade and reach carbon neutrality by the middle of the century.

While researchers have illustrated what is at stake and what needs to be done, young people have increased pressure on leaders to act. A global movement, kick-started by the now world-famous Swede Greta Thunberg, has engaged millions of people on all seven continents – the largest climate mobilisation in world history.

At the same time, a growing number of countries, cities, businesses and investors are taking action. Many climate solutions are more efficient and affordable than ever. Be it setting targets for climate neutrality, divesting from fossil fuels or pricing carbon pollution, indicators for climate action point in the right direction: forward.

It is therefore clear that urgent and ambitious action is needed, and that the solutions are available and attractive. But translating this understanding into concrete decisions is happening way too slowly.

What can accelerate this process? One answer lies in learning to learn.

Previous Green to Scale studies have looked into the potential of scaling up existing climate solutions. The three reports released so far have clearly shown that we can go much further much faster. No technology breakthroughs, no breathtaking innovations – just reaching the same level of deployment that some already have today.

This report takes the same approach – scaling up existing climate solutions – but brings it closer to where we all live: cities and municipalities. Again, the message is promising: we can reduce emissions much more by simply learning from our Nordic peers. The report documents case studies and lessons learned that can help all local governments take immediate action.

In autumn 2019, the prime ministers of the Nordic countries presented a vision of becoming the most sustainable and integrated region in the world. They committed to work even more ambitiously and faster and to set climate action as the highest priority.

The prime ministers also stated that the solutions already exist – they are right in front of us. This study further supports their message.

I hope this report inspires local leaders and citizens in Nordic countries and globally to act now.

Paula Lehtomäki
Secretary General
Nordic Council of Ministers

Executive summary

TACKLING THE CLIMATE CRISIS requires an unprecedented transformation of our societies. The good news is that the necessary solutions exist. The key bottleneck is implementing them too slowly.

Green to Scale has been analysing how much emissions can be reduced by scaling up existing climate solutions. With this approach, other countries would just reach the level of implementation the leading peers already have today.

Cities and communities can play a key role in driving climate action. This study analyses the potential of scaling up 14 Nordic climate solutions in other Nordic municipalities. We also estimate the costs and savings, key barriers, enablers and required policy changes.

Climate impact

If other Nordic communities implemented the 14 selected solutions to the extent that their leading peers already have, it would cut annual emissions by 25.6 megatonnes (Mt). This is equal to 12% of current total emissions in the Nordic countries or around half of the emissions in Sweden.

About half of this potential comes from increasing wind power. District heating solutions can cut emissions by 4.7 Mt and ground source heat pumps by 2.7 Mt.

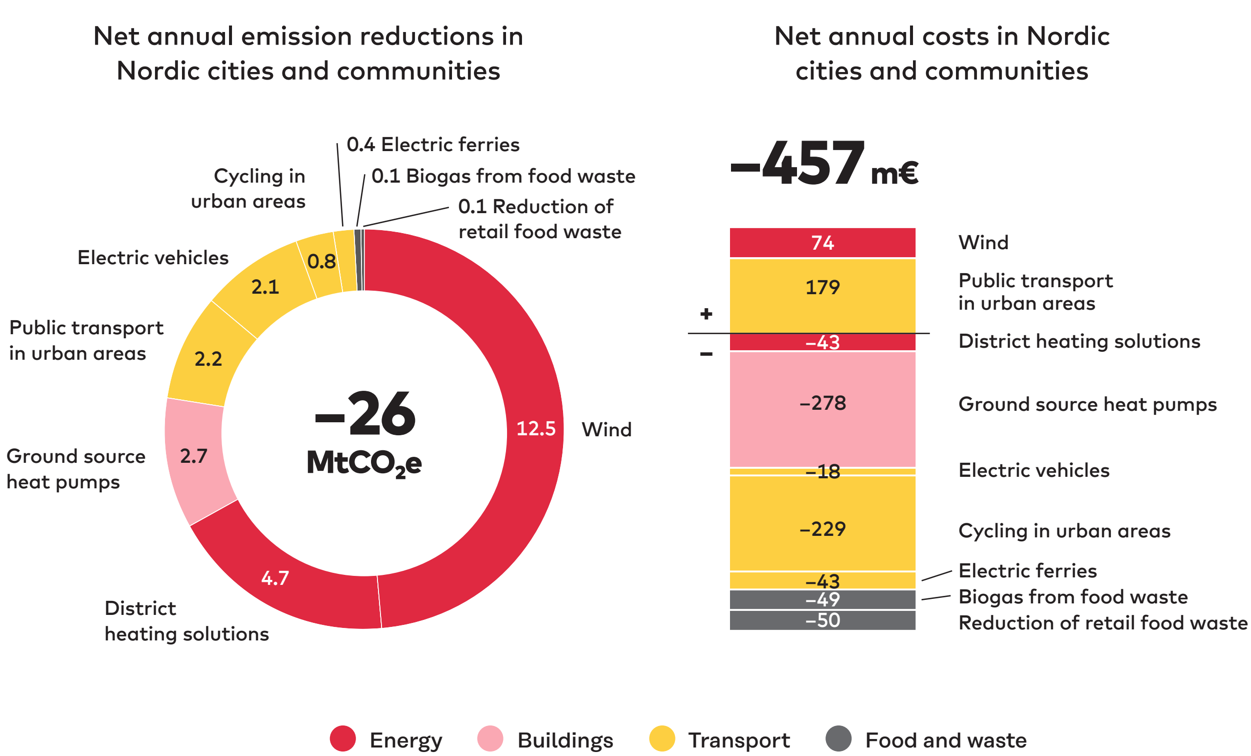
Scaling up the transport solutions could cut 5.6 Mt, or 10% of Nordic transport emissions. Public transport could deliver 2.2 Mt, electric cars 2.1 Mt, cycling 0.8 Mt and electrifying ferries another 0.4 Mt. Food and waste solutions offer a more modest potential of 0.2 Mt.

Costs, savings and co-benefits

Taking into account both costs and savings for the cities and their inhabitants, the solutions would save money over time. The annual total net saving would be more than 450 million euros.

Overall, the solutions are cost-efficient in the Nordics. The only solutions that come with a net cost are offshore wind (60 € per reduced tonne

Total annual emission reductions and net annual costs in Nordic cities and communities



of emissions), solar heating (19 €/t) and public transport (80 €/t). The largest absolute savings come from ground source heat pumps (–278 m€ annually) and cycling in urban areas (–229 m€ annually).

The solutions also provide other benefits to people and the environment. These include avoiding health problems from air pollution, reducing dependency on fossil fuel imports and creating jobs.

> **Learning from those that have already introduced the solutions to scale can help mitigate barriers.**

Barriers and enablers

Climate solutions are held back by various barriers. Implementation is slowed down by large investment costs, the legacy infrastructure, perverse incentives and a lack of awareness, to name just a few.

Luckily, learning from those that have already introduced the solutions to scale can help mitigate barriers. Enablers include financial incentives, dialogue with local organisations and residents, clear road maps, improved access to finance and closer co-operation between public authorities.

Results by country

Denmark. If Danish communities implemented the selected solutions to the extent that the leading Nordic peers already have, it would cut emissions by 4.8 Mt. This is equal to 10% of Denmark's emissions today. The annual net savings would be 135 million euros.

Because Danish averages are used as benchmarks for scaling up wind power, wind does not provide further emission reductions. District heating solutions could cut 2.1 Mt and ground source heat pumps 1.1 Mt. Transport solutions can cut emissions by 1.5 Mt, two thirds coming from public transport.

Finland. If Finnish communities scaled up the solutions, it would cut emissions by 6.7 Mt. This is equal to 12% of Finland's emissions today. The annual net savings to Finnish communities and citizens would be 43 million euros.

Almost half of the emission reductions comes from wind power. District heating solutions could cut 1.4 Mt and ground source heat pumps 1 Mt. Transport solutions can cut emissions by 1.1 Mt.

Iceland. If Icelandic communities implemented the solutions to the extent of leading Nordic peers, it would cut emissions by a relatively modest 118 kilotonnes (kt). This is equal to just 2% of Iceland's emissions today. The annual net savings would be 19 million euros.

Because Iceland has largely de-carbonized its production of electricity and heat, the biggest mitigation potential linked to fossil fuel use is in transport. The analysed transport solutions can cut emissions by 101 kt, half of this coming from electric cars. Biogas from household food waste has a potential for 15 kt.

Norway. If Norwegian communities implemented the solutions as well as the leading Nordic peers, it would cut emissions by 7 Mt. This is equal to 13% of Norway's emissions today. The annual net savings would be 177 million euros.

Most of the emission reductions come from wind power. Ground source heat pumps would cut emissions more than all the district heating solutions combined. Transport solutions can cut emissions by 1.2 Mt, half of it coming from public transport.

Sweden. If Swedish communities scaled up the solutions, it would cut emissions by 7.1 Mt. This is equal to 13% of Sweden's emissions today. The annual net savings would be 84 million euros.

Over half of the emission reductions comes from increasing wind power. Scaling up district heating solutions could cut 1.1 Mt. Solutions in the transport sector can cut emissions by 1.6 Mt.

Policy recommendations

Policy changes at national and local level are needed to scale up the solutions faster. The experiences in Nordic communities can help decision-makers choose effective tools.

Governments can, for example, set ambitious goals, outline long-term frameworks, price emissions, provide funding and introduce enabling regulation. Municipalities, in turn, can present climate strategies, use spatial planning, harness public procurement and require municipality-owned companies to implement climate solutions, for instance.

Many Nordic municipalities have been exploring effective policy approaches. These include setting climate budgets in Oslo, tracking consumption-based emissions in Gothenburg, introducing green bonds in Reykjavik, providing training at the Samsø Energy Academy and bringing key actors together under the Smart & Clean Foundation in Helsinki.

Sammanfattning

ATT HANTERA KLIMATKRISEN kräver en betydlig omställning av vårt samhälle. Den goda nyheten är att de nödvändiga lösningarna finns. Det stora problemet är att implementeringen av dem går för långsamt.

Studien "Green to Scale" har analyserat mängden utsläpp som kan undvikas genom att utöka befintliga klimatlösningar. Med detta tillvägagångssätt kunde andra länder nå upp till samma nivå av implementation som de ledande länderna redan har idag.

Städer och kommuner kan spela en nyckelroll i att driva lösningar på klimatfrågan framåt. Denna studie analyserar det potential som kan nås genom att skala upp 14 nordiska klimatlösningar. Vi uppskattar också kostnader och besparingar, största hinder, möjliggörare och nödvändiga politiska förändringar för lösningarna.

Klimatpåverkan

Om också de andra nordiska kommunerna implementerade de 14 utvalda klimatlösningarna i den utsträckning som de ledande kommunerna redan har gjort, skulle det minska de årliga utsläppen med 25.6 Mt. Detta motsvarar 12 % av den nuvarande mängden utsläpp i Norden eller ungefär hälften av utsläppen i Sverige.

Ungefär hälften av denna potential kommer från en ökning i användning av vindkraft. Fjärrvärmelösningar kan minska utsläppen med 4.7 Mt och markvärmepumpar med 2.7 Mt.

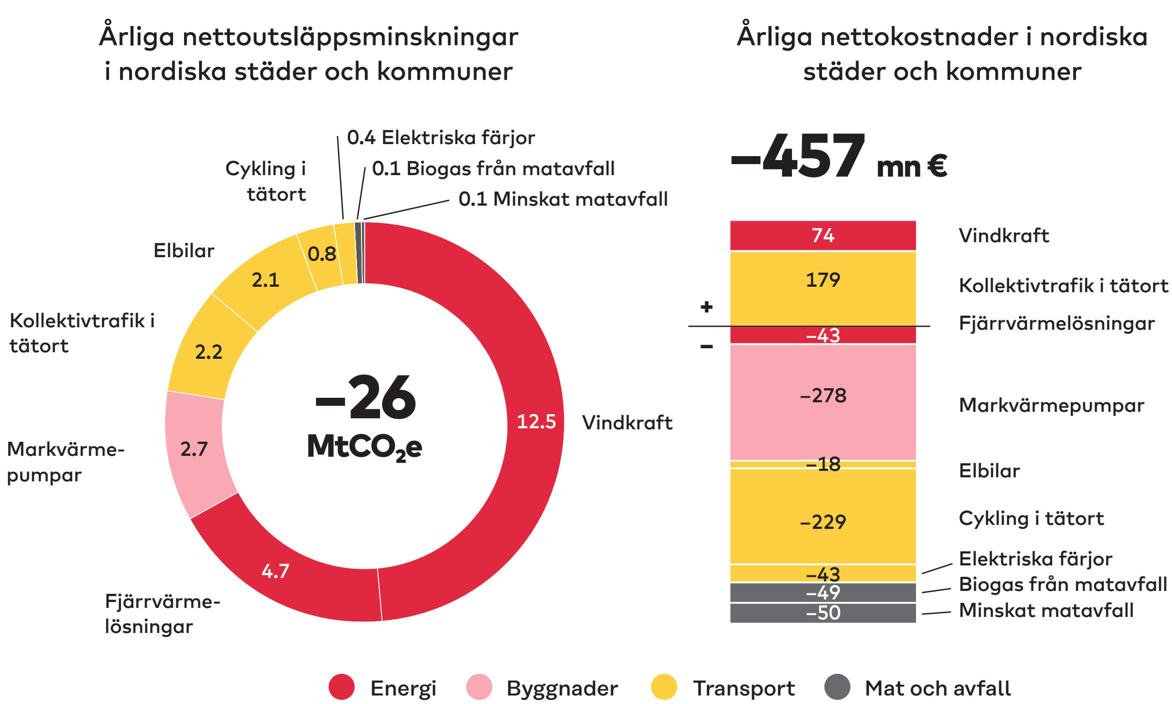
En utökning av transportlösningarna kan minska utsläppen med 5.6 Mt, vilket motsvarar 10 % av de nordiska transportutsläppen. Kollektivtrafiken kan minska utsläppen med 2.2 Mt, elbilar med 2.1 Mt, cyklar med 0.8 Mt och elektrifiering av färjor ytterligare 0.4 Mt. Lösningar angående livsmedel och avfallshantering har potential att förminska utsläppen med 0.2 Mt.

Kostnader, besparingar och fördelar

Om man beaktar både kostnader och besparingar för städerna och deras invånare skulle lösningarna spara pengar över tiden. Det årliga totala nettobesparandet skulle vara mer än 450 miljoner euro.

Lösningarna är överlag kostnadseffektiva i Norden. De enda lösningarna som har en nettokostnad är havsvindkraft (60 €/ton utsläpp), solvärme (19 €/t) och kollektivtrafik (80 €/t). De största absoluta besparingarna kommer från markvärmepumpar

Totala utsläppsminskningar och årliga nettokostnader i nordiska städer och kommuner



(–278 mn € per år) och cykling i tätortsområden (–229 mn € per år).

Lösningarna har också andra fördelar för både människor och miljön. Dessa är t.ex. undvikande av hälsoproblem som orsakas av luftföroreningar, minskat beroende av importerade fossila bränslen och ökad sysselsättning.

Förhinder och möjliggörare

Klimatlösningarnas förverkligande och utveckling hålls tillbaka av olika typer av förhinder, som till exempel stora investeringskostnader, den existerande infrastrukturen, förvrängda incitament och brist på medvetenhet.

Lyckligtvis kan man överkomma dessa förhinder genom att lära sig från de städer som redan har implementerat dessa lösningar. Lösningarnas möjliggörare omfattar finansiella incitament, dialog med lokalbefolkning, tydliga planer, förbättrad tillgång till finansiering och nära samarbete mellan olika myndigheter.

Resultat per land

Danmark. Ifall danska kommuner implementerade lösningarna till den utsträckning som de ledande nordiska städer och kommuner redan gjort skulle det minska utsläppen med 4.8 Mt. Detta motsvarar 10 % av Danmarks utsläpp i dagsläget. De årliga nettobesparingarna skulle vara 135 miljoner euro.

Eftersom danska medelvärden används som riktlinjer för vindkraft så ger ökad vindkraft inga ytterligare utsläppsminskningar. Fjärrvärmelösningar kunde förminska utsläppen med 2.1 Mt och markvärmepumpar med 1.1 Mt. Transportlösningar kunde förminska utsläppen med 1.5 Mt varav två tredjedelar kommer från kollektivtrafik.

Finland. Ifall finländska kommuner implementerade de lösningarna som de ledande nordiska städerna och kommunerna redan gjort skulle utsläppen kunna minska med 6.7 Mt. Detta motsvarar 12 % av Finlands utsläpp i dagsläget och de årliga nettobesparingarna för finländska städer och kommuner skulle vara 43 miljoner euro.

Nästan hälften av utsläppsminskningarna kommer ifrån vindkraft. Fjärrvärmelösningar skulle kunna förminska utsläppen med 1.4 Mt och markvärmepumpar med 1 Mt. Transportlösningar kunde förminska utsläppen med 1.1 Mt.

Island. Ifall isländska kommuner skulle implementera lösningarna i samma utsträckning som motsvarande ledande städer och kommuner har gjort, så skulle de kunna förminska utsläppen med 118 kt. Detta motsvarar endast 2 % av Islands utsläpp i dagsläget. De årliga nettobesparingarna skulle vara 19 miljoner euro.

Eftersom Island inte har mycket fossil energiproduktion kvar, så har vindkraft och fjärrvärme knappt någon potential att minska utsläppen. Transportlösningar kan förminska utsläppen med 101 kt, varav hälften kommer från elbilar. Biogas från hushållsavfall har en potential att minska utsläppen med 15 kt.

Norge. Ifall norska kommuner implementerade de lösningarna som de ledande nordiska städerna och kommunerna redan gjort så kunde de förminska utsläppen med 7 Mt. Detta motsvarar 13 % av Norges utsläpp i dagsläget. De årliga nettobesparingarna skulle vara 177 miljoner euro.

Största delen av utsläppsminskningarna kommer från vindkraft. Markvärmepumpar skulle kunna förminska utsläppen mer än alla fjärrvärmelösningar sammanlagt. Transportlösningar kan förminska utsläppen med 1.2 Mt, varav hälften kommer från kollektivtrafik.

Sverige. Ifall svenska kommuner implementerade lösningarna till samma nivå som de ledande städerna och kommunerna, skulle det kunna minska utsläppen med 7.1 Mt. Detta motsvarar 13 % av Sveriges utsläpp i dagsläget. De årliga nettobesparingarna skulle vara 84 miljoner euro.

Mer än hälften av utsläppsminskningarna kommer från ökad vindkraft. Ökandet av fjärrvärmelösningar kunde förminska utsläppen med 1.1 Mt. Lösningar inom transportsektorn skulle kunna förminska utsläppen med 1.6 Mt.

Politiska rekommendationer

Politiska förändringar behövs för att öka implementeringen av lösningarna. Erfarenheterna i de nordiska städerna och kommunerna kan stöda beslutsfattare i att välja effektiva verktyg.

Regeringar kan till exempel sätta ambitiösa mål, ange långsiktiga ramverk, prissätta utsläpp, erbjuda finansiering och införa möjliggörande lagstiftning. Kommunerna kan i sin tur till exempel presentera klimatstrategier, ta nytta av markplanering och kräva att kommunägda bolag implementerar klimatlösningarna.

Flera nordiska kommuner har undersökt effektiva politiska strategier. Dessa omfattar fastställandet av klimatbudgetar i Oslo, följa upp konsumtionsbaserade utsläpp i Göteborg, införandet av gröna obligationer i Reykjavik, erbjuda skolning som på Energiakademiet i Samsø och förenandet av nyckelaktörer som Smart & Clean Foundation gjort i Helsingfors.

Introduction

THE PAST YEAR has highlighted the need for urgent action to tackle the climate crisis. The recent special reports by the Intergovernmental Panel on Climate Change (IPCC) underscored the devastating impacts global heating could have if we fail to act quickly.

The IPCC reports also send a stark message: we need to peak world emissions in the coming years and reach carbon neutrality by the middle of the century. A good rule of thumb – the so-called carbon law – is that the world has to halve its emissions each decade. What this would require is nothing short of an unprecedented transformation of our societies and economies.

Unfortunately, the world is not yet rising to the challenge. It is actually moving in the opposite direction.

In 2018, world energy-related emissions continued to grow by 1.7%. The emissions gap – the difference between expected and needed emission pathways – in 2030 is estimated to be around 30 gigatonnes (Gt). This is equal to the current emissions of China, the United States, the European Union, India and Russia combined.

The size of the challenge is gargantuan. But so are the opportunities to address it.

Numerous studies have come to the same conclusion: we have the necessary solutions for deep and rapid emission reductions. For instance, the Exponential Climate Action Roadmap has showed that the world can halve emissions in key sectors in just a decade.

The key bottleneck is not the availability of solutions; it is their deployment. And here Green to Scale can help.

Since 2015, Green to Scale has been analysing the potential of scaling up existing climate solutions. We have looked at specific examples of the successful implementation of various solutions across several sectors. We have then analysed how much others could reduce emissions if they simply reached the same level as the leading peers already have today.

In the first phase, Green to Scale showed that scaling up 17 existing solutions to comparable countries would cut around 12 Gt – equal to a quarter of global emissions. Next, our study showed that 15 Nordic solutions could cut emissions by more than 4 Gt, or as much as the emissions of the European Union.

Last year, we turned our attention to specific countries: Estonia, Latvia, Lithuania, Poland and Ukraine in Europe, and Kenya and Ethiopia in Africa. We found that just 10 existing Nordic solutions could reduce emissions by as much as close to 40% in addition to current policies.

This report relies on the same basic approach, but takes it again in a new direction. As before, we analyse the potential of scaling up existing climate solutions, but this time at the local level.

Cities and communities can play a key role in driving climate action. Municipalities often have the power to influence major sources of emissions such as urban transport, energy production and buildings energy use. They can be more agile than countries, moving quickly and serving as test beds for new approaches. Local communities also operate closer to people, with a better understanding of their priorities. Many Nordic cities and communities have already taken the lead and adopted tougher deadlines for carbon neutrality than their home countries.

This study analyses the emission reduction potential of scaling up a selection of 14 Nordic climate solutions in Nordic communities. Most of the solutions focus on energy and transport – the main sources of emissions for local communities.

Based on the earlier Green to Scale studies, we know that energy efficiency is one of the biggest and most attractive options to reduce emissions. In this

A good rule of thumb – the so-called carbon law – is that the world has to halve its emissions each decade.

report efficiency solutions play a smaller role as it proved difficult to identify robust benchmark cases (see the Discussion section for more information).

Contrary to previous Green to Scale studies, we now estimate the emission reduction potential and the costs and savings of implementing the solutions with current emission intensities and prices – essentially to show what the impact would be if the solutions were implemented right away. We estimate the costs and savings from a user perspective, taking into account taxes and emission prices. We also look at barriers making it harder and enablers making it easier to adopt the solutions – and outline possible policy changes to do it faster.

The report only provides a sample of local Nordic climate solutions – and presents only a fraction of their full potential. Yet learning about the real-life experiences of Nordic communities implementing the solutions can help communities in Nordic countries and elsewhere to take stronger climate action now.

Green to Scale is part of the Nordic Prime Ministers' Initiative Nordic Solutions to Global Challenges.

The report only provides a sample of local Nordic climate solutions – and presents only a fraction of their full potential.

Nordic results

MANY NORDIC CITIES and communities have taken the lead in implementing climate solutions – and have proven them to be effective and feasible. Here we show what would happen at the regional level if Nordic cities and communities implemented the 14 selected solutions. Their starting point and other basic facts about Nordic countries are presented in Table 1.

Climate impact

Scaling up the Nordic solutions has large potential for reducing emissions. If other Nordic cities and communities implemented the 14 selected solutions to the extent that the forerunners already have, we estimate that it would cut annual emissions by 25.6 Mt. This is equal to 12% of current emissions (excluding LULUCF) in the Nordics or about half of the emissions of Sweden.

Table 1: Basic information about the Nordic countries and their emissions

	Unit	Denmark	Finland	Iceland	Norway	Sweden
Basic information (2018)[1]						
GDP	€ billion	310	241	23	383	486
GDP per capita	€ thousand	54	44	65	72	48
Population	thousand	5,797	5,518	354	5,314	10,183
Share of population in functional urban areas[2]	%	54	54	65	46	54
Surface area	km^2	42,900	338,400	103,000	385,200	447,400
Emissions (2017)						
Greenhouse gas emissions (excl. LULUCF)[3]	$MtCO_2e$	49.2	55.3	4.8	52.7	52.7
Electricity emission intensity[4]	gCO_2/kWh	207.7	117.4	8.8	8.0	12.3
Emissions per capita	tCO_2e	8.5	10.0	13.6	9.9	5.2
Public electricity and heat production emissions[5]	$MtCO_2$	9.3	15.2	0.2	1.8	6.4
Residential fuel use emissions[6]	$MtCO_2$	2.1	1.2	0.01	0.8	0.6
Transport emissions[7]	$MtCO_2$	13.5	11.5	1.0	12.5	16.6
Of which passenger car emissions[8]	$MtCO_2$	6.7	5.9	0.6	4.6	10.3

LULUCF = land use, land use change and forestry
1 World Bank
2 OECD (2019)
3 UNFCCC
4 IEA (2018), Environment Agency of Iceland
5 Emissions from electricity and heat produced by public thermal power plants. Industry's own energy production is not included. For Iceland we have included fugitive emissions from geothermal power and hydropower reservoirs. UNFCCC, Environment Agency of Iceland
6 Mainly emissions from heating buildings with oil or gas boilers and off-road vehicles; UNFCCC
7 UNFCCC
8 UNFCCC, for Finland VTT

About half of this potential, 12.5 Mt, comes from increasing wind power production – either onshore, offshore or a combination of both – to the level that Danish municipalities on average already have. In fact, less than half of Denmark's current wind power share in Finland, Sweden and Norway could theoretically eliminate all the remaining fossil fuel emissions from Nordic power production.[1] In addition, wind power offers great potential to cover the increasing electricity demand from decarbonising heating, transport and industry.

District heating solutions – i.e. waste water, seawater, solar thermal, data centre and geothermal heat – have the combined potential to cut emissions by 4.7 Mt. In total, the emission reductions from energy are equal to 52% of the Nordic public electricity and heat production emissions.

Using ground source heat pumps in a third of detached houses, like in Stockholm, has the potential to cut 2.7 Mt of emissions from oil, gas, and direct electric heating. This is equal to 57% of residential fuel use emissions in the Nordics.

Analysed transport solutions could cut 5.6 Mt, or 10% of Nordic total transport emissions. If public transport accounted for 21% of the distance travelled in all urban areas as it does in the Helsinki area, emissions could be cut by 2.2 Mt. Extending Oslo's 12% electric vehicle share of the fleet to all Nordic municipalities would cut 2.1 Mt. Cycling three kilometres a day in urban areas, as Copenhageners already do, should shave off 0.8 Mt. In total, passenger car emissions would be reduced by 5.1 Mt or 18%. In addition, we estimate that electrifying all suitable ferry connections in the Nordics could cut another 0.4 Mt.

The food and waste solutions we looked at offer a more modest combined emission reduction potential of 0.2 Mt. Collecting 45% of household food waste and processing it into biogas like Oslo does could replace fossil fuels and reduce emissions by 0.1 Mt. Reducing food waste by one kilogram per inhabitant, like Vantaa, would cut another 0.1 Mt.

Costs and savings

Taking into account both costs and savings from the point of view of the communities and their inhabitants, implementing the solutions would actually save money over time. We estimate the annual net saving in all the Nordic cities and communities to be 457 million euros. This figure includes purely techno-economic costs, i.e. it does not include additional benefits that would arise from reducing health problems caused by air pollution or tax revenue from increased economic activities, for example. Current taxes and emissions allowance prices have been taken into account in costs, and we have not assumed any changes in current fuel or technology prices. In the future we can expect the economics of the solutions to become even more favourable as prices of new technologies fall and fossil fuels are likely to be subject to rising taxes and emissions allowance prices.

Overall, the solutions are very cost-efficient for the Nordic communities. The only solutions that have been estimated to come with a net cost compared to current practices are offshore wind (60 €/tCO_2), solar thermal in district heating (19 €/tCO_2) and public transport (80 €/tCO_2). The other solutions we estimate to provide net savings.

The largest savings per unit of reduced emissions come from the reduction of food waste (–974 €/tCO_2), biogas from food waste (–364 €/tCO_2) and cycling (–287 €/tCO_2). The largest absolute savings can be achieved with ground source heat pumps (–278 m€ annually) and cycling (–229 m€ annually). However, the costs of the solutions vary by country depending on the taxes on fossil fuels and electricity, for example.

Other benefits

The solutions would also provide a range of other benefits to people and the environment. These include cutting air pollution and related health impacts, reducing dependency on fossil fuel imports, creating or retaining jobs and more equal opportunities for people to travel, for example.

When considering different solutions in decision making, the full benefits to society need to be taken into account. Even if some solutions may not deliver large reductions in greenhouse gas emissions or significant financial savings, on balance they may still be worth implementing. For some solutions the primary motivation may actually be the various benefits not directly related to climate, such as reduced congestion and air pollution in cities.

As the world transitions to carbon neutrality, there will be a growing market for climate solutions. Cities are perfectly sized units to function as test beds, and the solutions may generate successful business. Cities are also increasingly competing to attract commerce and young professionals. For some of them, a climate-friendly lifestyle may be an important part of a positive city image.

1 Excluding waste to energy, which we have assumed to be driven by the need to treat the waste. See Appendix I for methodology and Solutions catalogue for discussion.

Figure 1: Total annual emission reductions and net annual costs in Nordic cities and communities

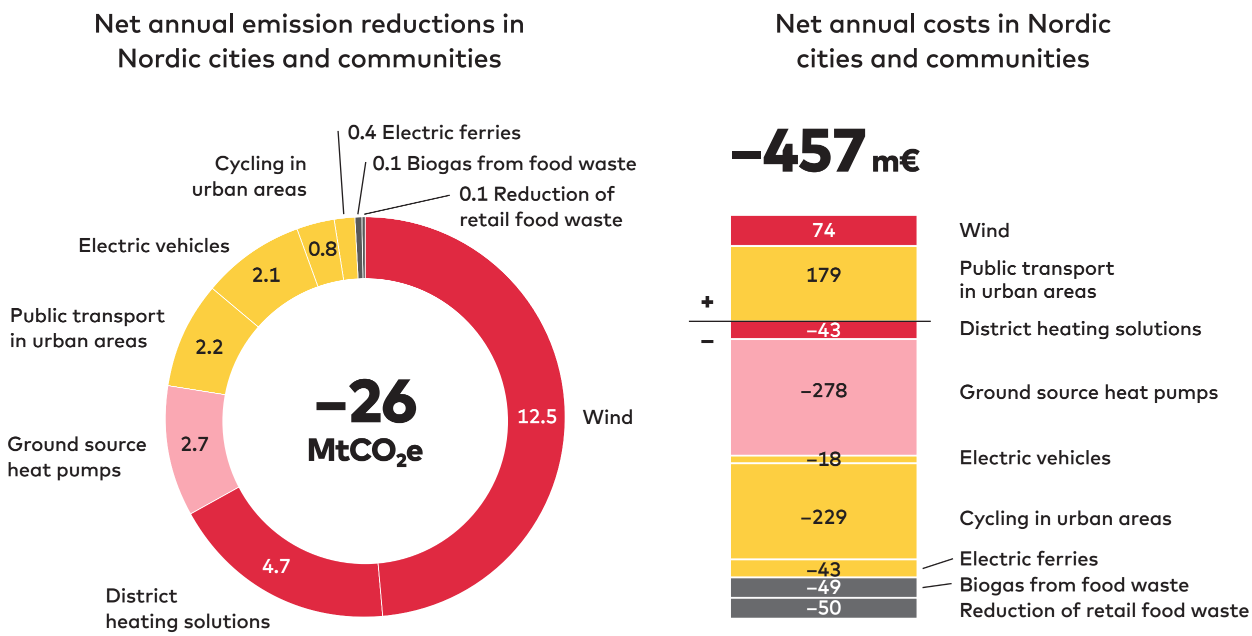
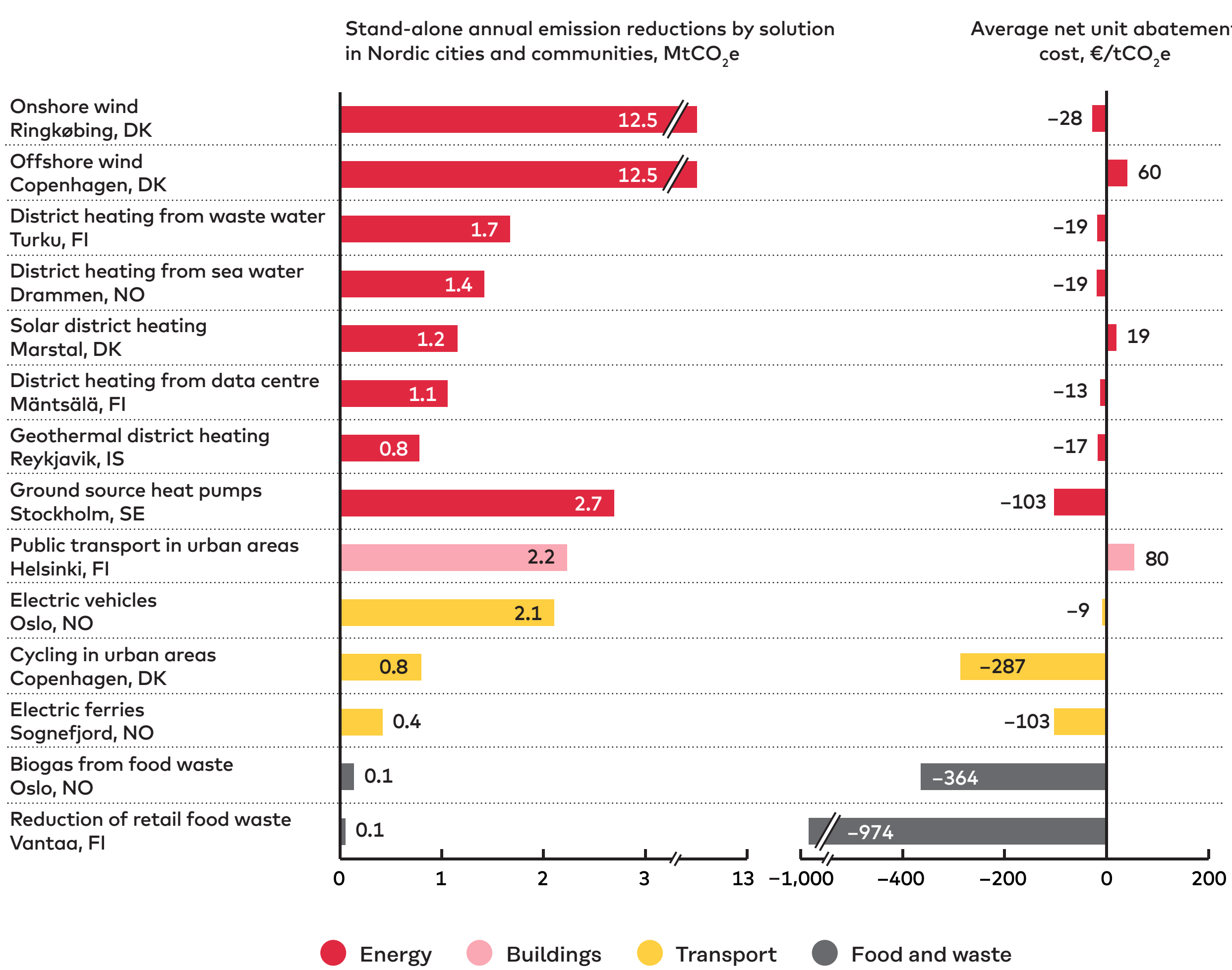


Figure 2: Stand-alone annual emission reductions and average unit abatement costs by solution in Nordic cities and communities



Barriers and enablers

The analysed solutions are feasible, affordable and attractive. So why are cities and communities not implementing them on a larger scale already?

Even the best solutions can be held back by various barriers. The issues slowing down implementation vary from one city, country and solution to another, but some common factors can be identified:

- Large investment costs and lack of financing
- The legacy infrastructure and spatial planning from the high-carbon era
- Subsidies to bioenergy and high taxes on electricity that decrease the competitiveness of electrification
- Negative public attitudes
- Lack of awareness about solutions and their benefits
- Lack of co-operation with neighbouring municipalities and the private sector

Luckily, these barriers can be removed or mitigated. Cities and communities can learn from peers that have already succeeded in introducing the solutions to scale. Some of the enablers common to many solutions include:

- Ambitious targets and clear road maps
- Targeted financial incentives and subsidies
- Improved access to finance
- Local public acceptance driven by dialogue, co-operative models and transparency
- Forward-looking development of the electricity grid
- Smart city and spatial planning
- Low-cost electricity
- Information, training and technical assistance
- Co-operation between public authorities and the private sector

Cities and communities can learn from peers that have already succeeded in introducing the solutions to scale.

Results by country

HERE WE PRESENT THE RESULTS BY COUNTRY. It should be noted that wind power differs from the rest of the solutions. Due to the joint electricity market in Finland, Sweden, Norway and Denmark, wind power built in a certain community does not necessarily cut emissions from that community – or even from that country. However, we have allocated the emission reductions to the places where we have scaled up the building of the wind capacity. The majority of the actual emission reductions will come from Finland and Denmark, where most of the remaining Nordic fossil and peat power capacity operates.

Denmark

Climate impact

If Danish cities and communities implemented 12 selected solutions to the extent that the benchmarks already have, it would cut emissions by 4.8 $MtCO_2e$. This is equal to 10% of Denmark's emissions today.

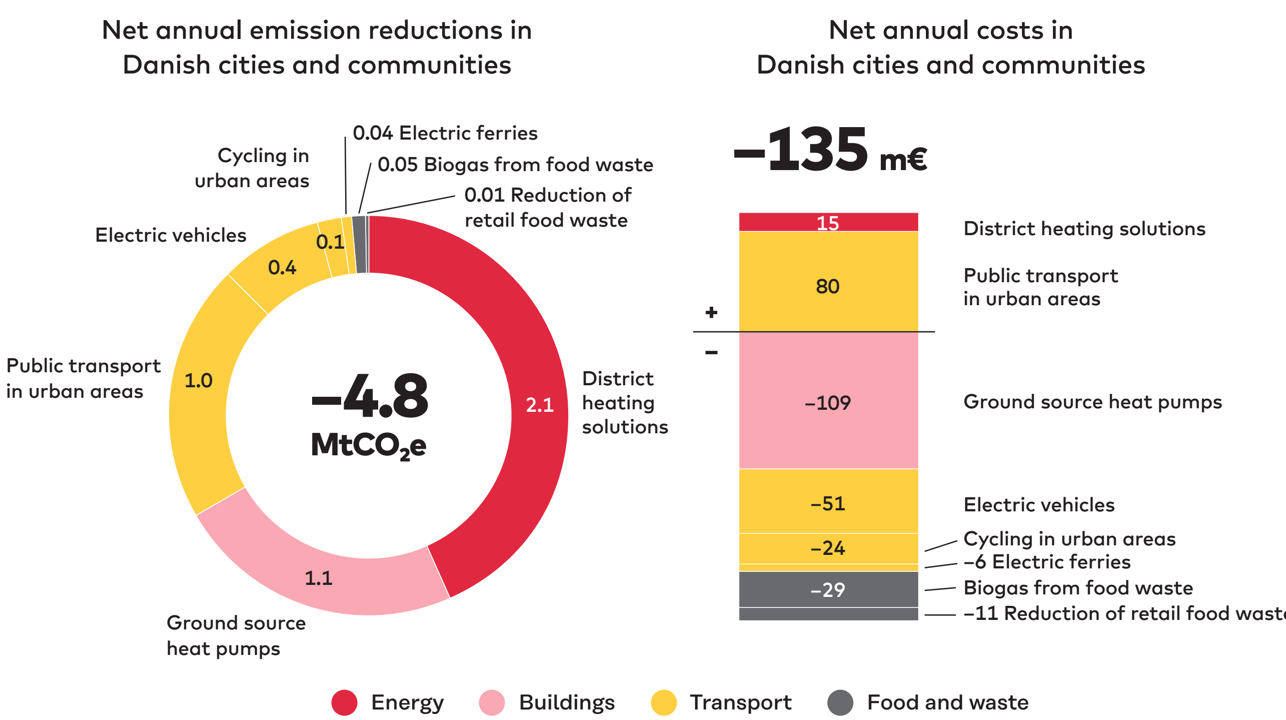
Because Danish averages are used as the benchmarks for onshore and offshore wind, wind solutions are not scaled further in Denmark. The wind power increases in other Nordic countries are expected to cut emissions from Denmark, but the emission reductions have been allocated to the places where we have scaled the building of wind capacity.

Scaling up waste water, seawater, solar thermal, data centre and geothermal heat could in total cut 2.1 $MtCO_2$. This equals 76% of Denmark's current district heating emissions.[2]

Ground source heat pumps in single-family houses could cut emissions by 1.1 $MtCO_2$. Of this, 0.8 Mt comes from replacing oil and gas boilers, representing a reduction of approximately 40% of the residential fuel use emissions, and the rest from saved grid electricity when replacing direct electric heating.

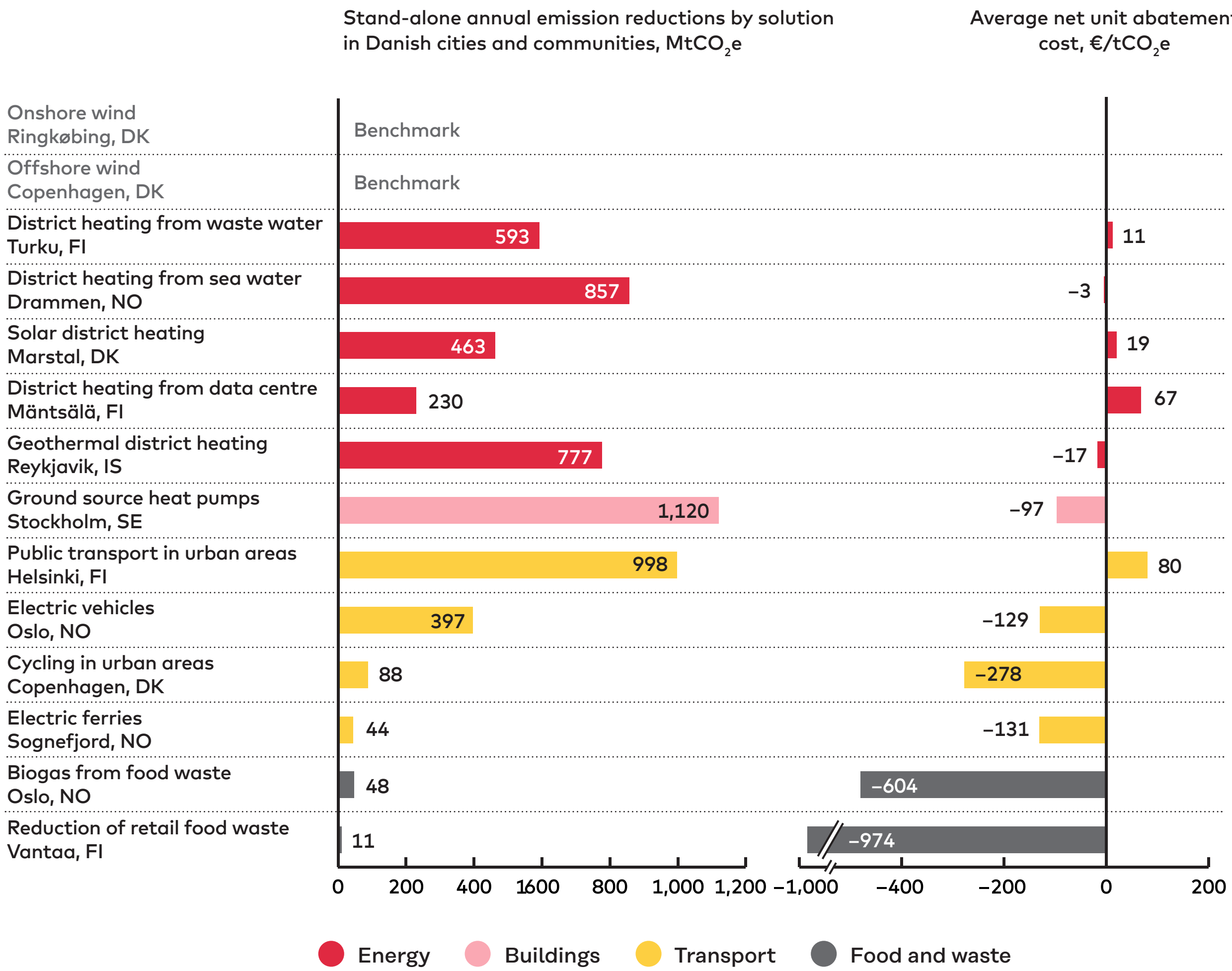
Solutions in the transport sector can cut emissions by 1.5 $MtCO_2$, representing 11% of current transport or 22% of passenger car emissions in Denmark. Two

Figure 3: Total annual emission reductions and net annual costs in Danish cities and communities



2 For Denmark, heat production data per fuel per district heating network was not available and hence the results are less accurate than for other countries. See Appendix I for further information.

Figure 4: Stand-alone annual emission reductions and average unit abatement costs by solution in Danish cities and communities



thirds of this comes from increasing the use of public transport in urban areas, as public transport is less used than in Finland, Sweden or Norway. Electric vehicles and ferries produce about 20% smaller emission reductions in Denmark than in the other Nordic countries due to the relatively high emission factor of grid electricity.

Biogas from household food waste and reduction of retail food waste cut emissions by about 60 ktCO_2e.

Costs and savings

The total annual net savings from the solutions to Danish cities and communities would be 135 million euros or 1 billion Danish kroner. The district heating solutions come with a total cost of 15 million euros.

Compared to other Nordic countries, the electricity prices for heat pumps and consumers are very high in Denmark. Thereby direct electric heating but also ground source heat pumps are relatively expensive. In addition, gas heating in Denmark is relatively cheap, and thereby ground source heat pumps are not competitive against it. However, oil heating is relatively expensive, and in total ground source heat pumps still bring savings, totalling 109 million euros.

For Denmark, the transport sector solutions combined bring a small net saving of one million euros. The increased public transport costs 80 million euros, but savings from the other transport solutions balance it out. Electric vehicles bring savings in Denmark mainly due to the high registration tax imposed on conventional vehicles. Electric ferries in Denmark are exempt from the electricity tax and therefore bring larger savings than in the other Nordic countries.

Reduction of retail food waste and biogas production from household food waste lead to a saving of 39 million euros. In Denmark, biogas production replaces the incineration of biowaste, which brings larger savings than replacing composting or landfilling.

Finland

Climate impact

If Finnish cities and communities implemented 13 selected solutions to the extent that the Nordic benchmark municipalities already have, it would cut emissions by 6.7 $MtCO_2e$. This is equal to 12% of Finland's emissions today.

Almost half of the emissions reductions, 3.1 $MtCO_2$, comes from increasing wind power production – either onshore or offshore, or a combination of both. Scaling up waste water, seawater, solar thermal and data centre waste heat could in total cut 1.4 $MtCO_2$ or 19% of the current district heating emissions in Finland. (Geothermal heat from underground reservoirs has no potential in Finland.)

Ground source heat pumps in single-family houses could cut emissions by 1 $MtCO_2$. Some 0.7 Mt of this comes from replacing oil boilers, representing a reduction of 60% of the residential fuel use emissions, and the rest from saved grid electricity when replacing direct electric heating.

Solutions in the transport sector can cut emissions by 1.1 $MtCO_2$, representing 10% of current transport emissions or 18% of passenger car emissions in Finland. About half of this comes from increasing the share of electric vehicles. Biogas from household food waste and reduction of retail food waste can cut emissions by about 50 $ktCO_2e$.

Costs and savings

The total annual net savings from the solutions for Finnish cities and communities would be 43 million euros. This assumes that 38% of the added wind capacity is offshore, so the wind power brings a net cost of 16 million euros.

The district heating solutions come with a total net cost of five million euros. The unit abatement costs of district heating solutions are more expensive for Finland than for the other Nordic countries on average. Compared to Norway, the electricity for heat pumps is expensive, and compared to Sweden heat production with fossil fuels is cheap. Even though oil heating is also relatively cheap in Finland, ground source heat pumps still bring a saving of 42 million euros.

For Finland the transport sector solutions combined are cost-neutral. Electric vehicles (EVs) are generally more expensive than for other Nordic countries as a result of cheaper fuel and smaller purchase incentives. Because of the cheaper fuel, cycling also brings smaller savings than elsewhere. Unlike in Norway and Denmark, Finnish electric ferries pay full electricity tax while diesel for ferries is tax free.

Despite a small emission reduction, reduction of retail food waste and biogas production from household food waste bring a significant saving of 22 million euros.

Figure 5: Total annual emission reductions and net annual costs in Finnish cities and communities

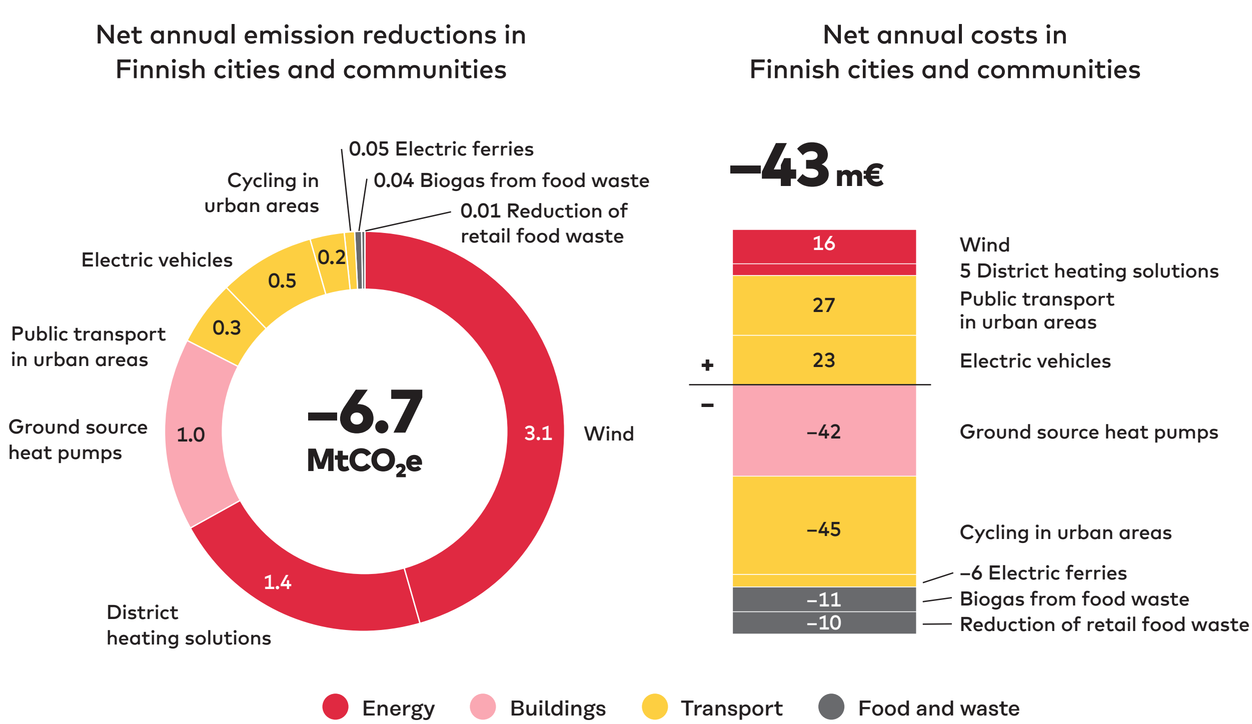
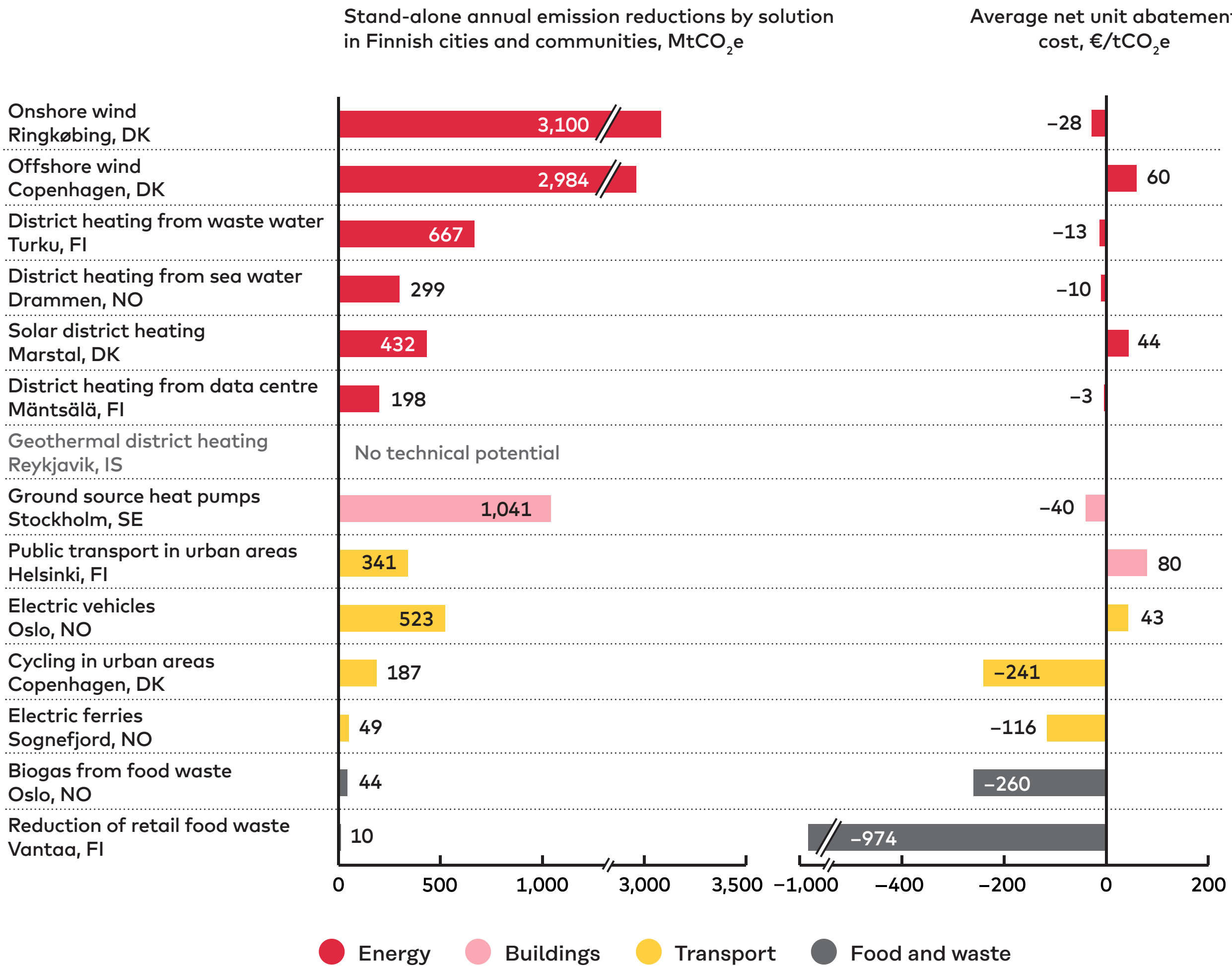


Figure 6: Stand-alone annual emission reductions and average unit abatement costs by solution in Finnish cities and communities



Iceland

Climate impact

If Icelandic cities and communities implemented 10 applicable solutions to the extent that the benchmarks already have, it would cut emissions by 118 ktCO_2e. This is equal to 2% of Iceland's emissions today.

Because Iceland does not have any fossil power production aside from some backup generators and two islands that are not connected to the grid, wind power has no potential to reduce emissions there. Also, geothermal district heat is already used wherever possible, and the technical potential of solar thermal is uncertain. We have not scaled these solutions further in Iceland.

Iceland does, however, have some district heating networks in geothermally cold areas, where electric boilers are used to produce the required heat. Scaling up waste water, seawater and data centre waste heat could in total cut a very modest 1 ktCO_2 as saved electricity, which is very low emission in Iceland. There is also a small number of buildings in Iceland that do not belong to a district heating network and use direct electric heating. Ground source heat pumps in single-family houses could cut emissions by 0.3 ktCO_2 in the form of saved electricity.

Solutions in the transport sector can cut emissions by 101 ktCO_2, representing 10% of current transport and 16% of passenger car emissions in Iceland. Half of this comes from electric vehicles. We assume there to be one ferry connection that can still be electrified.

Reduction of retail food waste cuts emissions by 0.6 ktCO_2e and biogas from household food waste by 15 ktCO_2e. Relatively speaking, biogas production in Iceland cuts emissions significantly more than elsewhere, because biowaste is still being landfilled. Even though landfills are equipped with gas capture systems, a considerable share of methane is still likely to escape into the atmosphere.

Figure 7: Total annual emission reductions and net annual costs in Icelandic cities and communities

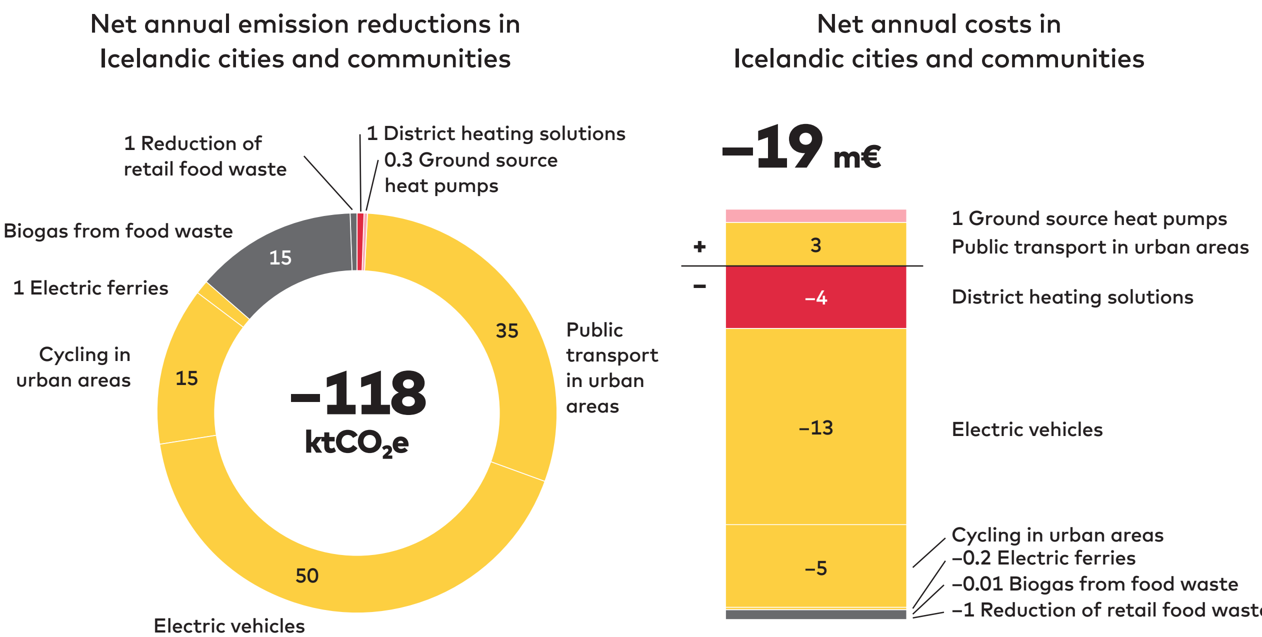
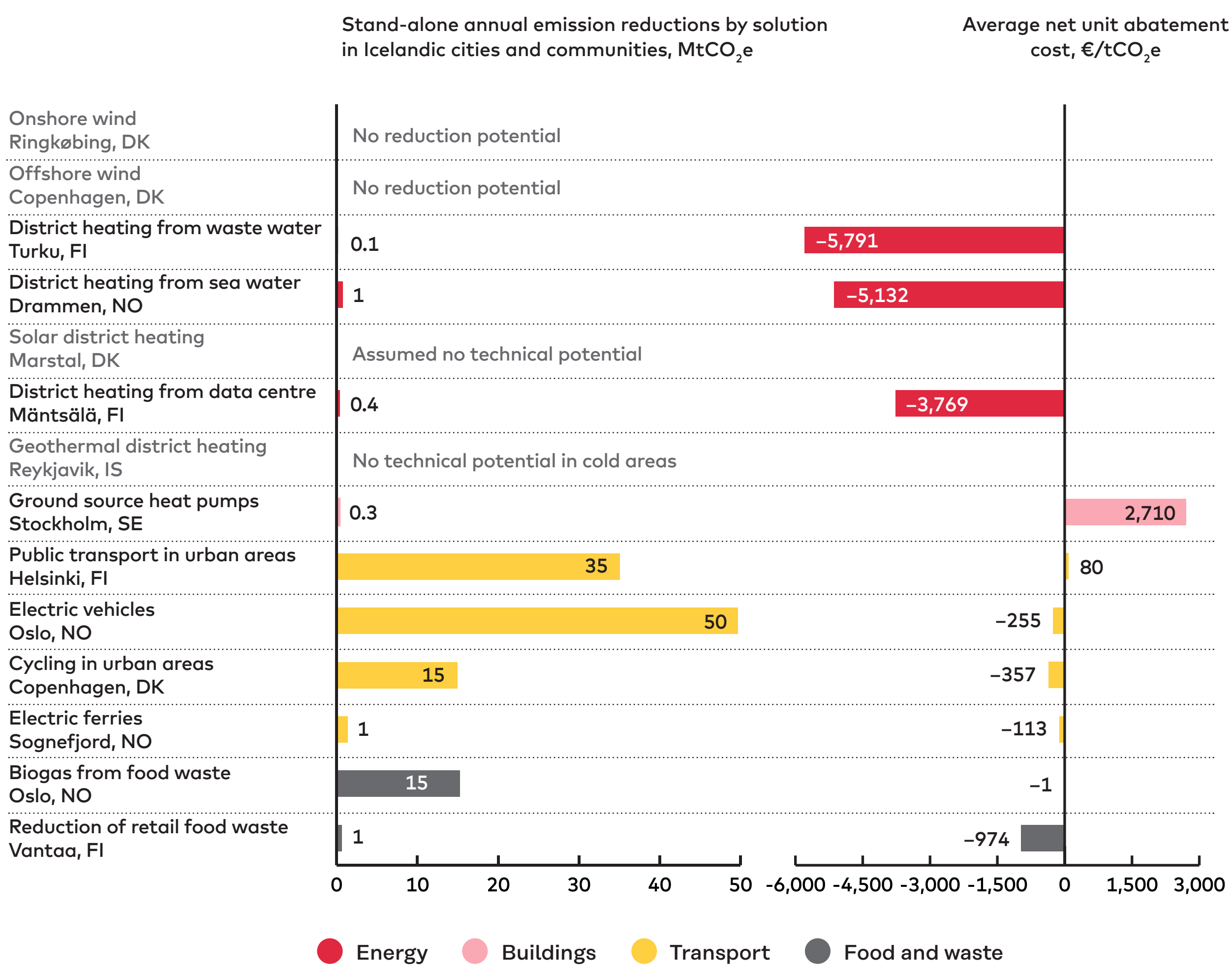


Figure 8: Stand-alone annual emission reductions and average unit abatement costs by solution in Icelandic cities and communities



Costs and savings

The total annual net savings from the solutions to Icelandic cities and communities would be 19 million euros or 2.7 billion Icelandic kroner. While the emission reduction is small, the district heating solutions come with a total net saving of four million euros. The large saving divided by the very small emission reduction make savings per reduced unit of emissions very large.

In Iceland, the electricity for households that use direct electric heating is subsidised, making it very cheap. Thereby the ground source heat pumps would come with a net cost of one million euros.

The transport solutions combined bring a net saving of 15 million euros for Iceland, as the increased public transport cost of three million euros is well offset by the savings of others. Electric vehicles in Iceland are relatively cheap due to tax exemptions, and cycling brings large savings because of the relatively expensive vehicle fuel.

Reduction of retail food waste and biogas production from household food waste bring a saving of 0.6 million euros. This comes mainly from the reduction of food waste, as anaerobic digestion is assumed to be only very slightly cheaper than landfilling the biowaste with gas capture.

Norway

Climate impact

If Norwegian cities and communities implemented 13 selected solutions to the extent that the benchmarks already have, it would cut emissions by 7 $MtCO_2e$. This is equal to 13% of Norway's emissions today.

The majority of the emission reductions, 5.3 $MtCO_2$, comes from increasing wind power production – either onshore or offshore or a combination of both. In Norway, district heating is less common than in other Nordic countries. Scaling up waste water, seawater, solar thermal and data centre waste heat could in total cut only 0.1 $MtCO_2$ of the current district heating emissions. (Geothermal heat from underground reservoirs has no potential in Norway.)

Norway has decided to phase out residential oil boilers in 2020, but there are still some left. Ground source heat pumps in single-family houses could cut emissions by 0.3 $MtCO_2$. Nearly all of this comes from replacing the remaining few oil boilers, representing a reduction of approximately 40% of the residential fuel use emissions. Some 40 kt come from saved grid electricity when replacing direct electric heating.

Solutions in the transport sector can cut emissions by 1.2 $MtCO_2$, representing 9% of current transport emissions in Norway. From passenger cars the

Figure 9: Total annual emission reductions and net annual costs in Norwegian cities and communities

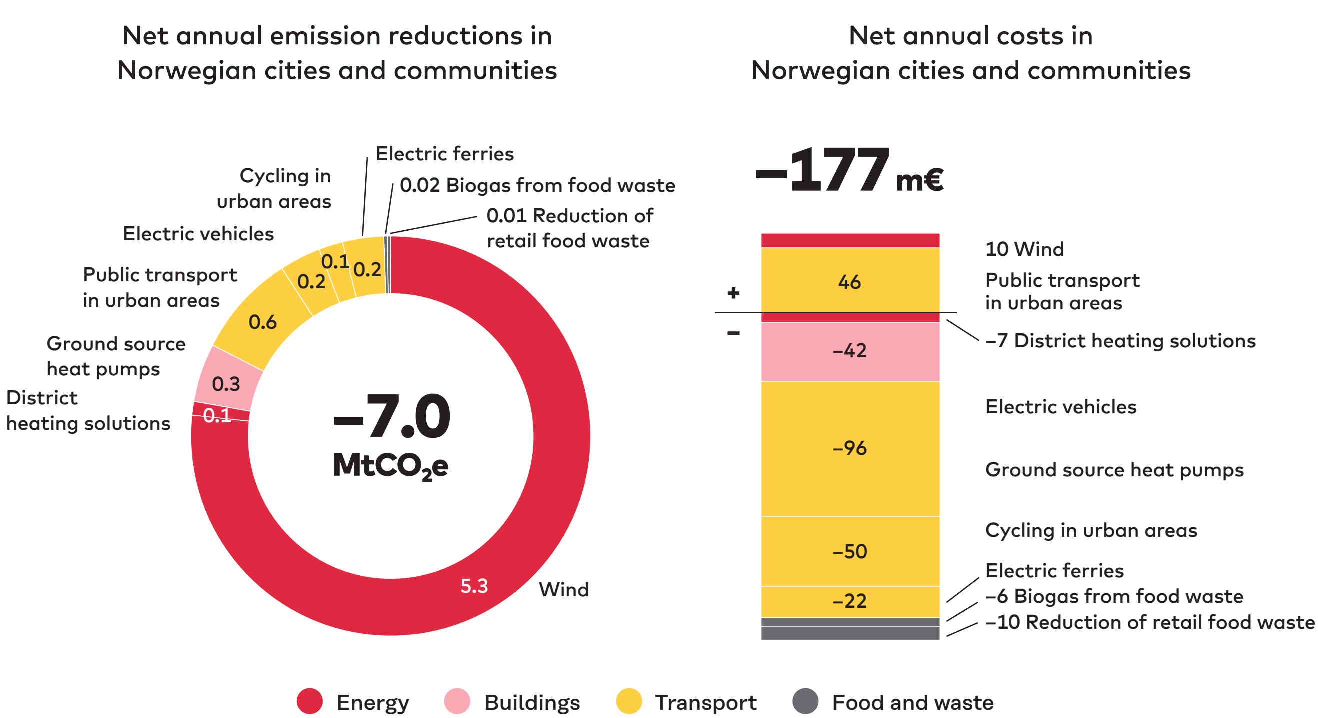
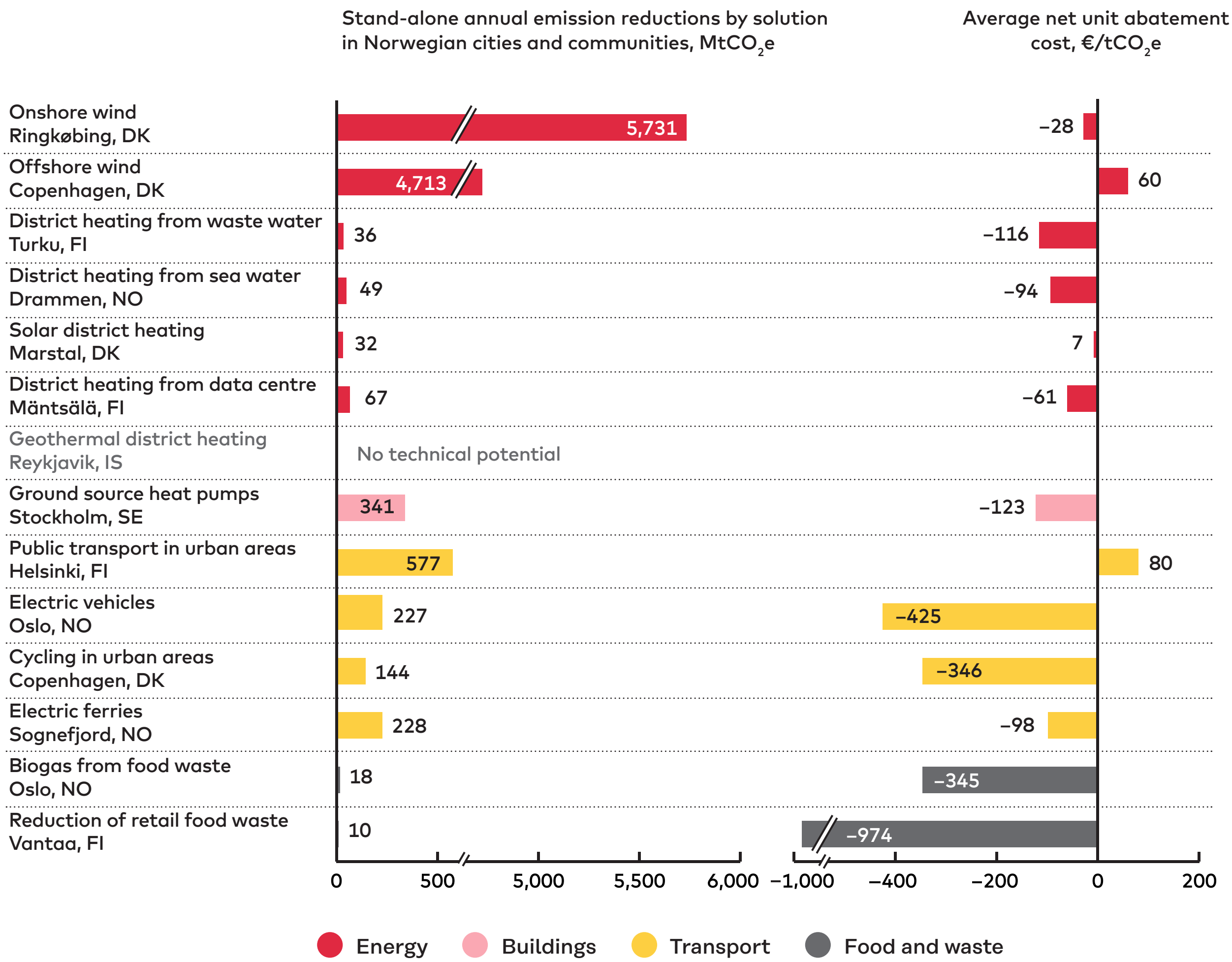


Figure 10: Stand-alone annual emission reductions and average unit abatement costs by solution in Norwegian cities and communities



reduction is 0.9 Mt or 20%. Half of the emission reduction comes from increasing the use of public transport in urban areas, as public transport is less used than in Finland or Sweden, while electric vehicles are already relatively widespread in Norway.

Biogas from household food waste and reduction of retail food waste cut emissions only by about 30 $ktCO_2e$. This is because Norway already produces biogas from a relatively large share of the food waste.

Costs and savings

The total annual net savings from the solutions to Norwegian cities and communities would be 177 million euros or 1.7 billion Norwegian kroner. This assumes that 34% of the added wind capacity is offshore, so the wind power brings a net cost of 10 million euros.

The district heating solutions come with a total net saving of seven million euros. Compared to Sweden, Finland and Denmark, the electricity for heat pumps is cheap as Norway applies industry's lower electricity tax rate.

In Norway oil heating price is quite close to Sweden's, but direct electric heating is cheaper than in the other Nordic countries (with the exception of Iceland). Ground source heat pumps bring a saving of 42 million euros.

For Norway the transport sector solutions combined bring savings of 122 million euros. Electric vehicles are cheap as a result of substantial purchase incentives, and cycling brings large savings because of relatively expensive fuel. Electric ferries enjoy the industry electricity tax rate, but the long average distances of Norwegian ferries increase the required investment above the other Nordics.

Reduction of retail food waste and biogas production from household food waste bring a saving of 16 million euros.

Sweden

Climate impact

If Swedish cities and communities implemented 13 selected solutions to the extent that the benchmarks already have, it would cut emissions by 7.1 $MtCO_2e$. This is equal to 13% of Sweden's emissions today.

Over half of the emission reductions, 4.1 $MtCO_2$, comes from increasing wind power production – either onshore or offshore or a combination of both. Scaling up waste water, seawater, solar thermal and data centre waste heat could in total cut 1.1 $MtCO_2$ of the current district heating emissions in Sweden. (Geothermal heat from underground reservoirs has no potential in Sweden.)

Ground source heat pumps in single-family houses could cut emissions by 0.2 $MtCO_2$. Nearly all of this comes from replacing the remaining few oil and gas boilers, representing a reduction of 26% of the residential fuel use emissions. Some 30 kt would come from saved grid electricity when replacing direct electric heating.

Solutions in the transport sector can cut emissions by 1.6 $MtCO_2$, representing 10% of current transport emissions in Sweden. Passenger car emission reductions total 1.5 Mt or 15%. Over half of this comes from increasing the share of electric vehicles, as the public transport use rates in Swedish metropolitan areas are already high.

Biogas from household food waste and reduction of retail food waste cut emissions by less than 30 $ktCO_2e$. This is because Sweden already produces biogas from a large share of the food waste.

Figure 11: Total annual emission reductions and net annual costs in Swedish cities and communities

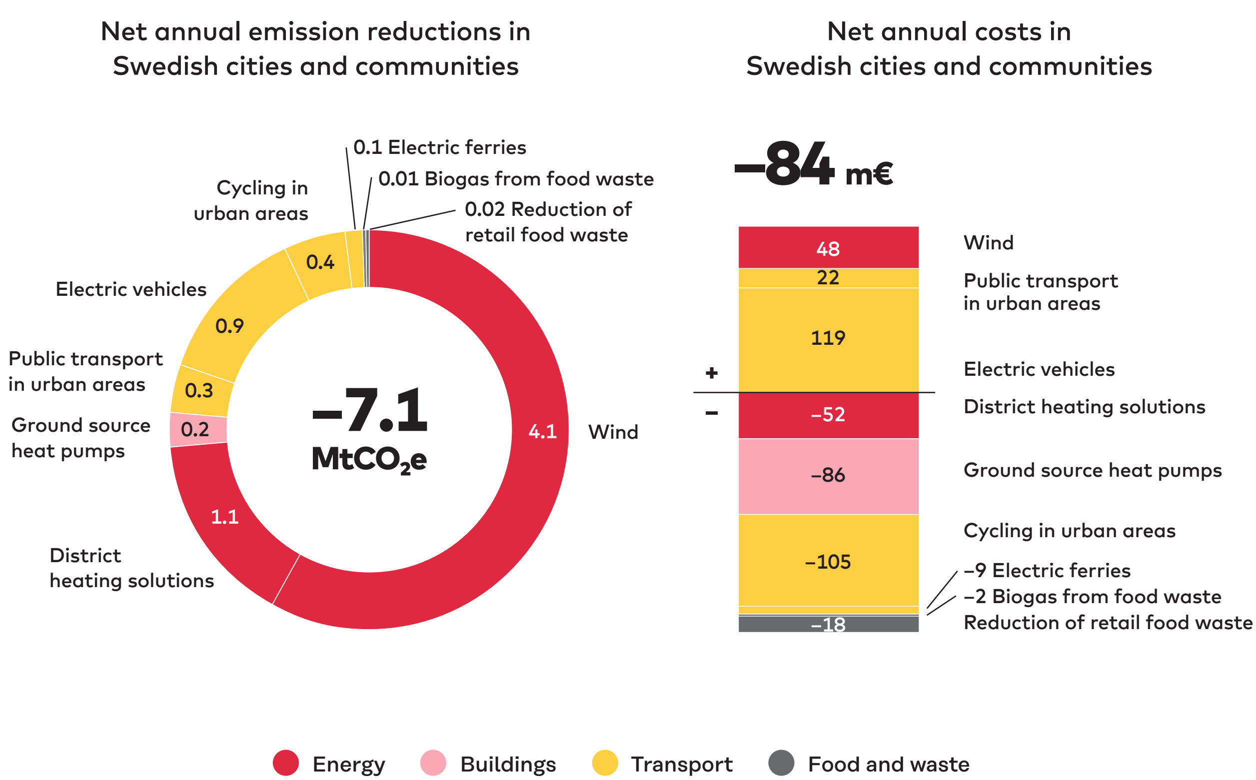
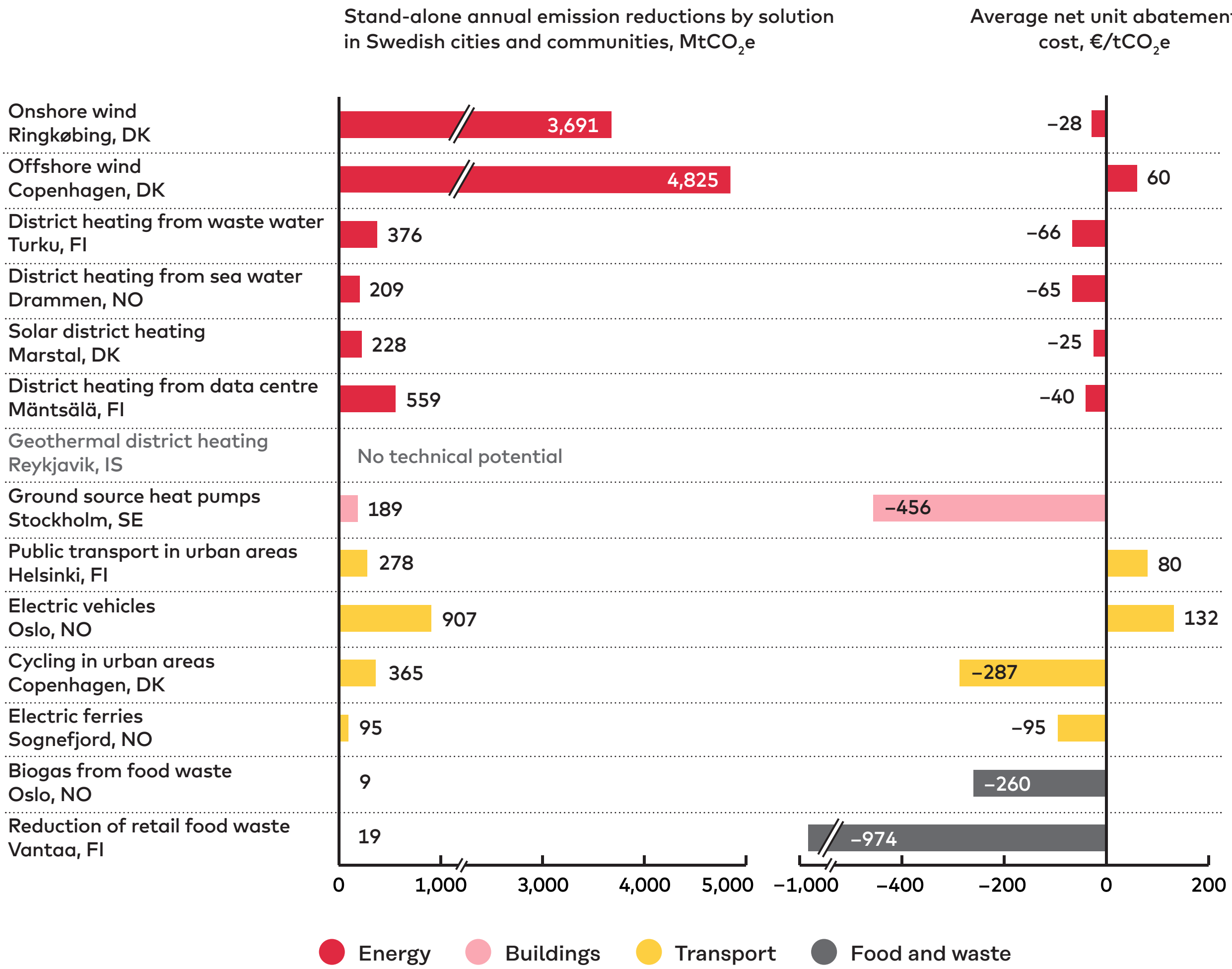


Figure 12: Stand-alone annual emission reductions and average unit abatement costs by solution in Swedish cities and communities



Costs and savings

The total annual net savings from the solutions to Swedish cities and communities would be 84 million euros or 0.9 billion Swedish kroner. This assumes that 45% of the added wind capacity is offshore (because Sweden has a higher share of onshore to start with) so the wind power brings a net cost of 48 million euros.

The district heating solutions come with a total net saving of 52 million euros. Compared to Norway, the electricity for heat pumps is expensive in Sweden, but the heat production from fossil fuels is also heavily taxed – with the exception of peat. In Sweden oil, gas and direct electric heating are relatively expensive, and even with a modest emission reduction ground source heat pumps bring a saving of 86 million euros.

For Sweden, the transport sector solutions combined cost 28 million euros. Of the Nordic countries, electric vehicles are the most expensive in Sweden as a result of smaller EV purchase incentives than in Norway, Denmark or Iceland and shorter average mileage than in Finland. Cycling in Sweden brings large savings as a result of relatively expensive fuel. On the other hand, the savings from electric ferries are slightly smaller than elsewhere because of the full electricity tax imposed on ferries, while diesel for ferries is tax free.

Reduction of retail food waste and biogas production from household food waste bring a saving of 21 million euros.

Policy recommendations

CHANGES IN POLICY are needed to remove the barriers preventing communities from fully implementing climate solutions – and to boost the enablers that help in doing so. Both national and local-level policies are required, as well as their co-ordination. The experiences in Nordic communities can help decision-makers choose effective policy tools to scale up climate solutions, considering national and local priorities and circumstances.

When designing policies, it is important to evaluate the potential impacts on other social and environmental goals, such as reducing inequality or preserving biodiversity. In addition, several measures combined often achieve better results than if they were carried out separately. Timing matters, too: awareness raising first can make other measures (such as tax increases) more publicly acceptable later.

Here we present policy recommendations that can advance the implementation of various climate solutions. Solution-specific recommendations are presented in the Solutions catalogue. Many of the recommendations are familiar to Nordic policy makers, but most countries and communities have a lot of room to push them much further.

National-level recommendations

National (and European) policies lay the groundwork for municipalities to take climate action. Options to consider include the following.

1. Set a good framework

- Set emission targets and budgets in line with the Paris Agreement, including reaching climate neutrality long before 2050
- Introduce sector-specific strategies with concrete measures to provide a clear blueprint for the future and a stable investment environment
- Establish within climate law robust mechanisms to monitor progress and an obligation for the government to introduce corrective actions if necessary
- Engage local governments and citizens in a dialogue when planning policies
- Collect and openly publish comprehensive data on the results of policies

2. Harness your tools

- Strengthen pricing emissions through emissions trading and an environmental tax reform on a sufficient scale in all sectors
- Apply a low tax for electricity used in heat pumps and data centres feeding into district heating networks
- Allow local governments to collect congestion charges
- Provide targeted support for investments in local climate solutions, such as public transport and the electric vehicle charging infrastructure
- Use regulation to ban unwanted activities, such as landfilling organic waste, and set strict standards for the energy efficiency of buildings

3. Ensure future success

- Ensure the availability of low-carbon electricity and transmission lines for widespread electrification
- Build the necessary capabilities within government, municipalities and wider society through training, education and R&D, for example

Local-level recommendations

With the support of national policies, local (and regional) action can make a big difference. Cities and communities are key to enabling sustainable life for their inhabitants and applying new solutions. They are also in a good position to act as they can move more nimbly, know local conditions and operate close to citizens.

Local governments can use a range of different policies to scale up climate solutions.

1. Set a good framework

- Set emission targets in line with the Paris Agreement, including reaching climate neutrality long before 2050
- Present a climate strategy with concrete measures for various sectors, based on local challenges and strengths
- Use robust metrics to monitor progress and ensure that necessary actions are taken

- Involve stakeholders and citizens in dialogue and decision-making about climate action
- Collect and publish data on emissions and measures to reduce them, including from companies owned by the municipality
- Require municipality-owned companies to develop and implement climate solutions
- Co-operate with neighbouring municipalities in areas such as traffic planning and waste treatment

2. Harness your tools

- Use spatial planning to support reducing emissions from transport and energy production by compact urban development, zoning waste heat sources near district heating networks and reserving space for heat pump facilities, for example
- Use financial measures to incentivise climate action through, for example, differentiated congestion charges, parking fees and waste fees
- Harness public procurement and use the municipality as a test bed for climate solutions

3. Ensure future success

- Develop the electricity distribution grid in a forward-looking way to enable electrification
- Recognise and build the capabilities necessary for decarbonisation within the local government in co-operation with local businesses and universities
- Raise awareness of climate solutions
- Share experiences with peers and learn from the experiences of others

Best practice approaches from Nordic communities

Many policy frameworks and institutional structures have been successfully implemented in Nordic cities and municipalities to support the implementation of climate solutions locally. Some interesting approaches are briefly described below.

Climate budget in Oslo, Norway

Oslo is committed to reducing emissions by 95% by 2030 and has co-created with 40 stakeholders a strategy to get there. A key governance tool is a climate budget, which Oslo prepares each year and presents together with the regular financial budget. The climate budget sets an annual limit for allowed emissions linked to transport, energy and buildings and resources (waste, landfill and water). The budget also presents the implemented or planned measures and their anticipated impacts. The city council can only adopt financial budgets that will provide the needed emission reductions, which has placed climate action at the heart of budget negotiations. To support more accurate progress assessment, statistics are being developed in co-operation with Statistics Norway.

Consumption-based emissions in Gothenburg, Sweden

The Climate Programme of Gothenburg also covers the consumption-based emissions of its citizens regardless of whether the emissions take place within the city or elsewhere. The programme from 2014 sets a goal of reducing emissions to 3.5 tCO_2e per person by 2035. Objectives for 2030 include reducing the climate impact of air travel by 20% and the impact of food consumed in the city by 40%. The target for emissions from the purchase of goods and materials will be set later. Measures to achieve these goals include educational initiatives, demonstrating climate benefits, communications and advice.

Urban planning in Oslo, Norway

Oslo is one of the fastest growing cities in Europe, but it has decided not to expand geographically. The city prefers to densify areas that are centrally located, along subway lines and surrounding major hubs. This will enable the greatest use of public transport and encourage cycling and walking. For the development of green spaces, Oslo has a masterplan that ensures a contiguous green network and good access to green areas in urban zones. The blue-green structure is used to achieve better local climate, air quality and natural water balance. To mitigate flood risk from increasing rainfall caused by climate change, Oslo has decided to reopen its previously enclosed waterways and regenerated the land adjacent to the waterways with indigenous plants and trees. They will also serve as new recreational spaces.

Green bonds in Reykjavik, Iceland

The City of Reykjavik issues green bonds to fund projects that bring quantifiable environmental benefits and are aligned with the city's carbon-neutrality objective. Thus far, the projects that have received funding include new and retrofitted public buildings and the construction of cycling and walking paths. In addition to buildings and transportation, projects can bring improvements in energy efficiency, waste management, sustainable land use or adaptation. The impacts will be estimated by sustainability experts and reported through annual impact reports for investors.

Helsinki Metropolitan Smart & Clean Foundation, Finland

Smart & Clean creates impactful, scalable solutions that keep global warming to below 1.5 °C. The foundation unites cities, companies, research organisations and government bodies to build systemic changes in practice. They work intensively together developing radical and innovative, but permanent, climate solutions for cities' and citizens' needs. The foundation orchestrates multi-stakeholder ecosystems to accelerate public-private co-creation actions, which lead to sustainable business and permanent climate-positive practices. Smart & Clean ecosystems operate in transport, energy, the built environment, waste and water, and consumer solutions.

Educational initiatives in Ii, Finland

Ii has engaged with its residents in many forums to encourage them to take climate action in different ways. In schools, pupils have monitored energy consumption and taken measures to cut energy consumption. Half of the savings from energy-efficiency improvements have been directed back to the school budget and the pupils have had a say in how the money is used.

In addition, the municipality has taken part in face-to-face meetings organised by local associations to give guidance on, for instance, how to transform the energy system in one's house to renewable energy. Within a year, more than 1,000 people took part in the meetings – not a small number in a municipality of 10,000 residents.

Samsø Energy Academy, Denmark

Samsø island has invested in a number of renewable energy projects, such as wind turbines, straw-based district heating, tractors that run on rapeseed oil and solar panels. The Samsø Energy Academy collects all experiences and information related to the projects and makes the information accessible to others. The academy functions as a conference centre where renewable energy, energy efficiency and new technologies can be discussed by scientists, businesses and politicians. They also house an exhibition and energy summer school for tourists and school students visiting the island.

Carbon-neutral municipalities network (HINKU) in Finland

Founded in 2008, HINKU is a network for municipalities that are climate forerunners and have committed to cutting their emissions by a minimum of 80% by 2030 compared with 2007. So far, 63 municipalities have joined, representing more than 1.5 million people. The network shares knowledge on best practices and provides support for climate work in municipalities, including emissions accounting, communications co-operation and project preparation. HINKU also brings the municipalities together with businesses offering climate-friendly products and services as well as climate and energy experts.

Discussion

What is different in the analysis this time?

The previous Green to Scale analyses assessed the potential emission reductions beyond expected baseline development in 2030. For estimating the costs, the reports mainly relied on the global average unit abatement costs between 2009 and 2030 assessed in other studies.

This time we have set the baseline at the current situation at the time of writing. The abatement costs we have calculated bottom-up, comparing the costs of the solutions with the actual incumbents they are expected to replace in the Nordic communities. We have also tried to capture the local-level view of the costs by including the European emissions allowances and national taxes in the perceived costs. In essence, we have tried to answer the question: what would happen to emissions if other Nordic municipalities did as soon as possible what the benchmark communities have done, and how much would it cost them?

Why exactly these solutions and benchmarks?

This study tries to identify particularly promising climate solutions from Nordic cities and municipalities. The project steering group selected the final solutions and benchmarks from a long list of best-practice examples.

The selection criteria included implementation at a wide scale in a benchmark community, emission reduction potential relevant to municipalities, scalability to other communities, compatibility with deep emission reductions and analysis feasibility. Preferred features included also cost-efficiency, co-benefits to people and environment, and balance between different sectors and reference countries.

Lack of available data or implementation at a wide scale in at least one community eliminated many otherwise interesting cases from the analysis. The examples presented in this report are not necessarily the municipalities that have implemented the solutions to the greatest extent, but they are cases that have been documented and acknowledged to be successful. The solutions focus on energy and transport, because that is where most of the emissions in Nordic municipalities come from.

Are the solutions applicable to other locations?

Generally, yes. Most of the solutions are already used by many communities to some extent and scaling up would just mean taking their deployment one step further. For instance, local governments are already working on increasing the use of public transport and cycling, but they could benefit from the experiences of leading peers.

Some of the solutions require certain environmental conditions, such as strong winds or geothermal heat. Some others can be applied to many different types of communities, but may work better in some, such as dense urban structures. This we have taken into account in the analysis, scaling solutions up only in places where the conditions are met.

However, depending on the solution and the local context, there might be a number of factors that limit the applicability of the solutions to a particular community. Considering the full range of situations in municipalities goes beyond the scope of this study.

On the other hand, similar results in reducing emissions can often be achieved with other measures. For instance, if a community does not have waste heat available from data centres or waste-water treatment, it might turn to industrial waste heat instead.

How realistic is the emission reduction potential?

Generally, very realistic. The Green to Scale approach is conservative by definition, as the solutions are only scaled up to the level that other locations have already

Green to Scale approach is conservative by definition.

achieved today. We have also applied constraints on the potential when deemed necessary, such as in the case of seawater or solar district heating. Moreover, this study only covers a small subset of all existing climate solutions; including all of them would increase the emission reduction potential considerably.

However, depending on the solution and the local context there might be limitations we could not take into account. For example, not all communities may have the space required for solar collectors readily available. On the other hand, some other locations might easily implement the solution even more widely. In the end, the success of actual practical implementation depends on the local policy choices.

What about the cost estimates?

They are intended to be indicative rather than exact. Cost estimates are very sensitive to the underlying assumptions of both the cost of the climate solution and the conventional option it is going to replace. Costs can vary widely depending on the local setting and may also change quickly, for example when a new government decides to change taxation.

The purpose of this study is not to give municipalities a detailed feasibility and cost analysis of a particular solution in their context. This would require a significant amount of additional analysis, due diligence and design. Instead, the study tries to provide a broader understanding of some of the available options to help communities identify promising solutions for a closer look.

Do the solutions overlap or have synergies?

Yes. Both wind solutions address the same base of emissions, that is the remaining power from fossil fuels and peat. The same goes for the district heating solutions in many cases. This overlap we have taken into account when calculating the total combined emission reductions.

The transport solutions do not overlap technically, but in reality it might largely be the same people that more easily switch to cycling, public transport or electric vehicles. This may make increasing all of them simultaneously more difficult, but not impossible, as some cities have shown.

The solutions also have significant synergies. For instance, the additional wind power increases the emission reductions from the solutions that use electricity: heat pumps, electric vehicles and electric ferries. These synergies have not been quantified here.

What is the expected time frame for the implementation?

This is left open. We have simply illustrated what would happen if the solutions were implemented on a larger scale in current conditions. In reality, the implementation will take some time, depending on the solution and the community.

The analysis uses current data so the results may change depending on when the solutions are actually implemented. The costs of many climate solutions – such as electric cars – are projected to come down rapidly, which would make them even more attractive. In the Nordic countries, remaining fossil fuels will likely be gradually squeezed out of the electricity system, which will affect the emission reduction potential of the solutions that either produce or use power.

When considering the time frame, it is important to keep in mind that limiting global heating to acceptable levels requires deep emission reductions at an unprecedented speed. Existing climate solutions should be implemented as quickly and to as large an extent as possible. This would buy the world time to develop new, innovative solutions to address emissions that are more difficult to abate.

Does the EU Emissions Trading System just move the emissions somewhere else?

The electricity and large-scale heat production in the Nordic countries operates under the EU Emissions Trading System. If the EU-wide emissions cap remained at a fixed level, the emissions reduced within the Nordics could be expected to simply relocate outside of the region.

Existing climate solutions should be implemented as quickly and to as large an extent as possible.

However, since the beginning of 2019 the cap has no longer been fixed as the market stability reserve operates to suck out excess emissions allowances. When allowances are being moved to the reserve, the additional emission reductions are likely to produce a net climate benefit.

On the other hand, the cap is also politically set and can be tightened. Faster implementation of clean production can also act as a driver to tighten the cap and to allow for even larger emission reductions.

Why are no energy-efficiency solutions included?

Study after study shows that energy efficiency is key to reaching long-term emission reduction targets. We spent a good deal of time trying to identify good energy-efficiency cases. However, many cases were not yet widely implemented in a municipality, there was no data available or the improvements were too modest to qualify as a benchmark for scaling up.

We have only included benchmarks that we see compatible with long-term deep emission reductions. For buildings energy efficiency this means that all new buildings and renovations of existing buildings must aim for maximal energy efficiency.[3] Buildings are not renovated very often, so small improvements are simply not enough. Some emerging cases we can learn from are showcased on page 63.

Why are no biomass solutions included?

Biomass is an important resource we can use to reduce emissions. However, sustainably sourced biomass is also scarce and the demand for it can only be expected to increase in the future.

Food-based biofuels entail a significant risk of indirect land-use change, potentially contributing to clearing forests and the emissions and biodiversity loss that come with it. Waste-based biofuels tend to be more sustainable, but even there the resource is much too limited to cover a significant part of energy needs. Before long, sustainable biofuels should be allocated to uses where other options to reduce emissions remain limited, such as international aviation and shipping.

We have only included benchmarks that we see compatible with long-term deep emission reductions.

3 See Buildings in Solutions catalogue.

Analysis methodology

THE BASIC CONCEPT OF GREEN TO SCALE is fairly straightforward: estimating the potential of scaling up existing climate solutions to the extent that some cities or communities have already achieved. However, getting from the idea to results requires a number of steps, several assumptions and the availability of data.

Selecting the solutions

Internal and external experts were first interviewed to put together a long list of known best-practice examples from the Nordic cities and municipalities. The project steering group then selected the solutions and benchmarks to be included in the analysis based on must-have criteria:

- Relevance to local-level emission reductions
- Scalability to other cities and municipalities within and outside of the Nordics
- Compatibility with deep emission reductions on a wider societal level
- Implementation at a wide scale in the benchmark community
- The availability of data on the solution itself, its implementation in the benchmark case and the current implementation level in other Nordic cities and municipalities

Additional preferred features included also cost-efficiency, co-benefits to people and environment and balance between different sectors and reference countries.

Many interesting solutions from various Nordic communities could not be analysed in this report due to a lack of data or the small scale of implementation achieved up until now. We have, however, highlighted some of them in the sector introductions, as they also offer great potential.

The basic concept of Green to Scale is fairly straightforward: estimating the potential of scaling up existing climate solutions to the extent that some cities or communities have already achieved.

Scaling up

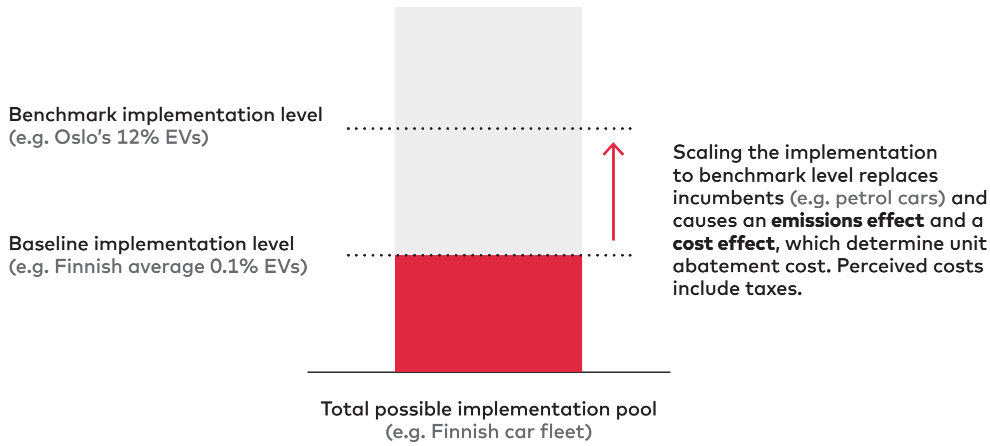
Identifying the benchmark implementation. We analyse scaling up climate solutions to the extent that a benchmark has already achieved. First, we had to determine the benchmark degree of implementation, which the other cities would then be expected to achieve. In many cases, this was quantified as a share of total possible implementation – the share of electric vehicles out of the total car fleet, for example.

However, for some of the district heating solutions there was considerable uncertainty regarding the actual technical potential of the solution in other municipalities. In these cases, the benchmark degree of implementation was capped at an absolute figure. For example, the amount of heat produced by a seawater heat pump into each (seaside) district heating network was capped at the same level as in Drammen, at 67 GWh.

Identifying the scaling subjects. Next, we had to consider which other cities and communities could be able to reach the benchmark implementation level. In some cases, this is limited by available natural resources, such as seawater for seawater heat pumps or hot underground water reservoirs for geothermal district heating. In other cases, the benchmark level is clearly easier to implement in urban than rural communities, and thereby we only scaled increased cycling and public transport use in functional urban areas.[4]

4 OECD (2019)

Figure 13: How does scaling up work?



Scaling up. The solution was then scaled up from the current baseline level to the benchmark level for each scaling subject. For example, the average share of electric vehicles in the car fleet in Finland is currently just 0.1%. We assumed that all Finnish municipalities can on average reach the EV penetration of Oslo, which is 12%, implying that the share of EVs must increase by 11.9 percentage points. This means in total 321,000 new EVs and 38 billion kilometres driven by EVs instead of conventional vehicles each year in Finland.

Estimating the net emission impact. The net emission impact of scaling up the solutions was based on comparing two factors: the emissions of the solution itself and the emissions from the current activities it would replace. For example, in the case of electric vehicles in Finland we compared the emissions related with the electricity used by an EV with the fuel combustion by a similar new petrol car. The emission difference per kilometre multiplied by the 38 billion additional EV kilometres gives the total emission impact in Finland.

The presented emission impacts are annual. They were assessed using current emission values, such as the current emission factor of average grid electricity, taking into account the differences between the Nordic countries. Therefore, they present reductions from current emissions and illustrate the reduction that would be achieved by scaling up the solution immediately. Of course in reality the implementation would take a varying amount of time depending on the solution and the community.

Estimating the net cost impact. Similarly to emissions, the net costs of scaling up the solutions are based on comparing the cost of the solution itself with the cost of the activity that it replaces – from the perspective of the user, i.e. the municipality or citizen. The cost of EU emission allowances and national taxes and different subsidies were included in the perceived costs.

For example, the costs of buying and operating an electric vehicle over the average car lifetime were compared with the costs of buying and operating a similar petrol car in different Nordic countries. The assessed costs include all tax breaks and subsidies that are currently given to EVs.

Sometimes the costs of implementing the solution might not be incurred by the user, and in these cases we assessed the joint net costs of the parties. For

The cost of EU emission allowances and national taxes and different subsidies were included in the perceived costs.

example, investments in the cycling infrastructure by a municipality were subtracted from the saved fuel costs of cycling instead of driving a car.

We used the current costs of the solution and the alternative activity. The cost estimate of the solution came from the actual benchmark whenever possible, and when not available from other, usually Nordic, studies.

The unit abatement cost for each solution and country was attained by dividing the net cost of the scaling by the resulted net emission reduction. The estimate is highly sensitive to the relative costs of the solution and the replaced alternative. Thereby, even the smallest improvement in favour of the replaced alternative can in some cases turn savings into costs and vice versa. However, many of the presented climate solutions are rapidly becoming cheaper, and the savings from implementing these solutions can be expected to increase in the future.

Other considerations

Enablers, barriers and co-benefits. Both benchmark-specific and more general enablers, barriers and co-benefits were identified based on a literature review and information from local experts. Enablers are factors that facilitate, and barriers are factors that limit, the scaling up of the solution. Co-benefits are social, economic and environmental gains that stem from the deployment of the solution, in addition to reducing greenhouse gas emissions and providing possible financial savings.

Policy recommendations. Both national-level and local-level policy recommendations were identified based on the analysis of each solution.

Lifecycle emissions. The analysis covers so-called production-based emissions that take place within a country's territory – for example, the grid electricity used by heat pumps and the replaced fuel combustion. The results do not include indirect impacts, such as the carbon footprint of manufacturing the equipment or the emissions from extracting, refining and transporting the fuels. However, for electric vehicles we have included an approximation of lifecycle impacts, recognising that their production may result in significant emissions.

Overlaps and synergies. Some of the solutions address emissions from the same sources. For example, many of the district heating solutions can be applied to the same networks. These kinds of overlaps have been taken into account when calculating the total abatement effect in the Nordics and per country. On the other hand, some solutions have synergies, such as increasing the share of wind power reduces the emissions from powering heat pumps. These synergies would make the total emission reduction potential of the solutions larger than presented here.

Assumptions, data and sources. For more information on calculation methodology, assumptions, data and sources considering specific solutions, please see Appendix I.

The results do not include indirect impacts.

Photo: Istock

SOLUTIONS CATALOGUE

14
SOLUTIONS

Energy

GLOBALLY THE PRODUCTION OF ELECTRICITY and heat is the largest source of emissions. In the Nordics, electricity production has for a long time been relatively low emission as a result of large shares of hydro, nuclear and, more recently, wind power. Iceland has managed to nearly eliminate emissions from electricity and heat production with widely available geothermal energy. However, especially in Denmark, Finland and Sweden the widespread district heating systems in urban areas still often rely on the combustion of fossil fuels and peat.

One solution to replace fossil fuels is the electrification of heat production with heat pumps, which can capture and upgrade low-temperature heat from various sources. The City of **Turku** in Finland utilises the heat of waste water (p. 47) and the town of **Mäntsälä** covers over half of its district heating needs by capturing the waste heat from a local data centre (p. 56). The City of **Drammen** in Norway gets most of its heat from the sea (p. 50) and **Reykjavik** heats nearly all its buildings with geothermal heat (p. 59).

Electrifying heating, transport and industrial processes means that in addition to cleaning existing electricity production by removing fossil fuels, much more electricity will be needed in the long run. While in many countries solar offers the most potential, the Nordics are better suited to wind. The Danish municipalities of **Ringkøbing** and **Copenhagen** provide great examples of onshore (p. 40) and offshore (p. 44) wind power deployment, respectively.

The variability of most renewable energy production leads to a growing need for flexibility in the energy system, which can be created by, for example, energy storage or increased system integration. The town of **Marstal** in Denmark managed to significantly increase the share of solar heat in their district heating with seasonal heat storage (p. 53). Interesting pilots include the development of a two-way open-access district heating network in **Skanssi, Turku** and the **EnergyLab Nordhavn in Copenhagen** that aims to demonstrate how renewable power and heating, energy-efficient buildings and electric transport can be integrated into an intelligent, flexible and optimised energy system.

The remaining carbon dioxide emissions from energy production can in some cases be either utilised or stored to achieve carbon-neutral or even carbon-negative energy. The waste-to-energy plant at Klemetsrud in **Oslo** considers capturing the CO_2 and storing it in geological formations under the sea floor. **Reykjavik Energy** has demonstrated the storage of CO_2 through mineralisation in basaltic rock.

Bubbling under – the solutions of tomorrow

Two-way district heating in Turku, Finland
Turku is developing a low-temperature open-access district heating grid in a new residential area, Skanssi. The new network will enable buildings and other potential heat producers to sell their excess heat to the network and will therefore support the deployment of local renewable energy. The project develops and pilots various local heat production and storage solutions as well as technologies to optimise heat production and use. The vision is to create a smart district heating network that can significantly reduce energy consumption by optimising the system as whole.

EnergyLab Nordhavn in Copenhagen, Denmark
Innovative energy solutions are demonstrated in the EnergyLab project in the Nordhavn harbour area. The project aims to efficiently integrate a large share of renewable energy through a cost-effective smart energy system that integrates energy infrastructures from electricity, heat and transport sectors, and allows the necessary flexibility for efficient use of renewable energy.

Carbon capture and storage from waste incineration in Oslo, Norway
Oslo plans to turn the Klemetsrud waste-to-energy plant into a full-scale carbon-capture facility. The plant has the potential to capture annually around 400 kilotonnes of CO_2 produced by the incineration of non-recyclable waste. The captured greenhouse gas is to be liquified, transported by ship and injected into offshore geological formations in western Norway. The plant is competing against a cement factory in Breivik for government funding for carbon capture and storage (CCS).

Carbon capture and storage in basaltic rock in Reykjavik, Iceland
Reykjavik Energy and the CarbFix collaboration team have shown that carbon dioxide injected into subsurface basaltic rock mineralises into carbonite rock in less than two years, storing carbon at a significantly lower cost than conventional CCS methods. Industrial-scale carbon capture and storage have been ongoing at the Hellisheiði geothermal power plant since 2014. Currently the method is being tested at new injection sites of various geological conditions and combined with technology to capture CO_2 directly from the air. There are plans to apply the method to capture and store CO_2 from high-emitting industrial plants such as aluminium and ferro silicon.

Onshore wind, Ringkøbing

Wind power built on land is an increasingly affordable way to produce large amounts of low-carbon power.

Solution description

Ringkøbing is home to Denmark's largest onshore wind farm of 22 turbines with a total capacity of 72 MW and an annual electricity production to meet the needs of 57,000 households. Overall in 2018, Denmark covered 27% of its electricity demand with onshore wind alone.

The Ringkøbing wind farm project was driven by local investors and landowners. The realisation of such a large wind farm required a long-term process, a good working relationship with the local authority and the purchase of 12 properties. Residents close to the turbines were offered the chance to buy shares in the project, and consequently 20% of the windmills are now owned by nearby neighbours.

Climate impact

Wind power production does not reduce emissions just within the municipality boundaries but everywhere in the grid by pushing out fossil fuel-based generation with higher marginal production costs. In Denmark, wind power has historically mostly replaced coal-based electricity, which emits on average nearly 800 kilograms of carbon dioxide per MWh produced. The farm in Ringkøbing produces annually around 230 GWh of electricity and therefore has reduced annual emissions by 180 $ktCO_2$ if we assume that it has replaced coal power.

Many Nordic municipalities have large potential for installing onshore wind capacity. If other Nordic municipalities increased their onshore wind production to match the total level of Denmark and produced 27% of the current electricity demand of their country with onshore wind, wind production would be increased by 73 TWh.

However, there is no fossil power production to be replaced in Iceland and theoretically only 40 TWh is needed to push out all remaining fossil-based condensing and CHP power generation from the joint electricity grid between Finland, Sweden, Norway and Denmark.[5] This would reduce emissions by 12.5 $MtCO_2$.

In reality, the effects of adding this much wind power would be more complex. Variation of wind power production within smaller timescales than was possible to look at in this study might mean that not all fossil production can be replaced without additional measures in the energy system.

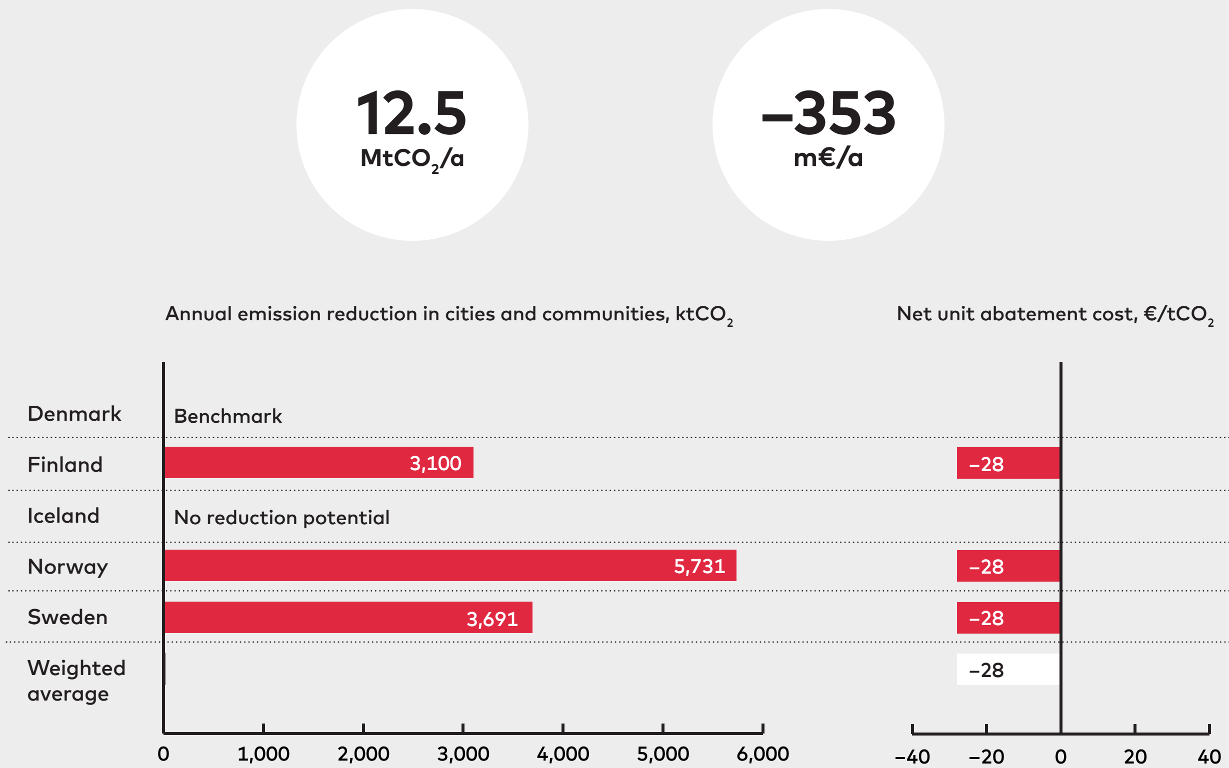
Also, most of the fossil-based electricity in the Nordics comes from the cogeneration of power and heat, which is often driven by the demand for heat production. The wind power might then be exported rather than replace large amounts of CHP production in the short term, although the emissions would then be reduced outside of the Nordics.

The increased wind production would also be likely to drive down the price of electricity, which would lead to increased demand for it. The demand for electricity will also grow if many of the other solutions presented in this report are implemented, and wind power offers great potential to fulfil that demand.

1/5 of the Ringkøbing wind farm is owned by local citizens.

5 See Appendix I for more information on the methodology.

Figure 14: Scaling up onshore wind production to 27% of electricity demand



Note: costs calculated for the 40 TWh that is enough to theoretically replace fossil power production.

Costs and savings

The installation cost for onshore wind power is still fairly high, but operational costs are very low. On a levelised cost basis, onshore wind power is already in most cases the cheapest way to produce electricity in the Nordics. The costs have decreased rapidly during the last few years and are often cited to be already below 30 €/MWh for new projects.

However, wind power will bring along systemic costs from the increased need for flexibility, so we have chosen to use a higher, conservative estimate of 41 €/MWh. This is still lower than the levelised cost for coal, gas, oil or peat when we account for the need to buy emission allowances under the emissions trading scheme. The abatement cost is negative, –28 €/tCO_2, when calculated for the addition of 40 TWh.

Other benefits

Wind power cuts harmful air pollution from fuel combustion, reduces reliance on fuel imports and can create local jobs. In the Ringkøbing case, the wind turbines were produced at a local factory and installed by local operators. A local operator also holds the 20-year service agreement. In total, around 28,000 people in Denmark today work in the wind power industry.[6] Wind power can also be a source of property tax and land rental income for the municipality.

Barriers

Wind power projects often face resistance by some of the local residents. This is often based on impacts such as changes to the landscape, noise, danger to flying animals and other impacts on the natural environment.

Lengthy and rigid permit-granting processes can also act as a significant barrier. The existing power grids limit the placement of wind parks, as too great a distance to the existing transmission grid can make the connection too expensive. In some cases, disturbance to radar equipment can severely limit the placement of wind parks. As a variable power source, wind also requires flexibility from the rest of the energy system in the form of transmission capacity,

6 Region Midtjylland

demand response, storage, increased backup power or interconnections with neighbouring countries.

If a wind power project does not receive any state subsidies, a long-term power purchase agreement (PPA) is usually required for the project investment to get long-term financing. Increasing amounts of wind power tend to drive down electricity prices as a result of wind's extremely low marginal cost. This in turn reduces incentives to invest in any power production and makes it hard to maintain generation capacity profitably.

Enablers

The best conditions for wind power are areas with strong and stable winds, often found in open areas near the coast. However, the development of technology enables the harnessing of weaker winds. Consequently the placement of wind farms can be done more and more freely within the limits of the grid infrastructure.

The main drivers for wind power have traditionally been subsidies, which also have a long history in Denmark. Currently, the dominant support scheme for onshore wind is an auctioned price premium paid on top of the wholesale market price for electricity. However, recently in the Nordics, many onshore wind projects have been carried out completely without subsidies, their revenue secured by long-term corporate PPAs. Wind PPAs protect the buyer from the electricity market price volatility and can enhance sustainable brand image.

Local public acceptance is also necessary. Denmark has promoted co-operatives that enable locals to buy shares in the wind farms. The interest on the loan is tax deductible from private income and co-operative members get tax rebates on their household electricity use.

In Denmark, wind projects also receive support during the pre-investment phase. Associations of wind plant owners and other local initiatives may apply for guarantees for loans for feasibility studies, which are conducted in the run-up to the construction of a wind project.

Wind is a variable power source and the rest of the energy system must be able to balance the demand and supply of electricity at all times. In Denmark, this is achieved through the placement of wind farms in different regions, high flexibility by the country's power and CHP plants, and strong interconnections with neighbouring countries and the joint Nordic electricity market.

Policy recommendations

National level:

- Draw up ambitious goals and road maps for wind power to provide visibility for investors
- Map wind power potential in the country in detail and co-ordinate the placement of wind farms
- Keep legal frameworks and support instruments predictable and stable over long periods
- Ensure sufficient transmission capacity in the grid
- Incentivise municipalities to have wind power in their area by enabling them to benefit from it, for example through considerable property taxes
- Promote local co-ownership of wind projects through legislation and financial incentives
- Streamline and standardise application processes to make them as simple, transparent and quick as possible
- Guarantee flexibility in the permitting process to allow for technological advances
- Price fossil emissions through emission trading or taxation
- Commit to ecological compensation, i.e. when natural areas are used for wind power development, set aside another area of similar value and size to remain untouched

Onshore wind power is already in most cases the cheapest way to produce electricity in the Nordics.

Local level:

- Allocate suitable areas for wind power in zoning
- Streamline application processes to make them as simple and quick as possible
- Facilitate local co-ownership
- Invest in wind for example through the municipality's energy company
- Make a power purchase agreement of wind power
- Provide information on the actual impacts of wind power to promote public acceptance

Offshore wind, Copenhagen

Wind power built at sea has great potential for producing low-carbon electricity. Winds are generally stronger and steadier at sea, and therefore offshore wind can generate a more stable supply of electricity compared to onshore wind.

Solution description

In the 1990s, the Danish Action Plan for Offshore Wind identified Middelgrunden, a natural reef 3.5 kilometres outside Copenhagen harbour, as a potential site for offshore wind. The Copenhagen Environment and Energy Office took the initiative to set up a wind farm. A co-operative with local residents was formed and co-operation with the local municipality-owned utility established.

In 2000, after an extensive public hearing and dialogue phase, the co-operative built a 40 MW wind park of 20 turbines, which at the time was the world's largest offshore wind park. Half of Middelgrunden is owned by the co-operative of over 8,500 members, mostly locals.

In 2018, Denmark covered 13% of its electricity demand with offshore wind alone.

Climate impact

In Denmark, wind power has mostly replaced coal-based electricity, which emits on average nearly 800 kilograms of carbon dioxide per MWh. Middelgrunden produces annually around 100 GWh of electricity and therefore has reduced annual emissions by 80 $ktCO_2$ when compared with coal.

Nordic seaside municipalities have large potential to utilise offshore wind. If other Nordic municipalities increased their offshore wind production to match the total level of Denmark and produced 13% of their current electricity demand of their country with offshore wind, production would be increased by 46 TWh.

However, there is no fossil fuel production to be replaced in Iceland and theoretically only 40 TWh is needed push out all remaining fossil-based condensing and CHP power generation from the joint electricity network between Finland, Sweden, Norway and Denmark.[7] This would reduce emissions by 12.5 $MtCO_2$. See the description for onshore wind for discussion on the practical impacts of wind power.

Costs and savings

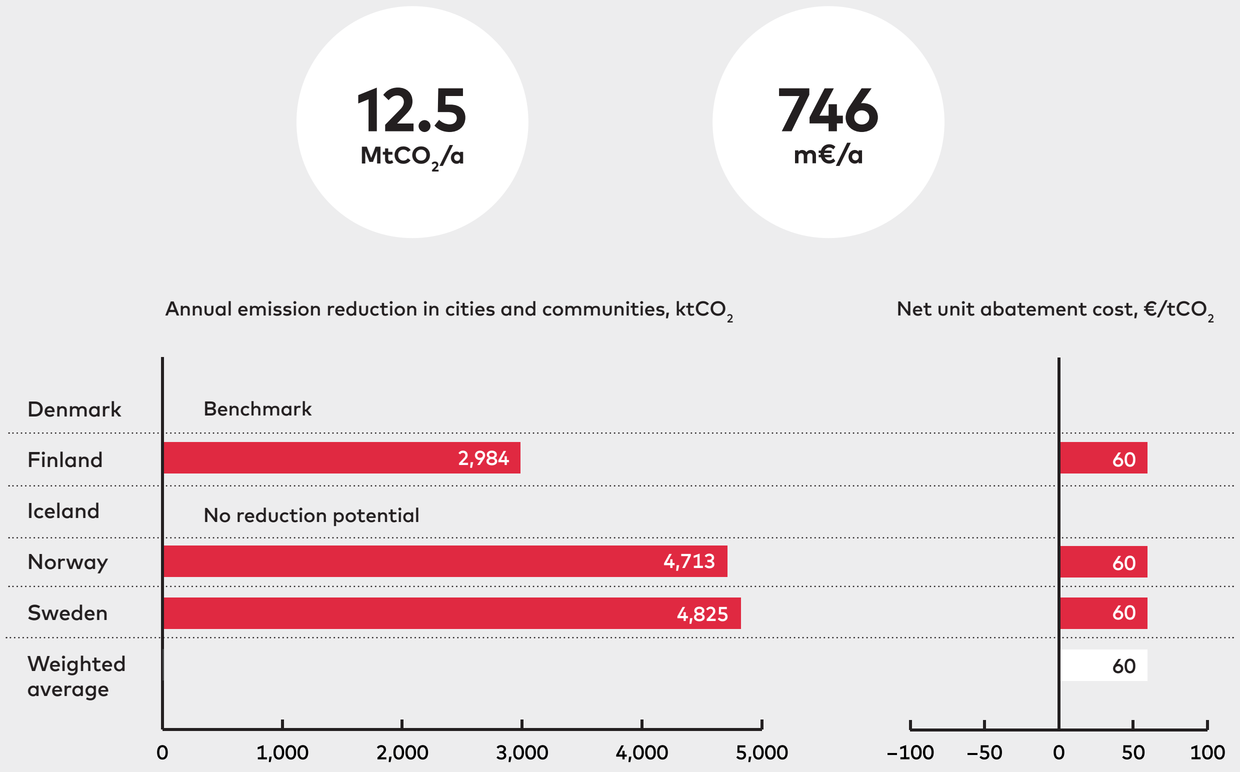
Offshore wind is currently significantly more expensive than onshore wind due to higher construction, grid connection and operation and maintenance costs, but the cost has been declining rapidly as the turbines grow in size. We use a relatively conservative cost estimate of 69 €/MWh calculated for Finland in 2017. This is still higher than the levelised cost we estimate for condensing coal power or coal, gas or peat CHP. However, the marginal production cost for wind is very low, and therefore wind power will push out fuel-based electricity production despite the higher total cost. The abatement cost is 60 €/tCO_2 for the 40 TWh.

Other benefits

Wind power cuts harmful air pollution from fuel combustion, reduces reliance on fuel imports and can create local jobs. Compared to onshore, offshore wind produces power in greater quantities and more steadily, which reduces the required flexibility from the rest of the electricity system and thereby system cost. Offshore wind is often built far away from land, which reduces visual disturbance, noise and, consequently, public resistance.

7 See Appendix I for more information on the methodology.

Figure 15: Scaling up offshore wind production to 13% of electricity demand



Note: costs calculated for the 40 TWh that is enough to theoretically replace fossil power production.

Barriers

Offshore wind is still significantly more expensive than onshore wind, which means installations require some kind of public support. Offshore wind located near the shore faces many of the same barriers as onshore wind, such as the possible lack of local public acceptance because of visual disturbance, noise and danger to flying animals.

All of these issues can be alleviated by increasing the distance from the shore, but the costs increase with the distance and the depth of water. Currently it is not commercially viable to install turbines in water depths of over 45 metres,[8] but floating technologies that could solve this problem are under development in some countries, including Norway.

Enablers

The best conditions for offshore wind farms are areas with strong and steady wind, shallow waters and proximity to the transmission grid. Denmark has spatial plans that identify potential locations for offshore wind farms.

Financial support is generally needed to get offshore wind parks built. Denmark has auctioned energy production support for offshore farms, and it also supports wind projects in the pre-investment phase. Until recently the grid connection of offshore wind was also publicly financed. In addition, the application processes are simple and quick, as the Danish Energy Agency can be used as a single point of access for assistance on issues related to permits for offshore wind farms. The agency will grant the required permits and co-ordinate these with other relevant authorities.

Local public acceptance is also necessary. Denmark has promoted co-operatives that enable local people to buy shares in the wind parks. The interest on the loan is tax deductible from private income and co-operative members get tax rebates on their household electricity use. In addition, the Middelgrunden project held a dialogue process among a wide group of stakeholders, including the relevant authorities, nature conservation NGOs and the public.

8 Afewerki et al. (2019)

Policy recommendations

National level:

- Draw up ambitious goals and road maps for offshore wind power to provide visibility for investors
- Map offshore wind power potential in the country in detail and co-ordinate the placement of wind farms
- Auction production support for offshore wind and keep legal frameworks and support instruments predictable and stable over long periods
- Make property taxation competitive compared to other energy production
- Share the cost of grid connection
- Price fossil emissions through emission trading or taxation
- Promote local co-ownership of wind projects through legislation and incentives
- Streamline and standardise application processes to make them as simple, transparent and quick as possible
- Guarantee flexibility in the permitting process to allow for technological advances

Denmark already produces 13% of electricity with offshore wind.

Local level:

- Allocate suitable areas for offshore wind power in zoning
- Streamline application processes to make them as simple and quick as possible
- Facilitate local co-ownership
- Invest in offshore wind for example through the municipality's energy company
- Provide information on the actual impacts of wind power to promote public acceptance

District heating from waste water, Turku

Heat pumps can be used to harness the heat energy that goes down the drain with waste water. Waste water is a free, stable and predictable source of heat for district heating.

Solution description

In Finland, municipalities in the Turku region teamed up to build a new facility to treat the waste water of the area's 300,000 inhabitants. The facility includes two 21 MW heat pumps that capture heat from the cleaned waste water before it is released into the sea. The temperature of the cleaned waste water varies seasonally between 7 and 20 °C. Heat pumps extract the heat energy and feed 85-degree water to the district heating network. The cooled 4-degree waste water is then used as a source for district cooling.

Heat and cool storages improve the flexibility of the facility. The facility is also used for balancing the national electricity demand in the balancing energy market – instead of ramping up a fossil power plant, the heat pumps can be switched off during a power demand peak.

Climate impact

The climate impact of waste-water heat capture depends on the carbon footprint of the electricity used by the heat pumps and the heat generation it replaces. The Turku facility produces 302 GWh of heat a year – enough for 24,000 inhabitants, or 8% of the residents in the area from which the waste water is collected. The heat has mainly replaced burning oil and coal, which is estimated to have reduced emissions by 80 $ktCO_2$.[9] Other larger Nordic cities such as Helsinki, Stockholm, Gothenburg and Oslo are also using their waste-water heat.

If all the Nordic municipalities with district heating captured their waste-water heat and produced 8% of their district heat with it, it could replace 5.7 TWh of fossil heat production and reduce emissions by 1.7 $MtCO_2$. District cooling and improved demand flexibility also provide emissions savings, but they have not been quantified here. Additional emission savings not included here are produced from the waste-water sludge, which is dried and transported to a nearby biogas plant to produce both biogas for power and heat production and recycled fertilisers.

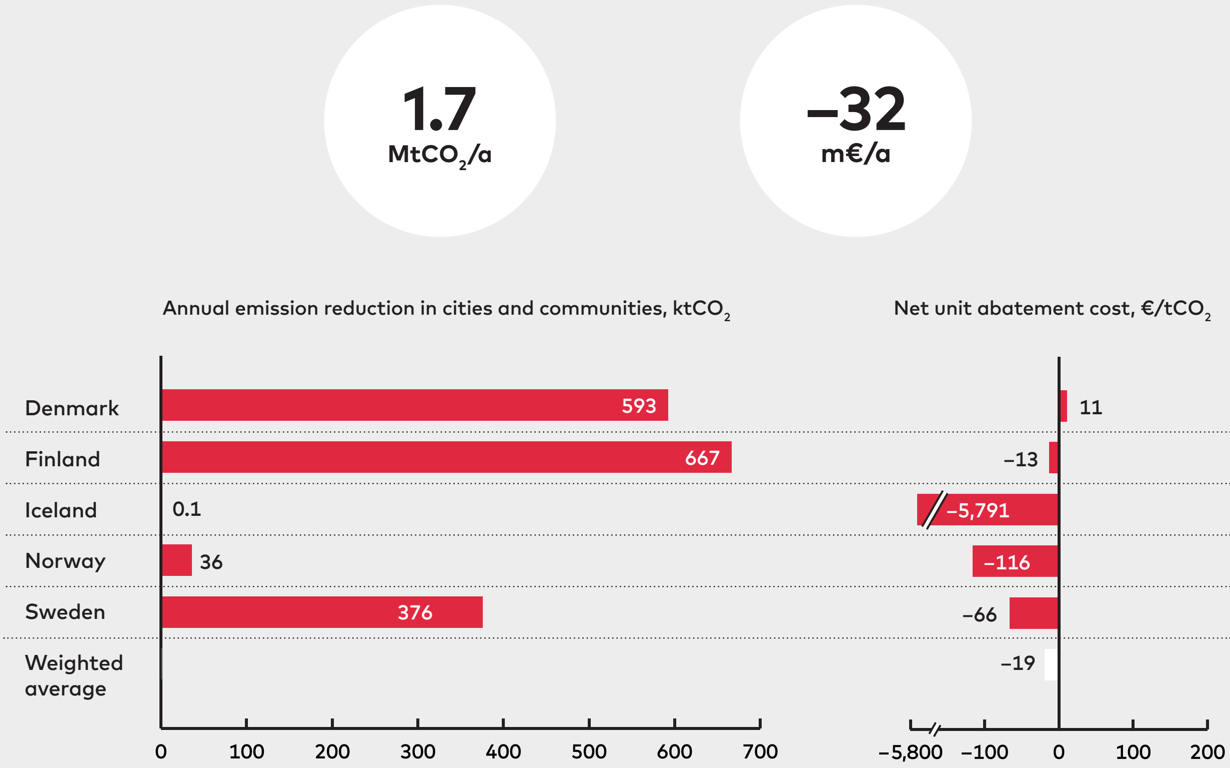
Costs and savings

The total cost of heat energy captured from waste water depends mainly on the investment cost, the efficiency of the pump and the cost of electricity for the heat pumps. The cost varies between the Nordic countries as a result of the differing taxes applied to heat pump electricity. We estimate the cost of waste-water heat to range from 23 €/MWh in Norway to 55 €/MWh in Denmark, the weighted average in this scaling being 42 €/MWh.

As heat pumps often do not fully replace a heat or cogeneration plant in the district heating network, we compare the heat pump cost to the variable cost of thermal plants, which we estimate to range between 30 (peat CHP in Sweden) and 90 (oil heat plant in Sweden) €/MWh for different fuels under different Nordic taxation schemes. The weighted average abatement cost of municipal waste-water heat capture in the Nordics is –19 €/tCO_2.

9 Turun seudun puhdistamo (Turku region waste water treatment facility)

Figure 16: Scaling up district heating from waste water to 8% of heating demand



Other benefits

Replacing fuel combustion with heat pumps cuts air pollution. It also reduces the need for importing fossil fuels and increases energy security. Heat pumps can be used to provide flexibility to the energy system.

The new treatment plant has also brought other benefits in Turku. The recycled fertilisers produced from waste-water sludge reduce the need for virgin fertiliser production and increase the sufficiency of the limited supply of mined phosphorus. They also avoid emissions of ammonia and nitric acid production, two key inputs for nitrogen fertilisers.

The new waste-water treatment plant in Turku has also improved water purification and reduced the nutrient load on the vulnerable sea ecosystem nearby. Phosphorus in Turku sea areas has decreased by 72% as a result of the new treatment plant.[10]

Barriers

Large heat pumps can face a number of techno-economic barriers. The heat source needs to be located close to the end users so that the investment in the extended pipe infrastructure and heat losses do not become too large, but there might be limited space for a water treatment facility in a city. The facility also requires a significant amount of electricity, so the electricity grid in the desired location must be strong enough or it must be fortified, which adds costs.

The initial investment for the heat pump facility is often large, and therefore the heat pumps require a sufficient number of load hours to keep the price of the heat down. In some networks this may be restricted by the existing heat production system.

On the other hand, the required district heating water temperature in winter may be higher than can be provided by heat pumps and the heat requires priming. If this cannot be done with existing facilities, it can become expensive. Also the price of the main input, electricity, can limit the profitability of the investment.

Enablers

The initial investment costs in large heat pump solutions are kept at bay if the heat source is close to an existing district heat network, space for the pumping facility is available and there is a strong enough electricity grid. Free or low-cost heat,

10 Turun seudun puhdistamo (Turku region waste water treatment facility)

Photo: Istock

relatively inexpensive electricity and low network temperature allow for low operating costs. Stability and predictability of the heat source enable investment costs to be divided over a sufficient amount of lifetime production.

Waste water as a heat source is free, stable and predictable. In Turku's case, the treatment plant was built underground within the city, very close to the heat loads. The electricity grid was already strong enough and no priming of the 85-degree heat is needed. In Finland the electricity price is relatively low and fossil fuel taxation relatively high.

Policy recommendations

National level:

- Draw up ambitious goals and road maps for phasing out fossil fuels in energy production
- Keep legal frameworks and support instruments predictable and stable over long periods
- Set a low tax on electricity used in heat pumps
- Set a high tax on fossil fuels for heat production

Heat pumps can be used to provide flexibility to the energy system.

Local level:

- Draw up ambitious goals and road maps for phasing out fossil fuels from district heating production
- Set up modern waste-water treatment combined with heat recovery
- Set aside space for heat pumps in spatial planning
- Develop the electricity distribution grid in a forward-looking way
- Lower the temperature of the district heating network to decrease the need to prime the heat produced by heat pumps

District heating from seawater, Drammen

Heat pumps can utilise heat in seawater for district heating. Seawater deep enough provides a stable heat source all year round.

Solution description

The municipality of Drammen in Norway has since 2011 used seawater to provide district heat for the town. Three large heat pumps totalling 13.5 MW extract heat form a nearby fjord, which has a seawater temperature of about eight degrees at a depth of 18 metres all year round. The heat pumps can deliver a temperature of up to 90 °C.

The heat pumps provide 67 GWh of heating, covering the needs of around 6,000 homes and currently 63% of the municipality's district heating needs. A few years back, when the heat demand was lower, the heat pumps covered up to 85%.

Climate impact

The climate impact of seawater heat depends on the emissions associated with the electricity used by the heat pumps and the heat generation replaced. In Norway the electricity is nearly completely fossil-free. The heat pumps in Drammen have replaced a mixture of fuel oil, biomass and electric boilers and reduced emissions by around 8 ktCO_2.

In this analysis we assume all the Nordic municipalities with a district heating network next to the sea to install a similar system and produce 67 GWh of heat – or in the case of smaller networks, up to 63% of their heat – from sea water. This could replace 7 TWh of fossil heat production and reduce emissions by 1.4 MtCO_2.

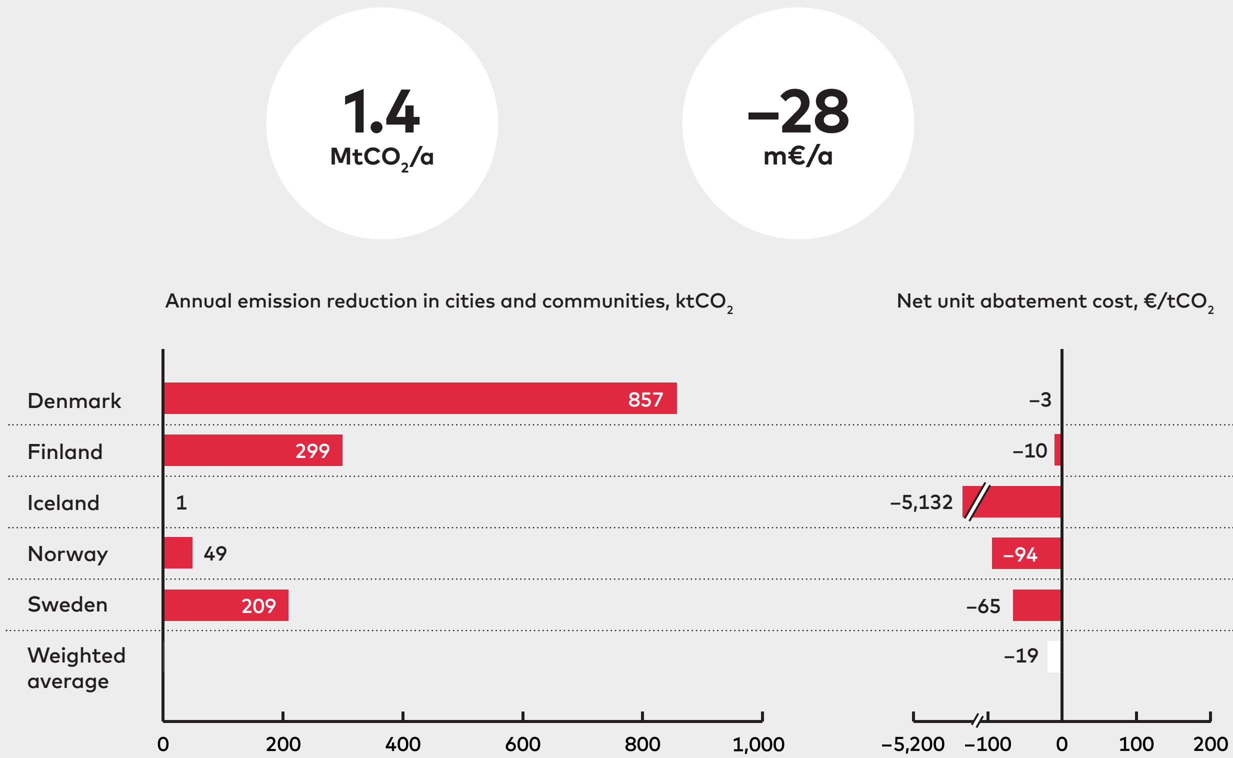
At most Drammen covered 85% of district heating needs with seawater heat pumps.

Costs and savings

The costs of seawater heat utilisation come from the pipeline into the sea to reach water of a stable temperature, the heat pump plant, electricity used by the pumps and a possible extension to the district heat network or fortification of the grid. The price of electricity for pumps varies in the Nordics as a result of differing taxation. We estimate the cost of seawater district heating to range from 26 €/MWh in Norway to 58 €/MWh in Denmark, the weighted average in this scaling being 52 €/MWh.

As heat pumps often do not fully replace a heat or cogeneration plant within the district heating network, we compare the heat pump cost to the variable cost of incineration plants, which we estimate to range between 30 (peat CHP in Sweden) and 90 (oil heat plant in Sweden) €/MWh for different fuels under different Nordic taxation schemes. The weighted average abatement cost of seawater district heating in the Nordics is –19 €/tCO_2. In Drammen, the heat pumps installed in 2010 have already recovered the investment.

Figure 17: Scaling up district heating from seawater to 67 GWh or a maximum of 63% of heating demand



Other benefits

Replacing fuel combustion with heat pumps cuts air pollution. It also reduces the need to import fossil fuels and increases energy security. Heat pumps can be used to provide flexibility to the energy system.

Barriers

To operate a seawater heat pump during winter, it needs access to water that is well above zero degrees. If the sea is not sufficiently deep near the shore, the piping needed can become long and expensive.

As for the other heat pump solutions, the heat source needs to be located close to the heat users so that the investment in the extended pipe infrastructure and heat losses do not become too large, and there needs to be space available for the facility. The facility also requires a significant amount of electricity, so the electricity grid in the desired location must be strong enough or it must be fortified, which adds costs.

The initial investment for the heat pump facility is often large, and therefore the heat pumps require a sufficient number of load hours to keep the price of the heat down. In some networks this may be restricted by the existing heat production system.

On the other hand, the required district heating water temperature in winter may be higher than can be provided by heat pumps and the heat requires priming. If this cannot be done with existing facilities, it can become expensive. Also the price of the main input, electricity, can limit the profitability of the investment.

Enablers

Seawater is free and, when deep enough, a stable source of heat. Enablers for seawater pumps include a seashore with sufficient depth to keep the piping costs low, proximity to an existing district heating network, space for the pumping facility and a strong enough existing electricity grid in the facility location. Costs can be kept low if there are relatively cheap electricity, enough use hours and no requirement to prime the heat or the priming is possible with existing facilities.

Policy recommendations

National level:

- Draw up ambitious goals and road maps for phasing out fossil fuels in energy production
- Keep legal frameworks and support instruments predictable and stable over long periods
- Set a low tax on electricity used in heat pumps
- Set a high tax on fossil fuels for heat production

Local level:

- Draw up ambitious goals and road maps for phasing out fossil fuels from district heating production
- Analyse whether a seawater heat pump would be technically and economically feasible
- Secure space for heat pumps in spatial planning
- Develop the electricity distribution grid in a forward-looking way
- Lower the temperature of the district heating network to decrease the need to prime the heat produced by heat pumps

Replacing fuel combustion with heat pumps cuts air pollution.

Solar district heating, Marstal

Solar thermal collectors convert sunlight to heat, which can be used for district heating. When combined with seasonal heat storage, solar can cover a large share of annual heat need.

Solution description

The town of Marstal in Denmark decided to demonstrate that district heating can be cost-effective and completely renewable even when more than half of the heat is supplied by solar energy – and have done so since 2013.

The district heating company is owned by Marstal's inhabitants, and their general assembly has taken all major decisions. The system has been built in phases, and it currently consists of more than three hectares of solar collectors, two pit heat storages, a heat pump and a biomass CHP plant. The heat storages enable the use of the solar heat until winter and the system as a whole can optimise heating, cooling and electricity production according to demand and electricity market prices. Today, 12 GWh or 50% of the district heating in Marstal is covered by solar heat and the heating costs of the small island town have decreased.

Climate impact

Heat provided by solar collectors is carbon free, and the climate impact of heat pumps depends on the emissions associated with the electricity used. Assuming that Marstal has replaced heating with fuel oil, the 12 GWh of solar has reduced emissions by about 4 ktCO_2.

We assume that all the Nordic municipalities with a district heating network install a similar system and produce 12 GWh of district heat with solar combined with heat storage and a heat pump – or in the case of smaller networks, produce up to 50% of their heat with solar. This could replace 4.2 TWh of fossil heat production and decrease emissions by 1.2 MtCO_2.

Costs and savings

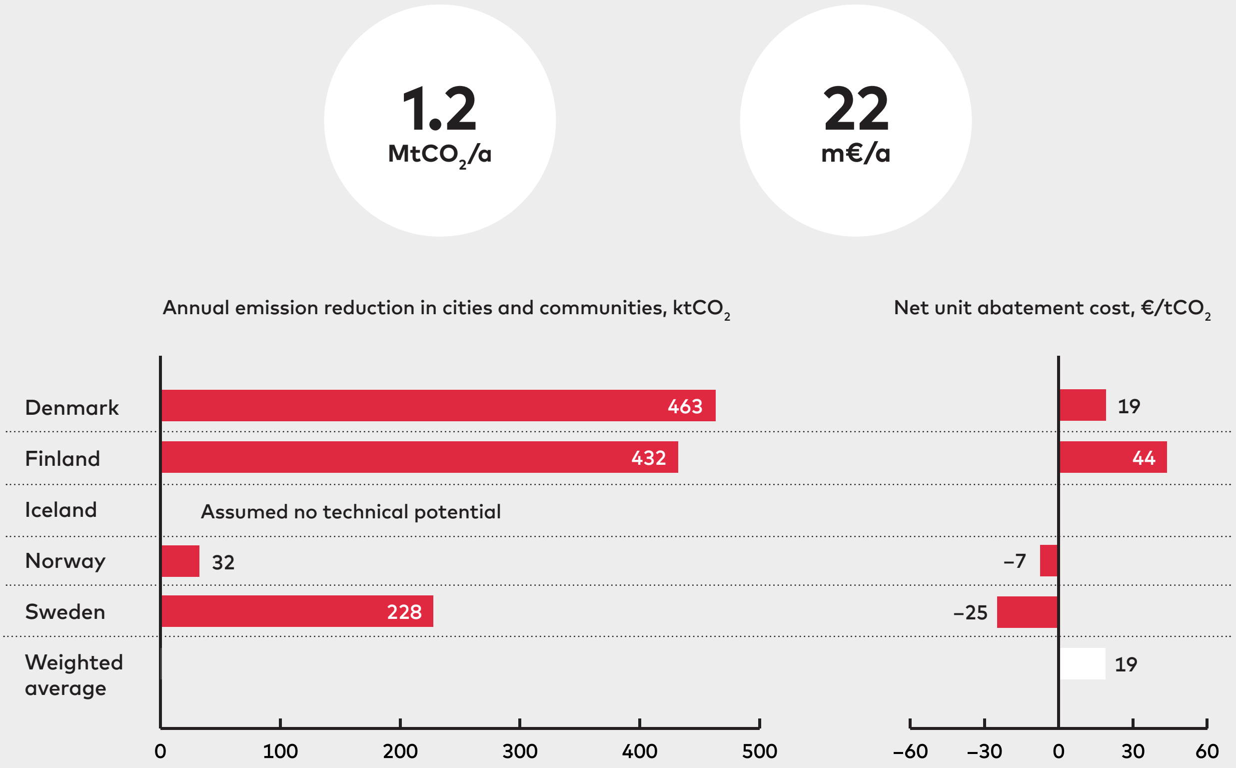
The cost of the solar thermal system includes investing in solar collectors, heat storage and a heat pump, as well as the electricity used by the pump. Additional costs may come from the possible extension of the district heat network. The price of electricity for heat pumps varies in the Nordics as a result of differing taxation. We estimate the cost of solar thermal district heating to range from 53 €/MWh in Norway to 63 €/MWh in Denmark, the weighted average in this scaling being 60 €/MWh.

As the system cannot fully replace a heat or cogeneration plant within the district heating network, we compare the cost to the variable cost of thermal plants, which we estimate to range between 30 (peat CHP in Sweden) and 90 (oil heat plant in Sweden) €/MWh for different fuels under different Nordic taxation schemes.

The weighted average abatement cost of a solar thermal system in the Nordics is 19 €/tCO_2. In Marstal, which is located on an island, the fuels cost more due higher transport costs, and there the solution has lowered the heating prices for the inhabitants.

Today half of the district heating in Marstal is covered by solar heat.

Figure 18: Scaling up solar district heating to 12 GWh or a maximum of 50% of heating demand



Other benefits

Replacing fuel combustion with solar collectors and heat pumps cuts air pollution. It also reduces the need to import fossil fuels and increases energy security. Heat pumps can be used to provide flexibility to the energy system. As a clear forerunner globally, Marstal's economy has even benefited from groups visiting the locality to learn about their solution.

Barriers

Solar collector fields and heat storage take up a significant amount of space but should be located close to heat users to minimise losses. It can therefore be difficult to find the required space within existing urban structures.

A set-up like Marstal's has relatively high installation costs, which can be seen as risky. To reach high shares of solar heat, the system must be complemented by a heat source that is economical to operate even if it is only used during wintertime. The intensity of solar radiation as well as the length of the season when the collectors are producing heat also matter for the economy of the solution. In some networks the required district heating water temperature may be higher than can be provided by solar collectors or heat pumps and the heat requires priming. If this cannot be done with existing facilities, it can become expensive.

Enablers

A large amount of open and sunny space available near the district heating network is a key enabler. But even with the solar collectors in place, the space can still be used in different ways. In Marstal the solar fields are also used as a grazing area for sheep.

The solution in Marstal was implemented in phases to reduce the financial risk and create acceptance among the community that owns the network. The district heating network operates at a temperature that can be provided directly by the solar collectors and heat pump – around 70 °C in summer and 75 °C in winter.

Policy recommendations

National level:

- Draw up ambitious goals and road maps for phasing out fossil fuels in energy production
- Keep legal frameworks and support instruments predictable and stable over long periods
- Set a low tax on electricity used in heat pumps
- Set a high tax on fossil fuels for heat production
- Support investment in low-emission technologies in municipalities
- Share the risk with the municipalities that pilot new technologies in their infrastructure

Local level:

- Draw up ambitious goals and road maps for phasing out fossil fuels from district heating production
- Estimate whether solar thermal would be technically and economically possible in the municipality
- Make use of local ownership and co-operative models to engage local people and decrease opposition to solar projects
- Secure space in land planning
- Lower the temperature of the district heating network to decrease the need to prime the heat produced by heat pumps

In Marstal the solar fields are also used as a grazing area for sheep.

District heating from data centre waste heat, Mäntsälä

Waste heat generated from the cooling of data centres can be used in district heating. Capturing the waste heat can be a win-win solution, as selling the waste heat also brings additional income to the data centre.

Solution description

The municipality of Mäntsälä, Finland made a deal to utilise the waste heat from a 15 MW data centre established by a large search engine company. In the past, Mäntsälä primarily used natural gas to produce district heating, but wanted to look for cheaper options.

After investments in heat recovery equipment and a heat pump plant, a third of the energy used by the data centre can be captured as heat. In 2018, 20 GWh or 54% of Mäntsälä's heat needs were covered by the waste heat from the data centre. The plan is to eventually cover the entire heat need as the data centre expands.

Climate impact

If the excess heat from a data centre is treated as a waste that has no emissions related to it, the climate impact depends solely on the emissions from the electricity used by the heat pumps and the heat generation replaced. The use of the waste heat has reduced the emissions of Mäntsälä's district heating production by 40%.

By 2025, new data centres requiring over 2,500 MW of electric power are expected to be located in the Nordic countries. Based on the benchmark of Mäntsälä, this translates into 3.4 TWh of waste heat that can be recovered. If this heat was to be utilised in district heating, we estimate that it could replace 3.2 TWh of fossil heat production and reduce emissions by 1.1 $MtCO_2$. In addition, also some existing data centres could possibly be equipped with heat recovery equipment, but their potential is not quantified here.

Costs and savings

The costs of waste heat utilisation consist of the heat recovery system, the heat pump plant, the price for heat and electricity used by the pumps and a possible extension to the district heat network. The price of electricity for heat pumps varies in the Nordics as a result of differing taxation. We estimate the cost of district heating from data centre waste heat to range from 33 €/MWh in Norway to 64 €/MWh in Denmark, the weighted average in this scaling being 45 €/MWh.

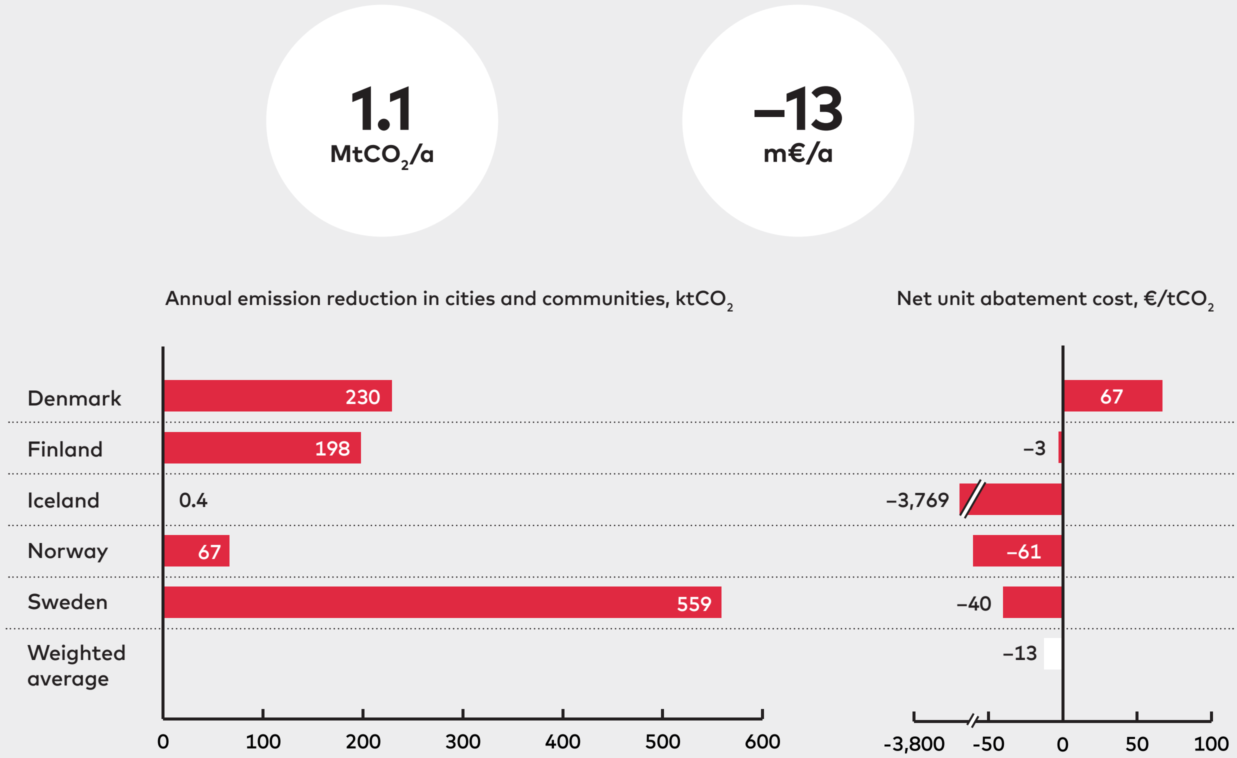
As heat pumps often do not fully replace a heat or cogeneration plant in a district heating network, we compare the heat pump cost to the variable cost of thermal plants, which we estimate to range between 30 (peat CHP in Sweden) and 90 (oil heat plant in Sweden) €/MWh for different fuels under different Nordic taxation schemes. We estimate the weighted average abatement cost of data centre waste heat capture in the Nordics to be –13 €/tCO_2. Mäntsälä has been able to reduce their district heating prices by 11% with this solution.

Other benefits

Replacing fuel combustion with heat pumps cuts air pollution. It also reduces the need to import fossil fuels and increases energy security. Heat pumps can be used to provide flexibility to the energy system.

The ability to utilise the waste heat and compensate the data centre for it improves the business case and can be a decisive factor in the decision to locate a

Figure 19: Scaling up data centre waste heat use for district heating to new Nordic data centre capacity by 2025



data centre, which can increase local investment and employment. However, if the data centre increases the production of fossil-based electricity, the overall impact can become negative.

Barriers

There may be local opposition to the data centres, which use large amounts of power. Sometimes the power is used for purposes that may be less acceptable to locals, such as bitcoin mining.

Having to rely on a data centre or another industrial application for heat means that there is some uncertainty about how long it will be in operation and what the price of the heat will be. The price of the heat, and also electricity, are crucial to the economics of the solution.

As for other large heat pumps, the heat source needs to be located close to the heat users so that the investment in the extended pipe infrastructure and heat losses do not become too large. Waste heat recovery also requires changes and investment in the facility generating waste heat, and the data centres can be reluctant to let outsiders in because of data security concerns. Therefore, these types of systems are easier to realise in new construction projects.

The initial investment for the heat pump facility is large, and therefore the heat pumps require a sufficient number of load hours to keep the price of the heat down. In some networks this may be restricted by the existing heat production system. On the other hand, the required district heating water temperature in winter may be higher than can be provided by heat pumps and the heat requires priming. If this cannot be done with existing facilities, it can become expensive.

Enablers

As long as the operations last, a data centre is a stable source of heat. The existing electricity grid near a data centre certainly is strong enough to also power some heat pumps. Nordic countries are good locations for data centres as they have a cold climate, good access to affordable renewable energy, fast data connections and stable societies.

Selling the waste heat provides additional income to the data centre. If the heat is affordably priced, the waste heat capture can be a win-win solution. In Mäntsälä, a key enabler was the zoning of industrial plots close to the district heating network. Other important enablers for the waste heat capture are low-cost electricity for the heat pumps and that priming of heat is not required or it is possible with existing facilities.

Policy recommendations

National level:

- Draw up ambitious goals and road maps for phasing out fossil fuels in energy production
- Keep legal frameworks and support instruments predictable and stable over long periods
- Set a low tax on electricity used in heat production, including data centres that feed waste heat into district heating
- Consider taxing unused industrial waste heat
- Set a high tax on fossil fuels for heat production
- Protect data security through legislation to make the country an attractive location for data centres

Local level:

- Draw up ambitious goals and road maps for phasing out fossil fuels from district heating production
- Zone data centres and other industrial plots close to district heating networks and secure space for heat pump facilities
- Lower the temperature of the district heating network to decrease the need to prime the heat produced by heat pumps
- Promote the municipality as a good location for data centre operations

Mäntsälä has been able to reduce their district heating prices by 11% with this solution.

Geothermal district heating, Reykjavik

Geothermal heat is continuously supplied from the core of the earth. With the help of heat pumps, it can be harnessed in also less volcanically active areas, like Denmark.

Solution description

Geothermal district heating was first employed in Reykjavik in 1930 and has since completely replaced coal and fuel oil, which used to be the main heat sources.

Today Reykjavik has the world's largest municipal geothermal heating service, and nearly all houses in the greater Reykjavik area are connected to it. The hot water is derived from both low and high-temperature fields. The wells in high-temperature fields are self-flowing and heat cold ground water in heat exchangers. From low-temperature fields Reykjavik pumps up the hot water and pipes it straight into the district heating network, from where it is eventually drained into the sewer system.

A classic set-up in less volcanically active areas is a doublet where water is pumped up from a hot reservoir, the heat is extracted and the water is pumped back into the source reservoir to maintain the pressure. New technologies are currently being developed to extract heat from the ground itself, which would enable even more widespread use.

Climate impact

Water from geothermal areas contains carbon dioxide. In low-temperature fields the content is low, and consequently the fugitive emissions are negligible. In cooler geological areas carbon dioxide separation is generally not an issue, and there are no emissions.

The rest of the emissions are determined by the energy used to run the pumps and the possible heat pumps. In the 1960s, before the large-scale adoption of geothermal district heating, the emissions from heating Reykjavik with fossil fuels were annually around 250 ktCO_2,[11] which have since been all but eliminated.

Traditional geothermal heating has no technical potential in Finland, Norway or Sweden, but Denmark has geothermal reservoirs which it can use to produce heat for district heating, especially if heat pumps are used. The potential has not been exhaustively mapped, but Ea Energianalyse (2015) investigated the possibility of introducing 376 MW's worth of geothermal plants in 28 district heating networks. We estimate that this capacity could produce 3.5 TWh of heat. If all of it replaced fossil fuels and was run with electric heat pumps, it could reduce emissions by 0.8 MtCO_2.

Costs and savings

The investment costs of geothermal heat generation are high and include screening geothermal potential, geophysical studies, the drilling of wells and pumping equipment. Additional costs may come from a potential heat pump plant and the possible extension of the district heat network or fortification of the grid. The operation costs are low and consist mainly of the electricity required by the pumps. The drilling and pumping costs increase with the depth of the well, and it is usually uneconomical to go below 3,000 metres.

11 Gunnlaugsson (2000)

Figure 20: Scaling up geothermal district heating to the known potential in Denmark

The price of the district heat to inhabitants in Reykjavik is very affordable, around 32 €/MWh.[12] We estimate that in Denmark geothermal heat with electric heat pumps would cost on average 52 €/MWh. We assume the geothermal heat would not fully replace a heat or cogeneration plant in the district heating network, and therefore compare the geothermal heat cost to the variable cost of thermal plants, which we estimate to range between 42 (coal CHP) and 71 (oil heat plant) €/MWh. The weighted average abatement cost in Denmark is estimated to be –17 €/tCO_2.

Other benefits

Replacing fuel combustion with geothermal heat and heat pumps cuts air pollution, which has been clearly demonstrated in Reykjavik. It also reduces reliance on fuel imports and enhances energy security.

A geothermal plant does not cause noise and does not necessarily require above-ground structures and therefore does not need to take up much space. If the heat is extracted by electric heat pumps, they can be used for balancing the national electricity demand. Geothermal boreholes can also be used for heat storage during the summer.

Barriers

Usable geothermal reservoirs do not exist everywhere, as the heat gradients and the permeability of the ground vary from location to location. Even in generally suitable areas, a good reservoir can be located too far away from the heat users, and in groundwater areas geothermal exploration is often banned. The potential of a reservoir is never certain before an exploration well is drilled and the properties tested, and insurance companies are often reluctant to cover the risks of the initial phase. After this, the risk is greatly reduced, but a small risk of unexpected response to long-term use always remains.

Investment costs are high, and it generally only makes sense to use geothermal heat as a baseload to secure a sufficient number of load hours and in sufficiently large networks that have an annual demand exceeding 80 GWh.[13] While we estimate that geothermal heat brings savings in Denmark when compared with fossil fuels, the current subsidies for biomass combustion and the high taxation of electricity for heat pumps make geothermal heat unprofitable in comparison with biomass.

12 Iceland National Energy Authority

13 PlanEnergi (2017)

Photo: Johannes Jansson / norden.org

Enablers

Traditional geothermal district heating is based on proven geotechnical and drilling technology from the oil and gas industry, and there is no technology risk. Geophysical modelling can significantly reduce the risks of exploration. In the Netherlands, the government helps businesses to cover the risks associated with drilling. In Denmark, Icelandic and Danish drilling experts have joined forces to form a company which offers turnkey installations and will thereby take on the investigation risk.

Other enablers include an existing and sufficiently large district heating network near the identified reservoir, a strong enough existing electricity grid in the facility location, relatively cheap electricity and enough use hours. In the case of Denmark, most of the district heating networks operate with a temperature easily supplied with heat pumps, so no priming of the heat is needed.

Policy recommendations

National level:

- Draw up ambitious goals and road maps for phasing out fossil fuels in energy production
- Keep legal frameworks and support instruments predictable and stable over long periods
- Map the geothermal potential in the country
- Set a low tax on electricity used in heat production
- Set a high tax on fossil fuels for heat production
- Ensure that biomass subsidies do not make electricity-based heating solutions uncompetitive
- Help companies cover the risk of exploration drilling
- Do not overregulate – research the environmental risks related to geothermal heat and regulate exploration only based on the knowledge of real risks, to groundwater, for example

Local level:

- Draw up ambitious goals and road maps for phasing out fossil fuels from district heating production
- Map local geothermal potential and take the identified potential into account in spatial planning and zoning
- Help companies cover the risk of exploration drilling in the municipality's area
- Develop the electricity distribution grid in a forward-looking way
- Lower the temperature of the district heating network to decrease the need to prime the heat produced by heat pumps

Buildings

THE HEATING, COOLING AND LIGHTING of buildings are a major source of emissions globally. The emissions are roughly determined by how much space there is, how much energy is needed per unit of space and how the energy is produced. From a life-cycle point of view, the emissions from construction and the materials used also play a significant role.

Many Nordic cities have made commitments to cut the emissions of buildings. Stockholm, Oslo and Copenhagen have pledged to reach net zero carbon in their new buildings by 2030 and in all buildings by 2050.[14]

In the Nordic countries, some buildings are still heated by oil and gas boilers. **Stockholm** in Sweden has replaced most of these with ground source heat pumps (p. 64). A pilot in **Espoo**, Finland is experimenting with new semi-deep technology to allow the use of ground source heat in even more densely populated areas.

Finland[15] and Denmark[16] have calculated that in order to achieve their 2050 emission reduction targets, the energy use of the entire building stock must be halved. This means that new buildings must be very energy efficient, like the Powerhouse at Brattørkaia, the world's northernmost energy-positive office building in **Trondheim**, Norway. But the efficiency of new buildings is not enough – the renovation of existing buildings must also aim for maximal energy efficiency, like the Powerhouse Kjørbo in **Sandvika**, Norway.

Having less space per person is another way to increase efficiency. **Helsinki** in Finland has experimented with digital solutions to enable the sharing and more efficient use of spaces.

To cut the emissions from construction, materials such as wood can be used to replace more emission-intensive concrete and steel, and construction machinery can be upgraded not to use fossil fuels. **Växjö** in Sweden has worked to promote wood construction for years and **Oslo** in Norway has adopted fossil-free construction sites as minimum criteria in all public procurement procedures.

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14 C40 Cities, the Net Zero Carbon Buildings Declaration, www.c40.org/other/net-zero-carbon-buildings-declaration

15 Koljonen et al. (2019)

16 Rose et al. (2018)

Bubbling under – the solutions of tomorrow

Semi-deep geothermal heat in Espoo, Finland
In Espoo, a two-kilometre-deep geothermal heat well is drilled in an industrial area to pilot a new heating technology. The facility should produce 30 to 40 times more thermal energy than a regular ground source heat well that may go down to depths of between 200 and 700 metres. The increased capacity would enable the use of ground source heat in much more densely populated areas than at present while keeping the costs low, potentially solving many of the heating challenges of cities. The heat wells could also be used for cooling in the summertime.

Powerhouse Kjørbo in Sandvika, Norway
In Sandvika, two office buildings from 1980 have been renovated to become plus-energy houses. Improved insulation and sun shading, among other applied solutions, dropped the energy consumption of the buildings to 85% below Norwegian minimum standards. Solar panels, energy wells and heat pumps now produce more energy than the building itself needs during its lifetime. The energy costs to tenants have dropped significantly.

Powerhouse at Brattørkaia in Trondheim, Norway
Norway's first new-construct energy-positive office building has been built in the Brattørkaia area in Trondheim. The building is designed to maximise the harvesting of solar energy through windows and solar cells while minimising cooling needs. Seawater will contribute to the cooling and heating of the building. The aim is that the excess energy the building produces in its operational lifetime will more than compensate for the energy used to construct the building.

Flexible space use in Helsinki, Finland
The Flexi Spaces project used smart locks and web-based space reservation and payment platforms to give people and communities easy access to various spaces in Kalasatama, Helsinki. The model proved to be a success, and now Kalasatama alone has 15 Flexi Spaces, which were reserved more than 600 times in the first year. The Flexi Spaces model is now being extended to the Finnish cities of Tampere, Turku and Oulu.

Wood construction in Växjö, Sweden
Växjö decided in 2013 that by 2020 half of all new municipal buildings should be made of wood. Various types of wooden buildings have already been constructed – apartments, office buildings and arenas – and multiple projects are underway. The municipality conducts active dialogue with researchers and private companies to develop wood construction further and to extend it beyond public projects. Wood buildings have been estimated to have a 40% lower carbon footprint than concrete buildings.[17]

Zero-emission construction sites in Oslo, Norway
The City of Oslo has adopted fossil-free construction sites as minimum criteria in all public procurement procedures since 2017. In practice, the diesel-driven machinery and equipment in construction sites are replaced with fossil-free options, biofuels or electricity. By setting the new standard, the city has been able to influence the market supply. Construction machinery has been estimated to account for 30% of Oslo's traffic emissions.[18]

17 VTT (2017)
18 City of Oslo

Ground source heat pumps, Stockholm

Ground source heat pumps utilise the heat from the bedrock for space heating and hot water. In the summer, the system can also provide cooling.

Solution description

The heat is typically collected by circulating a fluid in a well that is 100 to 200 metres deep and extracted by a heat pump, which delivers three units of heat for each unit of electricity used. Ground source heat pumps can replace the fuel or electricity-based heating systems of buildings.

Sweden has the most heat pumps per capita in the world. Almost a quarter of all single-family houses in Sweden have ground source heat pumps. The City of Stockholm requires a permit for the borehole, but has made getting it especially easy; they have set up an e-platform for the planning and applications for drilling wells, and the local environment authority takes care of everything with the utility companies and the neighbours. In Stockholm, one third of all single-family houses have a ground source heat pump.

Climate impact

The climate impact of heat pumps depends on the emissions of the electricity used by the pumps and the heat generation replaced. In the Nordic countries, the electricity is relatively low emission. In Sweden, the ground source heat pumps together with district heating have just about eradicated oil heating, and the emissions from the heating of residential buildings have been reduced by 94% since 1990.[19]

Of the homes that are not connected to the district heating network in Stockholm, we estimate that 36% have a ground source heat pump. If ground source heat pumps made up 36% of the heating supply of single-family houses not connected to the district heating network in all Nordic municipalities, emissions could be reduced by 2.7 $MtCO_2$.

Costs and savings

The cost of a ground source heat pump includes drilling boreholes, installing pipes and the heat pump and electricity used by the pump. We estimate that the cost of producing heat ranges approximately from 96 €/MWh in Iceland to 143 €/MWh in Denmark as a result of differing electricity prices. As the systems that the heat pumps would replace have already been paid for, we compare the entire cost of the heat pump system to the alternative fuel cost – oil, gas or direct electricity.

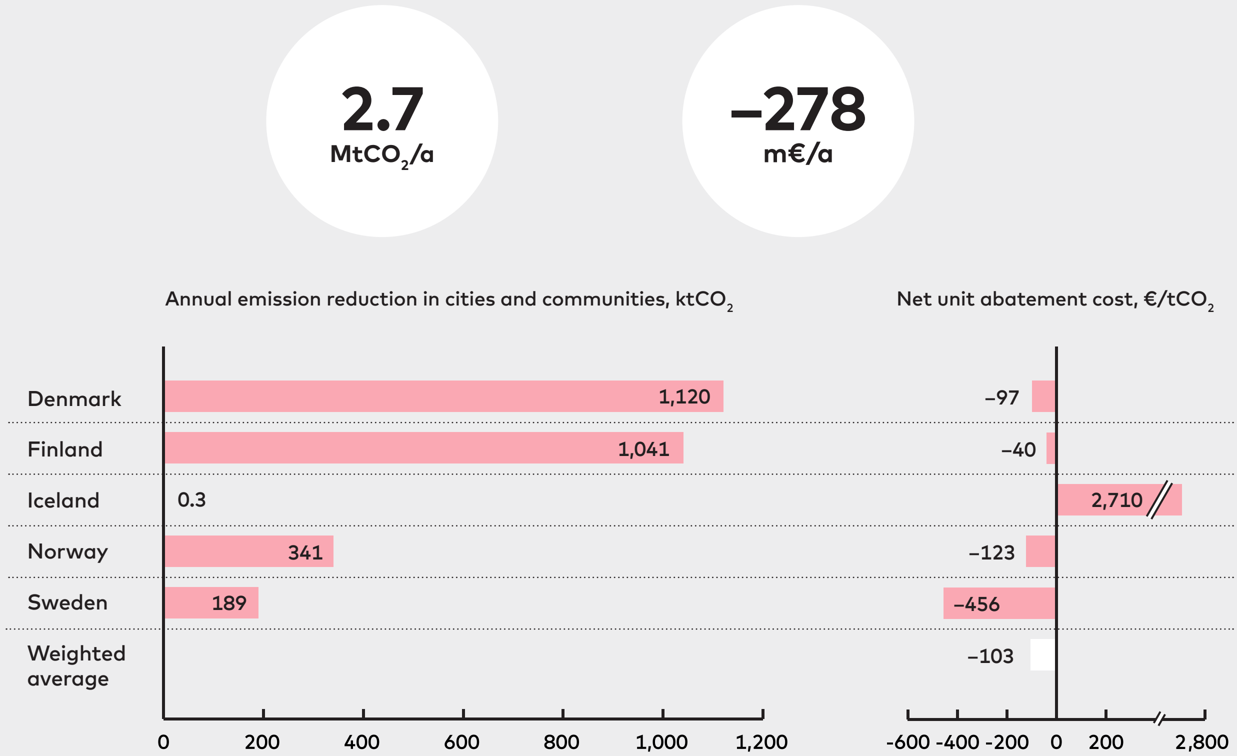
The abatement cost varies by country and alternative. Notably in Denmark we estimate the cost against gas to be 300 €/tCO_2 owing to the cheap consumer prices of gas, while in Iceland we estimate the abatement cost against direct electric heating to be 2,700 €/tCO_2 as a result of subsided electricity with low emissions. However, abatement costs in other situations are negative, and the weighted average is –103 €/tCO_2.

Other benefits

Heat pumps save space as there are no requirements for fuel storage. They are safe to use because there is no combustion involved and reduce local air pollution when replacing fuel combustion. Since heat pumps can be fully automated, they are low maintenance. As heat pumps can provide both cooling in summer and heating in winter, they can increase living comfort.

19 Emissions from stationary combustion in the residential sector; Naturvårdsverket (2019)

Figure 21: Scaling up ground source heat pumps to 36% of single-family houses outside of district heating



Barriers

The investment costs are high for ground source heat pumps compared to other residential heat pumps and other heating alternatives. The costs of a ground source heat pump system increase with the required depth of drilling, which is determined by how far from the ground surface the bedrock is. In some cases, the investment might not make economic sense if the tenancy is unlikely to continue for very long and the resale value of the house is low. The permit and installation process entails work, and some residents, elderly people in particular, might not feel up to it. In densely populated areas, the required 20-metre distance between the wells can limit their implementation.

Enablers

Relatively shallow bedrock reduces the costs of drilling the boreholes. Affordable electricity and high cost of heating fuels improves the economics. Sweden promotes the use of ground source heat pumps through economic incentives such as a 30% tax deduction for installation work (not included in the cost analysis) and high taxation of heating fuels. In addition, the use of heat pumps is facilitated by efficient application processes as well as available information and advice for municipalities and homeowners.

Policy recommendations

National level:

- Draw up ambitious targets and road maps for phasing out fossil-fuel based heating in buildings
- Set a high tax on heating fuels
- Offer tax deductions for installation works in households
- Support the investments by low-income households in ground source heat pumps
- Train local officials in heating solutions

Local level:

- Draw up ambitious targets and road maps for phasing out fossil-fuel based heating in buildings
- Simplify permitting processes
- Provide information and support to homeowners
- Set up joint acquisition campaigns, where municipalities facilitate the purchase by selecting one supplier whose offer they recommend

Sweden promotes the use of ground source heat pumps through a 30% tax deduction for installation work.

Transport

THE FOSSIL-FUELLED TRANSPORT of people and goods is one of the main contributors to climate change globally and in the Nordics. Transport emissions are determined by how much people and goods travel, how energy intensive the transport is and how that energy is produced.

Smart city planning is a key enabler to reduce the distances travelled and to enable the use of other transport modes than private cars. The energy efficiency of mobility can be substantially increased by using other forms of transportation instead of private cars.

In **Copenhagen** in Denmark (p. 75) cycling is the fastest way to get around. **Helsinki** in Finland (p. 69) has an efficient public transport system that large shares of locals and commuters use. Recently, the further development of mobility as a service (MaaS) in Helsinki has encouraged even more people to decrease car use. **Aarhus** in Denmark has piloted shared electric cars in housing associations.

Further emission reductions can be achieved by switching to electricity and alternative fuels in public and private transport alike. **Oslo** in Norway is leading the electric vehicle revolution (p. 72), **Reykjavik** in Iceland has good experience with electric buses, and biogas is a clean local fuel used to an increasing extent, for example in **Oslo** (p. 83). Synthetic fuels are an emerging option – a plant close to **Grindavik** in Iceland produces renewable methanol for transport fuel. In Norway, ferry transport is quickly becoming electric, led by the world's first electric car ferry, Ampere in **Sognefjord** (p. 78). The port of **Kristiansand** has recently started to offer shore power to even the largest cruise ships to allow them to shut engines down while in port.

Cities can also act on the emission and air-quality problems caused by the transport of goods. **Gothenburg** in Sweden has multiple logistics initiatives to promote the use of clean delivery vehicles.

Bubbling under – the solutions of tomorrow

Mobility as a service in Helsinki, Finland
In Helsinki, 45,000 people use the MaaS service provided by the local operator Whim. All urban mobility services and functions are combined in one app: public transport, city bikes, taxis, car-sharing, ride planning, booking, ticketing and payment. In Helsinki, the users can choose between three options: an all-inclusive service; a service with unlimited public transport travel and city bike rides together with discounts on taxis and car rentals; and a pay-per-ride option.

Shared electric cars in housing co-operatives in Aarhus, Denmark
Aarhus has piloted shared electric vehicles for public housing associations. The cars could be used by inhabitants for a small fee and the municipality ensured a parking space close to homes and reduced parking fees. The users were happy, and many said they would not buy a private car if such sharing service was available.

Electric buses in Reykjavik, Iceland
In 2018, Reykjavik's public transport operator Strætó obtained 14 electric buses, representing 10% of the bus fleet. The operator has calculated that the buses bring savings over their lifetime. Strætó reports that people love the quiet buses, drivers like driving them and they are looking to procure more.

Shore power in Kristiansand, Norway
The port of Kristiansand has opened Norway's first, and Europe's largest, shore power installation, where even the world's largest cruise ships can connect during their time in port. Using shore power instead of auxiliary engines will improve air quality and reduce noise, greenhouse gas emissions and the maintenance needs of the engines.

Sustainable city logistics in Gothenburg, Sweden
Among Gothenburg's policies and initiatives to develop clean urban logistics is a new consolidation centre. Clean and quiet electric vehicles and electric cargo bikes can deliver goods from the centre to shops, instead of diesel trucks making deliveries from different suburban depots.

Renewable methanol in Grindavik, Iceland
Carbon Recycling International (CRI) runs the George Olah methanol plant, which combines carbon dioxide from the Svartsengi geothermal power plant with hydrogen separated from water with electricity to produce renewable methanol. The fuel grade methanol has over 90% lower life-cycle emissions than fossil fuels. It can be used alone in dedicated methanol cars, blended with petrol, or used as a feedstock for other fuels or chemicals. Currently, the George Olah plant utilises 10% of Svartsengi's CO_2 emissions to make 4,000 tonnes of methanol – enough to cover almost 3% of all petrol sold in Iceland.

Methanol is considered a promising way to reduce transport emissions on land and sea. Unlike biofuels, the production requires no arable land and the feedstocks are both widespread and abundant.

Public transport in urban areas, Helsinki

Public transport is more energy efficient than having everyone travel in their own cars. Reduced car use will also alleviate congestion and improve air quality.

Solution description

In Helsinki in Finland, the commuter trains and metro form the backbone of the public transport network, which is supported by bus and tram services and complemented by city bikes.

Helsinki has increased the use of public transport by investing in the reliability and accessibility of transport services putting the focus on working travel chains and ensuring quick transfer connections. The city has also taken into consideration different travel needs and user groups – for example children, senior citizens and people with disabilities.

In Helsinki, the quality of public transport and passenger satisfaction have been rated as among the highest in Europe. In 2017, 77% of journeys to the city centre in the morning traffic were made using public transport,[20] and in the Helsinki metropolitan area 21% of the total travelled distance is made by public transport. The majority of households in Helsinki do not own a car, even in the wealthiest areas, and that share is growing.[21]

Climate impact

The climate impact of public transport depends on which transport modes are used, what kind of energy they run on and how full the vehicles are. In Helsinki, 65% of the passenger kilometres are made on trains, metro or trams, which use clean electricity and do not produce emissions. Some 35% are made by buses that mostly run on diesel and in 2017 emitted 60 gCO_2 per passenger kilometre, bringing the average public transport emissions to 21 gCO_2 per passenger kilometre.[22] In comparison, private cars used for urban driving emit on average 155 gCO_2 per passenger kilometre.

We assume that all the functional urban areas in the Nordics achieve the 21% public transport share of travelled distance. We further assume the increase to replace car travel and come with a similar emission factor to Helsinki. As a result, this would reduce emissions by 2.2 $MtCO_2$.

Costs and savings

The total average cost of public transport in the Helsinki area in 2018 was 0.33 euros per passenger kilometre, including the infrastructure capital costs, operating costs, overheads and VAT paid on the tickets.[23] Approximately half of this is covered by ticket income and half comes from the area's municipalities. In comparison, we estimate the average cost of urban car travel per passenger kilometre to be 0.32 euros, when all ownership costs are included.

When compared to the total cost of car ownership, the abatement cost of public transport is 80 €/tCO_2. Car travel of course also needs an expensive infrastructure and municipal services, but we have not considered their cost here as we have assumed them to already be in place.

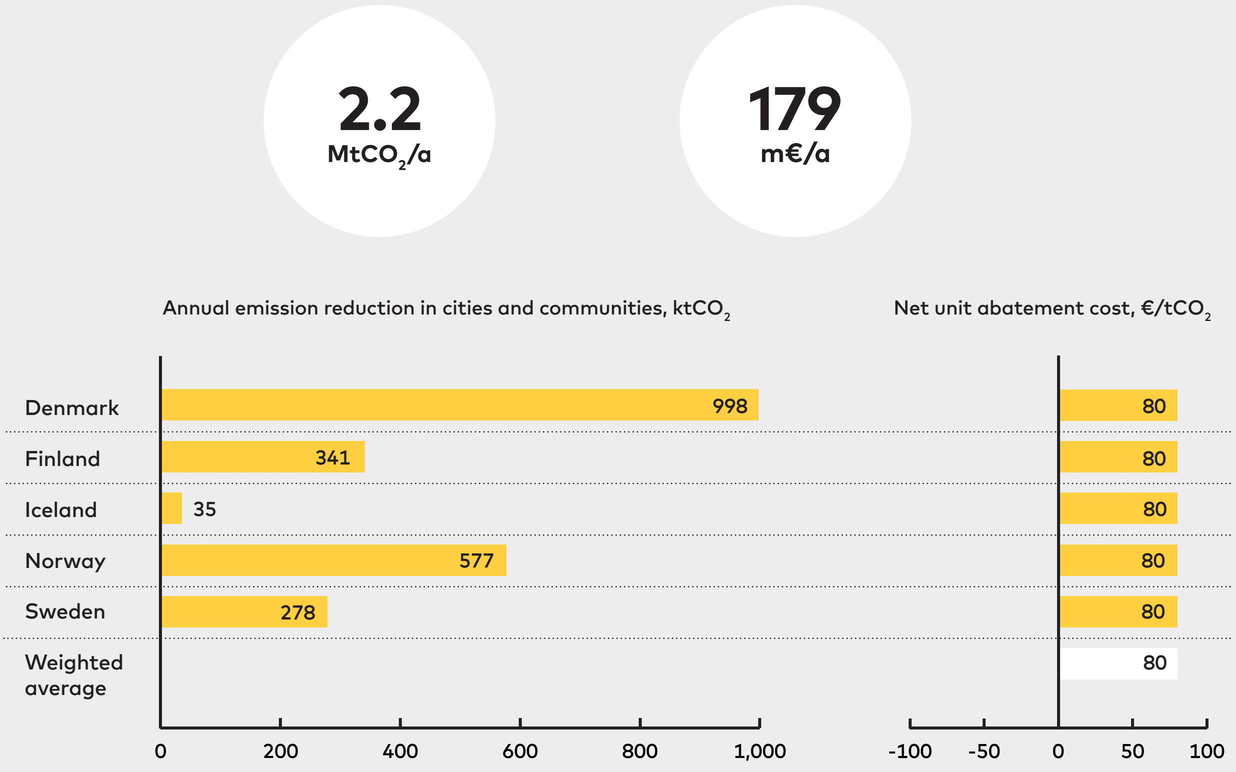
20 City of Helsinki (2018a)

21 City of Helsinki (2018b)

22 Helsinki has pledged to convert all buses to use only waste-based biofuels from 2020 onwards.

23 The infrastructure includes the costs borne by the city's public transport body (HSL) and the municipalities, but not government support.

Figure 22: Scaling up public transport to 21% of travelled distance in urban areas



Other benefits

Public transport reduces the use of private cars, which in turn reduces the amount of pollution, noise and traffic congestion. People who use public transport also walk more and gain positive health effects, while being able to use their transport time more productively than when driving. Comprehensive public transport makes it possible for inhabitants to travel more equally to work and leisure-time activities. Many studies have found that investments in public infrastructure generate jobs, increase business sales and raise nearby property values.

Barriers

To reach high-use shares, the quality of public transport should be high enough to completely replace a private car, as people who own cars use public transport much less than the people who do not. A major barrier is poor city and traffic planning dictated by the terms of private car use. To operate efficiently, public transport needs a relatively dense population – in sparsely populated areas it is very expensive to create a decent service.

If the quality of the public transport service is low, or it is considered expensive or unsafe, people prefer not to use it. Sometimes public transport can also suffer from a social stigma, which limits its use and causes political unwillingness to take on the high upfront costs of rail development in particular.

Enablers

Improving the quality of public transport services and discouraging private car use both facilitate high public transport use. The services need to be affordable, safe, frequent, punctual and fast. All of this is efficiently enabled by smart spatial planning (dense residential areas with walkable distances to services, along major public transport routes) and prioritising public transport over private car use in traffic planning. Private car use can be further discouraged by decreasing the parking options and increasing the cost of car use through higher parking costs or congestion charges, for example.

In Helsinki, public transport in the metropolitan area has benefited from co-operation between neighbouring municipalities in planning, investment and ticket harmonisation. Ongoing urbanisation trends and a willingness to live near city centres also facilitate growing public transport use.

Photo: Istock

Policy recommendations

National level:

- Draw up ambitious goals and road maps for reducing car use
- Guide the strategic development of growing urban areas to ensure sufficient apartment production in central areas and along major public transport routes
- Support major public infrastructure investments and provision of public transport in municipalities
- Provide benefits to people who use public transport
- Set a high and predictably increasing tax on fossil transport fuel

The majority of households in Helsinki do not own a car.

Local level:

- Draw up ambitious goals and road maps for reducing car use
- Ensure sufficient apartment production in central areas and along major public transport routes
- Allow housing developers to build only the number of parking spaces that they can sell with the true construction cost
- Prioritise public transport, cycling and walking in city planning, including setting up car-free zones
- Increase the price of parking, set congestion charges and use them to finance public transport
- Ensure sufficient coverage and frequency of public transport services
- Ensure convenient travel experiences by optimising travel chains and maintaining clean and safe public transport equipment and the associated infrastructure

Electric vehicles, Oslo

Electric vehicles cause significantly less emissions over their lifetime than cars using fossil fuels, when fuelled with relatively clean electricity. Increased use of electric vehicles also reduces local pollution.

Solution description

Oslo is often called the EV capital of the world – 12% of its car fleet was electric in 2018, and another 12% of the car fleet were plug-in hybrids. The success has largely been driven by policy making it cheaper to buy an electric vehicle than a comparable petrol or diesel vehicle.

The City of Oslo has encouraged the adoption of electric vehicles by setting up a city-owned network of public charging infrastructure and subsidising the installing of charging points in housing co-operatives and private companies. Oslo has also made electric vehicles exempt from road tolls and eligible for free parking as well as given them access to co-driving, bus and taxi lanes.

Climate impact

Manufacturing batteries is energy intensive and thereby the manufacturing of electric cars has a significantly larger carbon footprint than conventional cars. However, depending on the electricity used, the emissions from driving an electric vehicle are typically much lower.

Accounting for the tailpipe emissions, the electricity's emission factor and average driving habits, we estimate that each new electric car instead of a new petrol car reduces annual emissions in the Nordics between 1.3 tCO_2 (Denmark) and 1.7 tCO_2 (Iceland), the weighted average in this scaling being 1.4 tCO_2. If all the municipalities in the Nordics achieved Oslo's 12% electric share of the vehicle fleet, it would reduce emissions by 2.1 $MtCO_2$.

If we also include the emissions from the car manufacturing and an assumed necessary battery change for an EV, the average annual emission reduction per EV is 1.1 tCO_2. However, if we also factor in the emissions from the extraction and refining of the fossil petrol, the average reduction grows again to 1.6 tCO_2. The life-cycle emission reduction of EVs compared to petrol cars for the Nordic countries is between 50 and 70%, depending on the electricity emissions, annual driving and lifetime of the vehicles.

Driving with electricity is much cheaper and the maintenance costs are smaller.

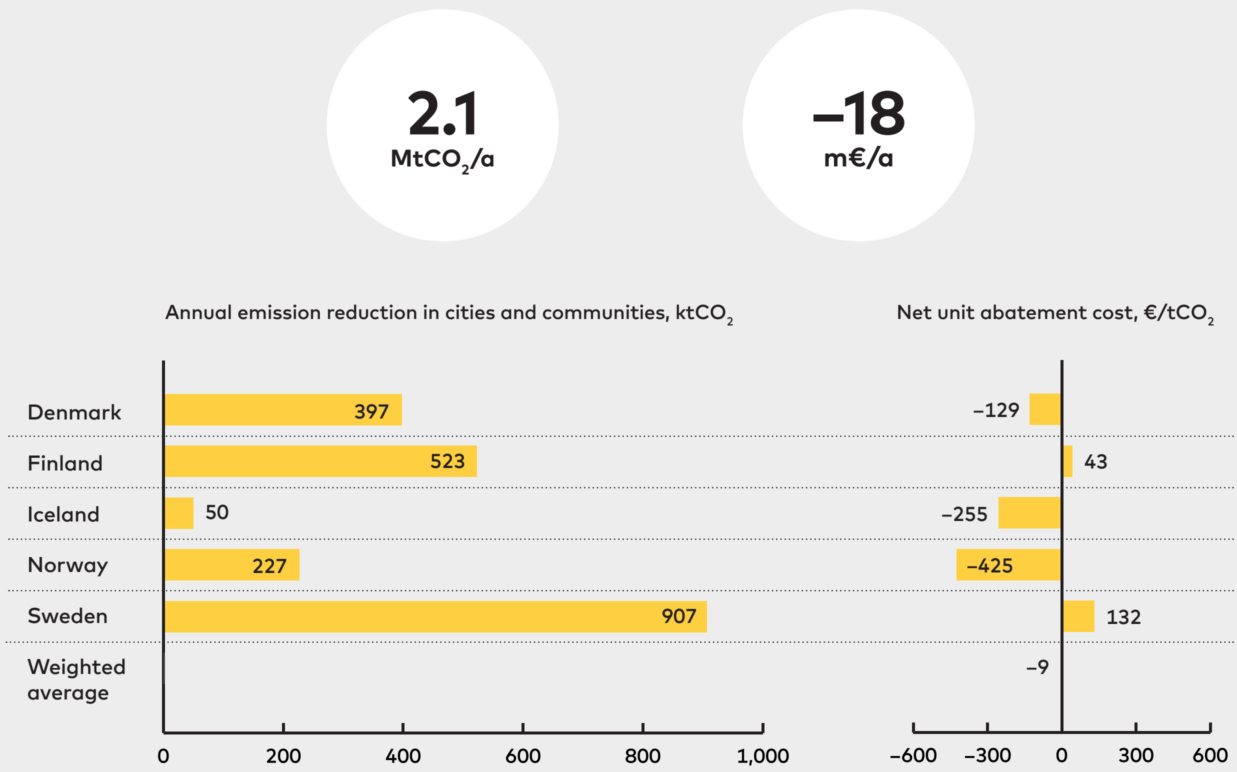
Costs and savings

Currently the factory prices of electric vehicles are still relatively high, but the significant tax incentives in Norway have already brought the purchase price to the level of a comparable petrol or diesel vehicle. Driving with electricity is much cheaper and the maintenance costs are smaller for electric vehicles because of the simpler engine.

The abatement cost faced by the car owner varies significantly between countries as a result of differing taxation schemes, and we estimate this to range from 132 €/tCO_2 in Sweden to –425 €/tCO_2 in Norway.[24]

24 Note that national taxation and subsidies are included in these perceived costs. Societal techno-economic cost analysis would find electric vehicles still come with net cost everywhere.

Figure 23: Scaling up electric vehicles to 12% of car fleet



The weighted average in the Nordics is slightly negative, –9 €/tCO_2. Currently, the negative costs are driven by national incentives, but electric vehicles are estimated to become cheaper in the near future, turning the total cost ownership in favour of EVs even without the incentives.[25]

Other benefits

Increased use of electric vehicles reduces local pollution, including noise, thereby bringing positive health effects. EVs are more comfortable to drive than conventional cars because of their quicker acceleration and seamless operation of the gearless engine. Through smart charging, electric vehicles can be used to balance the electricity demand in the grid. EVs can also use locally produced clean electricity, reducing oil imports and improving energy security.

Barriers

Electric cars are still more expensive to buy, particularly in the absence of substantial incentives. There is limited experience of how an electric car will hold its value in the longer term. The lack of a public charging infrastructure, the fear of short driving ranges and the still limited number of car models available also slow down deployment. In addition, installing multiple charging points in housing co-operatives often requires upgrading the electric cable capacity and brings extra costs.

Enablers

The most important drivers of the EV revolution in Norway have been the incentives that have brought down the prices of electric cars to the level comparable to petrol and diesel vehicles. Oslo has also developed an extensive public charging infrastructure, provided support for retrofitting charging points in buildings and given preferential toll and parking charge treatment to EVs.

The availability of reliable information on new technologies and their lifetime costs helps consumers make purchase decisions. Leasing the vehicle instead of buying it eliminates the need for the consumer to make a large investment and transfers the risk of a fast decrease in value to the leasing company. New smart charging systems are able to manage the load in buildings and can make the existing cables go further.

25 Sitra and McKinsey (2018)

Policy recommendations

National level:

- Set ambitious targets for electric vehicles and integrate them into national transport strategies
- Differentiate taxes and road charges strongly based on carbon emissions
- Consider subsidising electric vehicles or exempting them temporarily from purchase taxes and VAT
- Set a high and predictably increasing tax on fossil transport fuels
- Support the development of a nationwide fast-charging infrastructure
- Require new apartment buildings to install electric cables that can handle the charging of multiple EVs
- Require car sellers to give information about the total ownership costs of different vehicles

Local level:

- Support the development of a public charging infrastructure
- Provide incentives such as free parking spaces and exemptions from congestion charges
- Convert municipal car fleets to EVs and share experiences

EVs can use locally produced clean electricity, reducing oil imports and improving energy security.

Cycling in urban areas, Copenhagen

Bikes are a carbon-neutral mode of transport. Cycling also brings significant health benefits and decreases congestion.

Solution description

Cycling is a big part of the culture in Copenhagen, and the city's efforts to build a bike-friendly environment have played a major role in making cycling the most popular mode of transport. Copenhagen has invested in a comprehensive dedicated cycling infrastructure with separate cycle lanes and safe intersection design, as well as bicycle parking stands and DIY repair stations. Car driving is discouraged by limited parking spaces, high parking costs and banning vehicles from several streets.

In 2018, some 49% of commuter trips were made by bike in Copenhagen.[26] Copenhageners say they choose to cycle because it is faster, easier and good exercise. Copenhagen has targets to further increase the share of cycling and to decrease the share of car trips.

Climate impact

A Copenhagener bikes on average three kilometres every day. Between 2007 and 2017 the share of cycling of all trips in Copenhagen has grown, and over 80% of this increase has replaced car travel.[27] Average urban car travel emits 155 gCO_2 per passenger kilometre.

If the inhabitants of other functional urban areas in the Nordics cycled three kilometres a day and half of the additional cycling replaced current car travel, each kilometre biked would reduce emissions by 78 gCO_2. In total emissions would be reduced by 0.8 $MtCO_2$.

Costs and savings

Bike lanes and the related infrastructure are constructed by the municipalities. Over the past ten years investments in cycling-related initiatives in Copenhagen were about two billion Danish kroner. This translates to a cost of three euro cents per kilometre biked by a Copenhagener.

As biking often does not replace a car completely, we compare the cost of cycling to the resulted fuel saving, which we estimate to be around 10 cents per passenger kilometre in urban driving. Half of the increased cycling is assumed to replace public transport use or walking, which we assume not to bring any cost savings to the cyclist and municipality combined. The abatement cost varies between –241 €/tCO_2 in Finland to –357 €/tCO_2 in Iceland as a result of the differences in fuel prices, and the weighted average is –287 €/tCO_2.

Other benefits

Cycling has major health benefits. In Copenhagen, residents who cycle request 1.1 million fewer sick days annually, and every kilometre by bike instead of by car is estimated to bring a one euro gain in health benefits.[28] Biking also decreases congestion and air pollutants. As biking is a low-cost transport method, it creates more equal opportunities for people to move around and increases social cohesion between areas.

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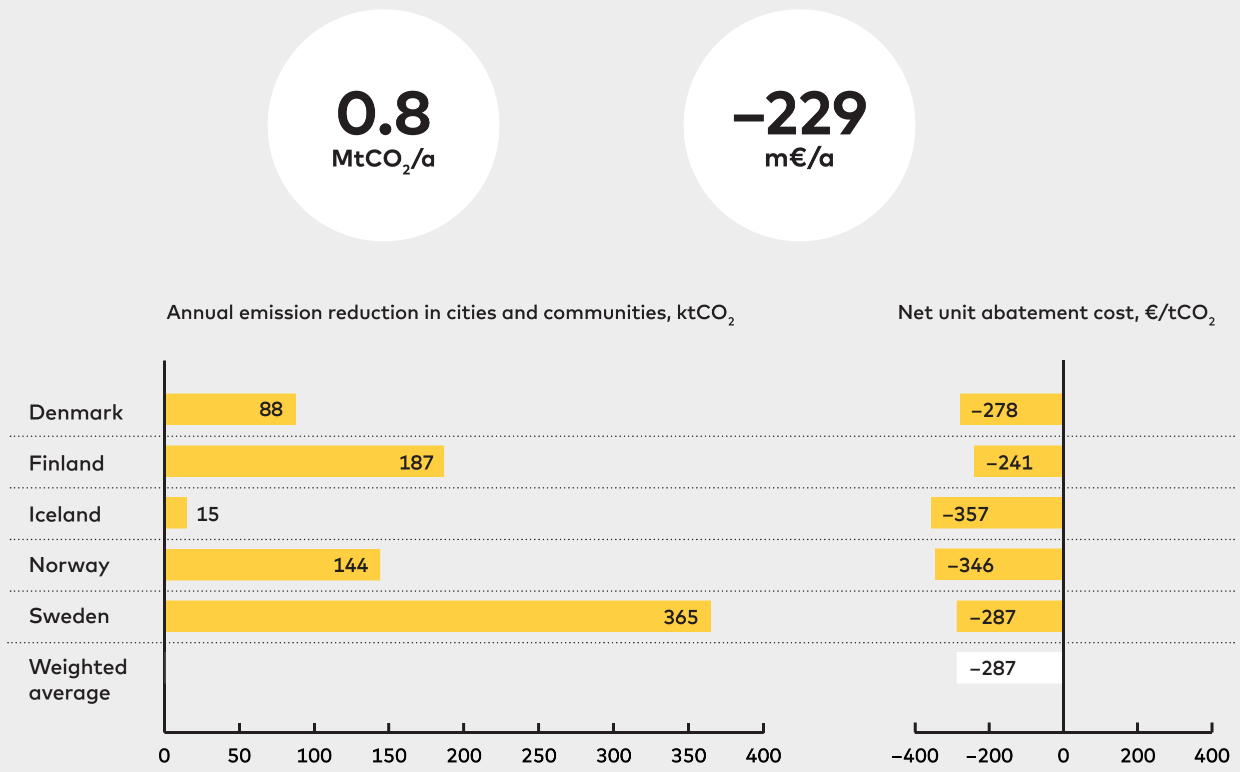
26 Copenhagen Bicycle Account 2018

27 Share of cycling of all trips starting or stopping in Copenhagen; City of Copenhagen.

28 Denmark.dk

Figure 24: Scaling up cycling to 3 km per day per urban dweller



Barriers

Often the biggest barrier to cycling is the convenience of car travel. Among other things, this is because cars have been prioritised in traffic policy and spatial planning. Parking tends to be subsidised as the price of parking often does not reflect the true costs and value of the space. Safety risks because of a lack of a proper dedicated cycling infrastructure or its inadequate maintenance also discourage cycling, as does a lack of secure bike parking. Long distances, difficult terrain and bad weather conditions can also hinder cycling.

1/2 of commuter trips are made by bike in Copenhagen.

Enablers

Copenhagen's cycling success is a result of treating cycling as an equal means of transport with cars, and in some cases prioritising it over cars. The convenience of cycling is guaranteed by a widespread, well-maintained, dedicated infrastructure and traffic design ensuring the safety of cycling, enough secure bike parking and the ability to combine cycling with the use of public transport. The city also offers shared electric bikes. E-bikes can encourage commuting even longer distances by bike.

In order to increase the share of cycling, it is often necessary to discourage driving. In Copenhagen, high fuel prices, taxes and parking prices as well as limited parking spaces and car access in inner Copenhagen all help maintain the attractiveness of the bike.

Photo: Alamy

Policy recommendations

National level:

- Draw up ambitious goals and road maps for reducing car use
- Guide the strategic development of growing urban areas to ensure sufficient apartment production in central areas and along major public transport routes
- Set a high and predictably increasing tax on fossil transport fuels
- Finance the bicycle infrastructure
- Require the prioritisation of bicycles and other sustainable transport modes in spatial and traffic planning
- Provide incentives for electric bikes

Local level:

- Draw up ambitious goals and road maps for reducing car use
- Ensure sufficient apartment production in central areas and along major public transport routes
- Prioritise bicycles, walking and public transport in city and traffic planning
- Invest in the cycling infrastructure, such as installing separate bike lanes and bike parking
- Integrate cycling with public transportation
- Offer shared (e-)bikes
- De-incentivise cars by pricing parking adequately and setting up car-free zones, for example
- Allow housing developers to build only the number of parking spaces that they can sell with the true construction cost

Success is a result of treating cycling as an equal means of transport with cars.

Electric ferries, Sognefjord

Electrically powered ferries can replace diesel ferries on most short routes under 60 minutes. Batteries are charged at land-based charging stations while boarding.

Solution description

In Norway, a growing number of diesel ferries have been replaced by electric ones. The very first electric ferry was MF Ampere and it entered service in early 2015. It operates on a 5.7 km crossing on the Sognefjord. The vessel won the tender in a competition for the most environmentally friendly ferry.

After the reported impressive emissions (–95%) and operating cost (–80%) savings, local politicians in Hordaland tasked the agency organising public transport with attaining a significant reduction in emissions. Together with the industry, new requirements were set for CO_2 and energy use cuts, and cuts above minimum requirements were introduced as selection criteria with a combined weighting of 30%. The public transport agency drafted new schedules that left a few minutes extra between arrival and departure to allow the electric ferries to recharge their batteries. In the end, all of the contracts tendered were won by fully electric ferries.

Climate impact

The climate impact of an electric ferry depends on the emissions of the electricity used and how much diesel it replaces, which again is determined by the capacity, length and frequency of the ferry service. *Ampere* displaces approximately one million litres or 800 tons of diesel every year. According to industry studies, electrifying an average diesel ferry avoids diesel use by between 500 (Denmark) and 1,000 (Norway) tonnes per ferry per year. This corresponds to emission reductions of 1 $ktCO_2$ in Denmark and 3 $ktCO_2$ in Norway.

We assume the Danish average diesel replacement per ferry to also reflect the situation in Finland, Sweden and Iceland. If all ferry connections shorter than 60 minutes were electrified in the Nordics, it would reduce emissions by 0.4 $MtCO_2$.

Costs and savings

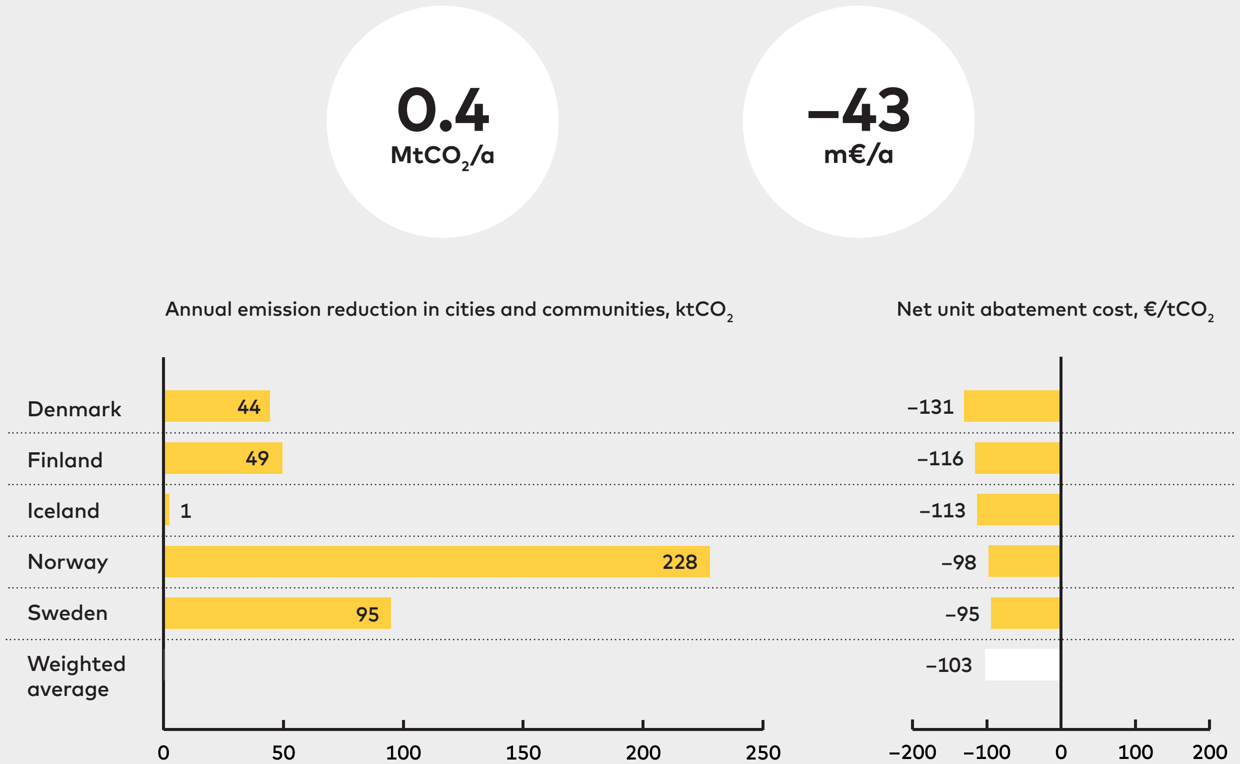
Electric ferries require higher initial investment than conventional diesel options. Electric ferries are often built from lighter but more expensive aluminium and there are also the costs of the batteries, building the charging stations and potentially expanding the existing electricity grid.

On the other hand, operational savings are obtained because electricity is a cheaper fuel, electric ferries consume less energy by having more efficient engines and being lighter, and electric motors require less maintenance. The diesel used by ferries is tax free in all Nordic countries, but the electricity for electric ferries has differing tax treatments – in Finland and Sweden they pay the full taxes, in Norway the industry tax rate and in Denmark no taxes. Despite this, the abatement costs differ relatively little: between –131 €/tCO_2 in Denmark and –95 €/tCO_2 in Sweden, the weighted average being –103 €/tCO_2.

Other benefits

The perks of operating an electric ferry are the absence of exhaust gases, vibrations and noise produced by a diesel engine. Replacing fuel combustion cuts air pollution. It also reduces the need to import fossil fuels and increases energy security.

Figure 25: Scaling up electric ferries to all suitable ferry connections



Barriers

Electric ferries require a larger upfront investment for both the ferry itself and the charging infrastructure. If the electricity grid in the harbour is not strong enough to charge the batteries as fast as is needed, which is often the case in remote areas, the grid must be fortified or additional battery buffers installed at the harbour, which adds costs.

With current technology, electric ferries are only feasible on relatively short distances (under 60 minutes and 2,000 kWh). The batteries require some time to recharge between trips, so schedules might need to be adjusted.

Enablers

Governments can operate as enablers by supporting new technology innovation. In the case of Norway, a national competition was launched to provide the most sustainable ferry option, and now electric ferries are rapidly spreading. Carbon emissions and energy efficiency can be used as criteria in public procurement for ferry services. In Norway, the government supports the building of battery buffers in locations where the grid is not strong enough for direct charging. Low-cost electricity and other low operating costs support the deployment.

Policy recommendations

National level:

- Draw up ambitious goals and road maps for electrifying ferry operations
- Require considering the climate impact in public procurement
- Support the deployment of electric ferries in areas with weak grids
- Reduce the tax on electricity and raise the tax on fuels used in ferries
- Encourage innovation, for example by tendering some contracts based on only environmental effects

Local level:

- Draw up ambitious goals and road maps for electrifying ferry operations
- Use emission cuts as central selection criteria when procuring ferry services
- Support the deployment of electric ferries in areas with weak grids
- Use municipal services as a platform to showcase new solutions

Electric ferries avoid the pollution, vibrations and noise of diesel ferries.

Food and waste

THE PRODUCTION OF FOOD has a large climate impact. Expanding agriculture reduces forested land and its carbon stock, common agricultural practices cause soil organic carbon loss, cattle produces methane, while the production and application of fertilisers release nitrous oxide, a strong greenhouse gas.

One of the most effective ways to cut emissions from agriculture is to shift for more plant-based foods. The City of **Helsinki** in Finland has recently decided to cut its meat and dairy consumption in half by 2025. Another important way is to decrease the amount of wasted food. The City of **Vantaa** in Finland has increased the donations of surplus food from retail and manufacturing by organising centralised collections (p. 86).

When organic waste is produced, it should be seen as a resource. **Eskilstuna** in Sweden is a pioneer in organising efficient food waste and material recovery. **Oslo** in Norway processes food waste into biogas and uses it to power city buses (p. 83). As a side product, they obtain biofertiliser, which can be used to return the nutrients to the fields and decrease the demand for emission-intensive virgin fertiliser production.

Organic waste can also be used to return carbon to the soil. **Stockholm** in Sweden produces biochar from garden waste and improves the soil and sequesters carbon with it.

Bubbling under – the solutions of tomorrow

Reducing meat consumption in city operations in Helsinki, Finland

The City of Helsinki aims to halve current meat and dairy consumption within all of its own operations by 2025. This includes, for example, the food in day-care centres, schools and nursing homes. In Helsinki's schools, already 60% of the food on the menu is vegetarian, which has resulted in approximately 30% of the served dishes being vegetarian. According to school food services, there is no price difference between meat and vegetarian food on this scale.

Biochar in Stockholm, Sweden

Stockholm converts garden waste from parks and households into biochar. The waste is carbonised by heating it in anaerobic conditions, which produces biochar and pyrolysis gas. The gas is then used to produce energy for the district heating system. Biochar stores carbon in the soil and improves the structure of it, reduces the leaching of nutrients and improves stormwater infiltration. The biochar is used to grow plants and trees in the city's public spaces. Residents who bring in garden waste can pick up biochar to use in their gardens.

Recycling in Eskilstuna, Sweden

The town of Eskilstuna reached long ago the EU's 50% recycling target for 2020. Since 2010, households in Eskilstuna separate waste into seven different colours of bags – food in green, plastic in orange, newspapers in blue, other paper in yellow, metal in grey, textiles in pink and the rest in white – and place them all in the same bins. The bags are then sorted optically at a central waste management plant. Recycling rates have gone up while the garbage collection needs have decreased as the same trucks can pick up all the waste at the same time. The collected biowaste is used to produce biogas for the town's buses and compost for the residents, while materials are recycled.

In 2015, the municipality opened a second-hand mall, ReTuna. There, residents can drop off their unwanted goods, which get sorted by the staff and repaired and upcycled by the mall shops. In 2018, the sale of second-hand products amounted to over a million euros.

Biogas from food waste, Oslo

Organic waste can be a valuable resource if turned into biogas, which can be used to replace fossil fuels in transport or energy production.

Solution description

In Oslo, households pre-sort their food waste into green bags, which are separated from other waste at an automated waste-sorting plant and sent to a biogas plant. There, the food waste is anaerobically digested and turned into biogas, which is then used to fuel the waste collection trucks and city buses.

The Oslo plant also processes biowaste from businesses and other municipalities. The plant has the capacity to process 50,000 tonnes of food waste per year, which they estimate to be enough to fuel 135 buses.[29] In 2017, the plant processed 30,000 tonnes.

Climate impact

Currently, 45% of Oslo's household biowaste is pre-sorted and sent to the biogas plant. Each tonne of biowaste treated at Oslo's plant produces around 900 kWh of liquid biomethane, which we estimate to replace around 80 litres of diesel as a transport fuel. We assume the biogas to be carbon neutral compared to the direct diesel emissions. Thereby, biogas reduces emissions by 180 kgCO_2 per tonne of digested biowaste.

For this analysis we do not consider biowaste treatment options composting or incineration for energy to produce net emission savings. For landfilling we estimate that 30% of the methane cannot be captured by landfill gas capture systems, which causes emissions of 770 kgCO_2e per tonne of landfilled biowaste. If all Nordic municipalities turned 45% of their biowaste into transport biogas instead of composting, incinerating or landfilling it, it would reduce emissions by 134 ktCO_2e.

Costs and savings

The production of biogas is a very cost-efficient way to treat biowaste because of the significant income generated through the sale of biogas. After sales of the end product, we estimate the total treatment cost per tonne of biowaste to be 43 €/t for composting, 105 €/t for incineration, –3 €/t for landfilling with gas capture and transport-fuel upgrade and –4 €/t for biogas production. Because of the differences in current biowaste treatment, the abatement cost varies between –604 €/tCO_2 for Denmark and –1 €/tCO_2 for Iceland, the weighted average being –364 €/tCO_2.

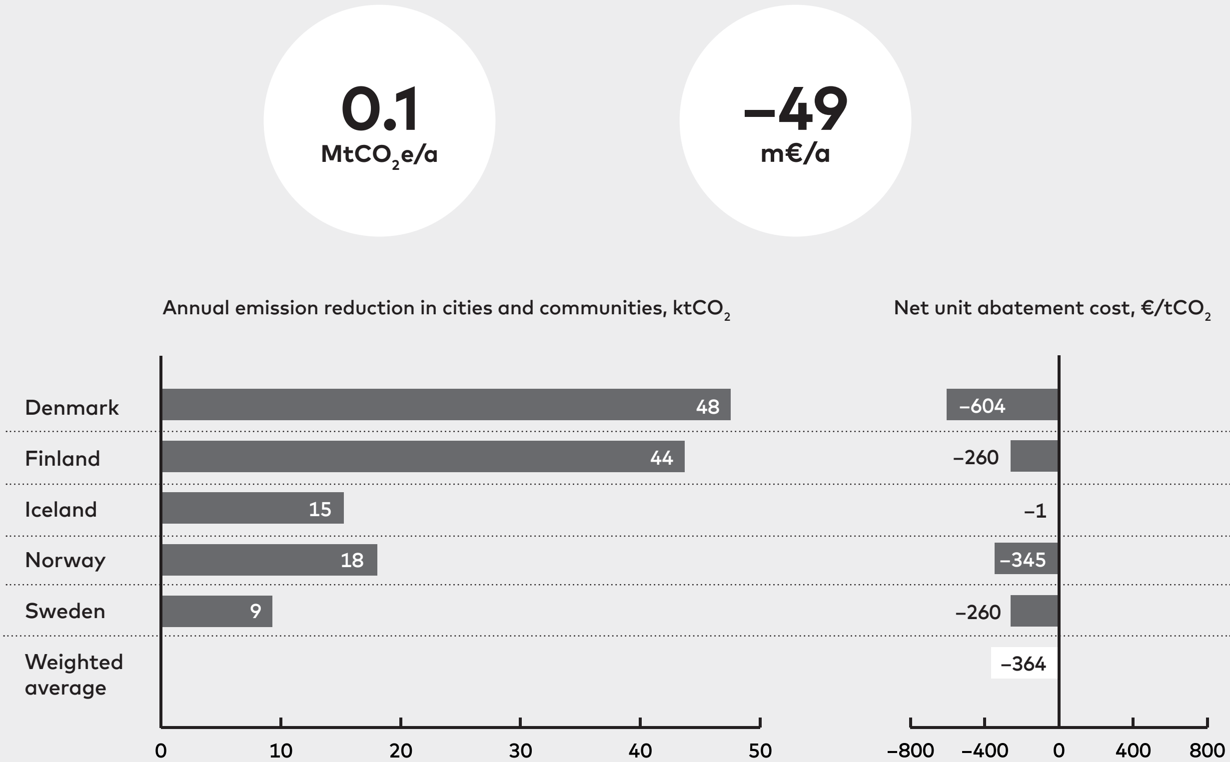
Other benefits

Biogas as a transport fuel reduces noise and air pollutants, such as nitrogen oxides and particulates. The production of biogas also leaves behind digestate, which can be processed into fertilisers. The Oslo plant produces three different kinds of biofertilisers, and if the plant runs at full capacity the fertilisers are enough for 100 medium-sized farms.[30] The use of recycled fertilisers keeps important nutrients such as phosphorus, nitrogen and potassium circulating. It also reduces the need for virgin fertiliser production, which is emission-intensive as a result of energy requirements and the leakage of nitrous oxide during the production.

The automated waste-sorting plant in Oslo is also able to sort different kinds of plastics, metals and paper from the residual waste stream. The system therefore increases the recovery of recyclable materials above the source separation rate.

29 City of Oslo Waste-to-Energy Agency
30 City of Oslo Waste-to-Energy Agency

Figure 26: Scaling up the share of household food waste used for biogas to 45%



Barriers

To produce biogas, biowaste needs to be separately sorted by households, which requires changes in behaviour. The plant in Oslo could handle all of the local food waste, but as only 45% gets pre-sorted, the plant is using approximately half of its capacity, which eats into the profitability of the operation.

Overall, it only makes economic sense to invest in a biogas plant to treat the municipal biowaste if there is enough waste available. The solution may only be suitable for relatively densely populated areas and requires co-operation between neighbouring municipalities.

Enablers

The landfilling of biowaste is banned by regulation in most Nordic countries, which often makes biogas production the cheapest option for treating it. The pre-sorting of food waste can be encouraged by education, providing opportunities for sorting at home and lowering biowaste fees relative to mixed waste.

In Oslo, the coloured waste-sorting bags are available free of charge at supermarkets. All the bags go in the same bin, so there is no need to take the sorted waste to another location. Tax exemptions for biogas as a transport fuel improve its competitiveness. Biomethane plants in Norway are also eligible for investment grants.

Biogas as a transport fuel reduces noise and air pollutants.

Photo: Johnér

Policy recommendations

National level:

- Ban the landfilling of biowaste
- Require the capture of landfill gases
- Require biowaste sorting opportunities to be provided to everyone
- Make biogas exempt from fuel taxes
- Educate people about the need to sort waste

Local level:

- Invest in a biogas plant together with neighbouring municipalities
- Provide sorting opportunities for everyone
- Set lower fees for biowaste to encourage sorting
- Educate households about the need to sort waste
- Use biogas in municipal vehicle fleets, such as bin lorries and buses

To produce biogas, biowaste needs to be separately sorted by households.

Reduction of retail food waste, Vantaa

Services that distribute surplus food reduce the amount of food waste and the need for further production – or hunger. Centralised collection enables more efficient operations.

Solution description

In Finland, the City of Vantaa, together with the Vantaa Parish Union, founded what is known as a Shared Table action model that focuses on distributing surplus food through communal meals and bags of food.

Since 2015, the city and the parish union have organised the centralised logistics of food collection from 35 donor factories, wholesalers and supermarkets. The food is distributed to 65 food-aid deliverers, half of which started to deliver food aid as a result of the Shared Table network. The model has been adopted by ten other regions across Finland.

Climate impact

Avoiding food waste reduces emissions if less food is produced because of it. We assume that the emission reduction of avoided food waste equals the climate impact of that food. The average carbon footprint of a kilogram of typical retail surplus food in Finland is estimated to be 1.9 $kgCO_2e$.

Before the Shared Table model, the donated retail and wholesale surplus food in the capital area was approximately 2.3 kilograms per inhabitant. In Vantaa, the Shared Table distributes yearly between half a million and one million kilograms of surplus food. This corresponds on average to 3.3 kilograms of avoided food waste per inhabitant of Vantaa, increasing the avoided food waste by one kilogram per inhabitant. If all the other municipalities in the Nordics reduced their food waste by one kilogram per inhabitant, it would reduce emissions by 51 $ktCO_2e$.

Costs and savings

The collection logistics in Vantaa amount to an average of 0.8 €/kg of delivered food. In addition, the distribution is carried out by volunteers. We estimate that the savings in biowaste fees and the reduced need to purchase food are 2.6 €/kg of delivered food. Therefore, the abatement cost is –974 €/tCO_2e.

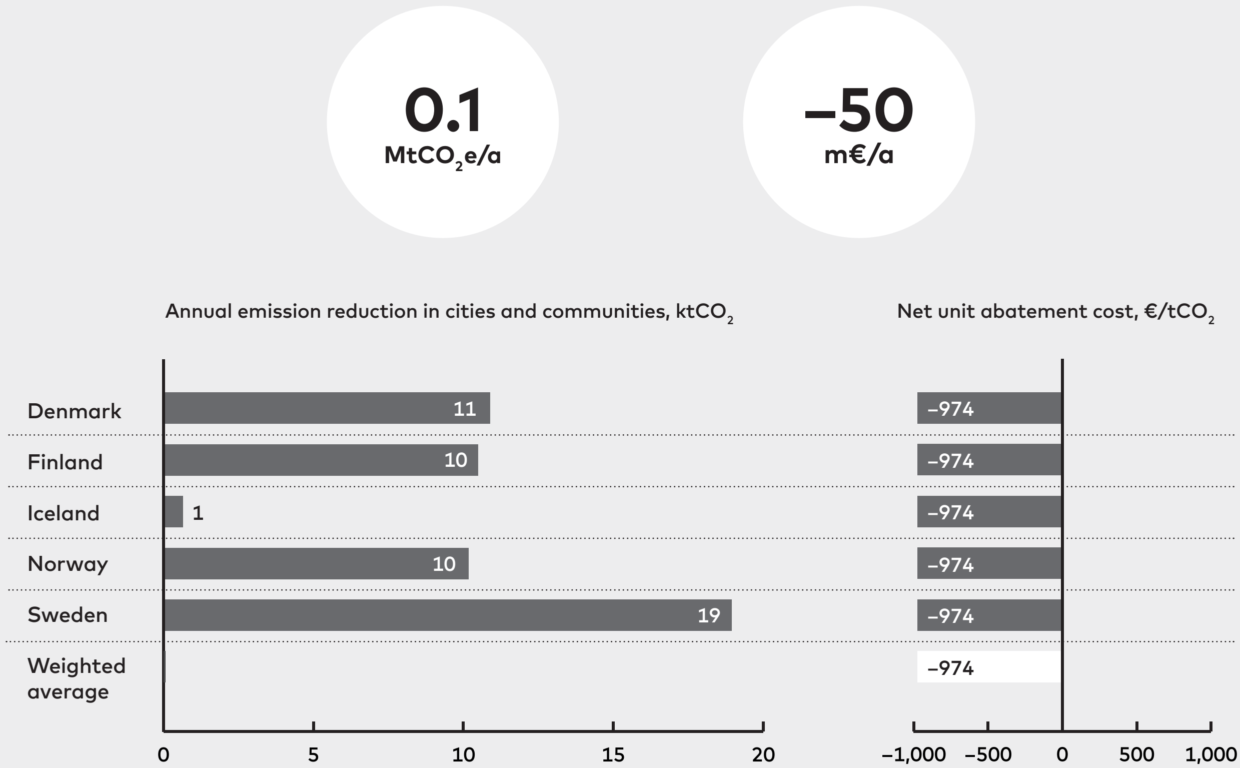
Other benefits

In Vantaa, the project has created local jobs and employed long-term unemployed people, giving them a chance to come into contact with work life again. Food aid can help some of the poorest people in the society. The communal approach to distributing food aid has also reduced loneliness among the people receiving it.

In general, the reduction of food waste reduces pressure to expand land, water and other resource inputs to agriculture. In countries where organic

In Vantaa, distributing surplus food has created local jobs and employed long-term unemployed people.

Figure 27: Reducing retail food waste by donating 1 kg more per inhabitant



waste is still landfilled, avoided food waste also avoids emissions of methane, but we have not included this in the analysis.

Barriers

Unnecessary bureaucracy can contribute to food waste and make it difficult to donate food. The ability to distribute food depends on the capacity of food-aid services, which are prone to a lack of resources and rely quite heavily on volunteer work. Often there is no readily existing co-operation model between the different participants, such as donors, logistics firms and the different types of food-aid deliverers. In addition, there might not be large financial incentives for the municipality to support food-aid services, or for the retail outlets and factories to donate surplus food.

Enablers

Public awareness of food waste encourages more people to pay attention to minimising it. A co-operative culture across public, private and third-sector organisations facilitates the creation of functioning co-operation models. Regulation that allows the distribution of food after the sell-by period can enable larger donation volumes.

In Finland, stores and commercial kitchens can donate frozen food after its use-by date, and food that has surpassed the use-by date by one day can be given as food aid if served warm. Relatively high biowaste fees encourage food donations. Regulation that gives food-aid organisations the right to return poor-quality products to the donor ensures that biowaste will not be dumped on them.

The communal approach to distributing food aid has also reduced loneliness among the people receiving it.

Policy recommendations

National level:

- Ensure that regulation enables effective food redistribution
- Allow the donation of mislabelled food with instructions for use without the need for relabelling
- Ensure that use-by dates are only used for products that are likely to cause immediate negative effects to human health
- Ensure that food-aid organisations can return poor-quality products to the donors

Local level:

- Set high fees for organic waste
- Support centralised surplus food collection logistics
- Support the organisations that deliver food aid in a communal way

Public awareness of food waste encourages more poeple to pay attention to minimising it.


Photo: Scanpix.dk

Appendix I: Analysis assumptions

Commodity prices and emission factors

Table 2: Electricity emission factors and commodity price assumptions by country

	Unit	Denmark	Finland	Iceland	Norway	Sweden	Sources
Grid electricity emission factor	gCO_2/kWh	207.7	117.4	8.8	8.0	12.3	IEA (2018); Iceland National Energy Authority (2019)
EU ETS allowance price	€/tCO_2	25	25	25	25	25	
Electricity price for electric ferries	€/MWh	79	84	75	66	98	Eurostat, 500 MWh < consumption < 2,000 MWh, 2016-2018 average; current tax rates for each country
Electricity price for large scale heat pumps	€/MWh	152-180	81	59	54	88	Eurostat, 2 GWh < consumption < 20 GWh, 2016-2018 average; current tax rates for each country. In Denmark price varies because electricity tax is capped at 21.9 öre/kWh of heat produced
Electricity price for electric vehicles (households)	€/MWh	243	137	132	122	160	Eurostat, 5,000 kWh < consumption < 15,000 kWh, 2016-2018 average
Electricity price for electric heating consumers (households)	€/MWh	222	114	80	108	139	Eurostat, consumption > 15,000 kWh, 2016-2018 average; Iceland National Energy Authority
Natural gas price for households	€/MWh	87	111			116	Eurostat, 20 GJ < consumption < 200 GJ, 2016-2018 average; Suomen Kaasuenergia
Heating oil price for households	€/MWh	127	88		101	105	Statistics Finland; the Swedish Energy Agency; the Danish Energy Agency; IEA. Average 2016-2018
Diesel price at the pump	€/l	1.33	1.29	1.61	1.56	1.48	Statistics Finland; Statista; Statistics Norway; Global petrol prices
Petrol price at the pump	€/l	1.56	1.45	1.67	1.66	1.49	Statistics Finland; Statista; Statistics Norway; Global petrol prices
Diesel price for ferries (tax free)	€/l	0.77	0.77	0.77	0.77	0.77	Statistics Finland, 2016-2018 average

Table 3: Fuel emission factors and price assumptions before taxes

	Unit	CO_2 factor	Lower heat value	Density	Price	Note
		t/TJ	GJ/unit	t/m³	€/MWh	
Petrol	t	67.0	41.9	0.74	see Table 2	Assumed to include 9.1% biofuel
Diesel	t	65.8	42.7	0.81	see Table 2	Assumed to include 10.7% biofuel
Light fuel oil	t	73.1	43.2	0.83	see Table 2	
Heavy fuel oil	t	79.2	40.4	0.99	37	Price excl. taxes
Coal	t	92.7	24.8		10	Price excl. taxes
Natural gas	1000 m³	55.3	36.4		27	Price excl. taxes
Peat	t	107.6	10.1	0.32	14	Price excl. taxes
Biomass	t	0	10.0		23	Price excl. taxes
Source		Statistics Finland Fuel Classification 2019			VTT (2016)	

Onshore and offshore wind

Abatement

Wind power does not produce any direct emissions, and thereby the abatement from the onshore and offshore wind equal the emissions from the power production they can replace. Biomass emissions are set at zero, as they are accounted for in the LULUCF sector. For combined heat and power (CHP) production, the emissions are allocated between power and heat production using the energy method. The assumed fuel-efficiency value for separate power production from coal is taken from Vainio (2011), and for gas, peat and biomass from Vakkilainen (2017). For CHP production the efficiencies are taken from VTT (2016). For oil these were not available, and for separate power production we have used the same fuel efficiency as for gas, and for CHP production the same values as for coal. See Table 4 for the values and resulted emissions per unit of power produced.

Costs

We compare the levelised cost of electricity (LCOE) for the different production methods. For wind, we use 41 €/MWh for onshore and 69 €/MWh for offshore, as presented by Vakkilainen (2017). It is noteworthy that at least for onshore this cost can be seen as conservative, as costs have been cited to be below 30 €/MWh for new projects in recent years.

The capital and operation and maintenance (O&M) costs for separate power production from coal are taken from Vainio (2011). For peat, biomass and gas they are taken from Vakkilainen (2017). For oil the costs were not available, and we have used the same costs as for coal. For CHP production we have assumed the same capital and O&M cost per produced MWh of electricity as for the separate power production, but some of this cost now gets allocated to heat as well according to the energy method.

The heating fuel taxes for CHP we use are for Finland in 2019, as Finland has the largest amount of fossil CHP production left. Finland also has the lowest taxes out of the Nordic countries, so the cost results are on the conservative side. See Table 4 for the resulted production cost.

Scaling up

As the benchmark we use the average Danish shares of wind power production of electricity demand in 2018, 27% onshore wind and 13% offshore wind (Danish Energy Agency). In this analysis we do not add any wind capacity for Denmark. In Iceland, wind also has no emission reduction potential, as there is no fossil fuel-based power production, except on two small islands that are not connected to the grid.

For scaling we assume that Finland, Sweden, Norway and Denmark form a seamless and closed joint electricity market, where additional wind power

Table 4: Power production cost assumptions and resulted levelised production costs

	Unit	Separate power production							Combined heat and power production				
		Coal	Gas	Peat	Oil	Biomass	Wind onshore	Wind offshore	Coal CHP	Gas CHP	Peat CHP	Oil CHP	Biomass CHP
Capital cost	€/MWh electricity	11.5	8.7	17.4	8.7	18.3	33.7	54.9	4.0	4.8	5.8	3.0	6.1
Net CHP-efficiency	%								86	88	84	86	84
Net electricity production efficiency	%	42	58	40	58	40			30	48	28	30	28
O&M cost	€/MWh electricity	8.0	7.0	10.5	7.0	6.9	7.7	14.0	2.8	3.8	3.5	2.5	2.3
Fuel taxes	€/MWh electricity	0	0	0	0	0	0	0	17	8	2	14	0
Resulted total production cost	**€/MWh electricity**	**63**	**71**	**87**	**91**	**81**	**41**	**69**	**45**	**54**	**39**	**71**	**35**
Resulted emissions	**kgCO_2/ MWh electricity**	**795**	**341**	**968**	**489**	**0**	**0**	**0**	**388**	**226**	**461**	**332**	**0**

Energy method used for CHP. See Table 3 for fuel price and emission assumptions and Table 2 for EU ETS allowance price assumption. Taxes are for Finland.

production replaces production with the highest marginal production cost.

The replacement calculation is based on monthly production data. The additional wind power production is divided between months according to the average production profiles for the period 2016-2018, and, likewise, the production type to be replaced in each month is determined as an average of the period 2016-2018. Fuel use data for condensing and CHP production is not available monthly, and therefore the same distribution of fuels is assumed for each month. For fuel use we use the average from 2016-2017, as these are the latest available years. Data is from Statistics Finland, Statistics Sweden, the Danish Energy Agency, Statistics Norway and the International Energy Agency (IEA). For Norway monthly production data is not available, and we use Statistics Norway's annual totals, Sweden's temporal distribution for wind and thermal and fuel distribution as reported by IEA for Norway.

The current shares of wind power production in Finland, Sweden and Norway are allocated to offshore and onshore based on the current capacity shares, as separate production data is not available. The same monthly production distribution is used for onshore and offshore.

Currently, there is approximately 29 TWh or 12.5 MtCO_2 of annual fossil-based power production left in Finland, Sweden, Norway and Denmark combined. This does not include energy produced from waste incineration, as we assume that to be driven by the need to handle the waste. This approach of replacing the production on a monthly basis results in all fossil-based power production being pushed out when the additional annual wind power production reaches 40 TWh. Also 11 TWh of biomass-based power production is pushed out in addition to the fossil fuels.

If Finland, Sweden and Norway increased their onshore wind production to 27% of their current electricity demand, wind power production would be increased by 73 TWh, and increasing offshore to 13% would increase wind power production by 46 TWh. Both of these alone are enough to theoretically eliminate all fossils – in fact, 55% of the onshore wind addition and 86% of the offshore addition is enough. We use these values to calculate the emission reduction costs (–28 €/tCO_2 for onshore and 60 €/tCO_2 for offshore) and to allocate the emission reductions to countries. For onshore and offshore combined, only 34% of the production additions are needed. These values we use to calculate the total wind power-induced emission reductions and costs by country and for the Nordic countries as a whole. See Table 5 for the resulted wind power production additions by country.

In this report, we have chosen to allocate the emission reduction to the country where the additional wind power production takes place, regardless of where the fossil production is pushed out. With the assumption of a closed Nordic power market, most of the actual emission reductions take place in Finland and Denmark, because that is where most of the fossil power production in the Nordic countries is.

See Solutions catalogue for discussion on the actual implications of adding this amount of wind power in the Nordic countries.

District heating solutions

Abatement

To calculate the abatement from the district heating solutions, we compare the emissions of the solution to the emissions from the fossil heat production it can replace. The solution emissions consist of the emissions related to the production of average grid electricity that the heat pumps and other necessary pumps use. We use the grid emission factors from the IEA, and in the case of Iceland the emission factor calculated in Iceland's National Inventory Report, which are presented in Table 2. The heat used by the heat pumps is assumed to be waste and thereby zero-emission for all the solutions.

The coefficient of performance (COP) of the heat pump system determines how much electricity is needed to produce a unit of heat energy. For solar thermal and geothermal, not all of the heat production needs to go through the heat pump, and therefore the heat pump can be relatively smaller and produce fewer emissions per unit of system heat output. See Table 6 for the COP assumptions and Table 7 for the resulted solution emission factors by country.

The emissions from fossil fuels are presented in Table 3. For all heat plants we assume an efficiency of 90%. For CHP production the emissions are allocated between power and heat production using the energy method, and the efficiencies are taken from VTT (2016). For oil CHP, the efficiency was not available, and we have used the same values as for coal. See Table 8 for the resulted emission factors of the produced heat.

Cost

The solution costs consist of investment costs, maintenance costs and fuel (electricity and, in the case of data centres, heat) costs. We have used data from the benchmark case when it was available, and otherwise general assumptions from other Nordic

Table 5: Wind power addition

		Unit	Finland	Norway	Sweden	Total
Onshore	Current onshore wind share of electricity demand	%	6.3	2.1	11.1	
	Additional onshore wind, if scaled to 27%	TWh	18.1	33.4	21.5	**73.0**
	Additional onshore wind, if 55% of addition implemented	TWh	9.9	18.3	11.8	**40.0**
	Additional onshore wind, if 34% of addition implemented	TWh	6.1	11.2	7.2	**24.5**
Offshore	Current offshore wind share of electricity demand	%	0.4	0.0	0.4	
	Additional offshore wind, if scaled to 13%	TWh	11.0	17.5	17.9	**46.4**
	Additional offshore wind, if 86% of addition implemented	TWh	9.5	15.1	15.4	**40.0**
	Additional offshore wind, if 34% of addition implemented	TWh	3.7	5.9	6.0	**15.5**

55% and 86% implementations are used to derive standalone emission reductions and costs. 34% implementation is used for combined emission reduction and costs.

studies. We use a uniform 4% interest rate for all analysed solutions. Assumptions are presented in Table 6.

The differing taxation for electricity used for heat production and the grid electricity emission factor cause cost and emission variation for the solutions between countries. Taxes included in the prices are current in 2019, other electricity price components are 2016-2018 averages from Eurostat. In Denmark, the electricity cost varies by solution, because the electricity tax is capped at 21.9 öre/kWh of heat produced. In Norway, heat pumps pay the industry tax rate, while in Sweden and Finland they pay the regular rate. We have assumed that in Iceland electric boilers and heat pumps would pay the industry tax rate. See Table 2 for resulted electricity prices by country. Table 7 presents the resulted heat production cost and emissions by country.

When scaling up the district heating solutions, we do not expect them to fully replace thermal heat production, but to operate alongside it. Therefore, we compare the levelised cost of the solution to the variable cost of the existing heat production, i.e. only the fuel cost and other variable operating costs. The fuel prices before taxes are presented in Table 3. Table 8 presents the fuel taxation rates retrieved from the tax authority of each country, variable O&M costs from VTT (2016) and the resulted variable production cost of the most common heat production technology for each fuel by country.

Scaling up

Each solution is scaled up individually in all district heating networks where there are fossil fuels to be replaced, and in Iceland within networks that cannot use geothermal heat. Even though solutions

Table 6: Assumptions for district heating solutions

	Unit	Waste water	Seawater	Solar thermal	Data centre waste heat	Geothermal
Interest rate	%	4	4	4	4	4
Lifetime	years	30	30	25*	30*	25**
Initial capital investment for heat pump facility	€/kW	500*	600	400*	600	500
Other initial capital investment				Solar collectors and pit heat storage 600 €/MWh/a*		1,400 €/kW geothermal heat** + 1.4 m€/site for screening and seismic analysis**
Annual maintenance cost		2% of initial investment	2% of initial investment	3 €/MWh solar* + 3 €/MWh heat pump* + 30,000 € for pit*	2% of initial investment	28 €/kW of geothermal heat** + 2 €/MWh** + 2% of initial investment for heat pumps
Heat pump COP		3.1*	3.2*	3.5*	4*	4.6**
Other					Assumed waste heat price 10 €/MWh	Pumps' electricity consumption 8% of heat generation**
Benchmark heat pump capacity	MW	42*	13.5*	1.5*	4*	6**
Benchmark system heat energy production	GWh	302*	67*	12.4*	20*	93**
Sources		Turun seudun puhdistamo, Motiva, Yle, Valor (2016)	Valor (2016), Star Renewable Energy	Marstal Fjernvarme (2014)	Valor (2016), Nivos	PlanEnergi (2017)

Numbers marked with * are true values for the benchmark case. Numbers marked with ** are taken from a local technology study.

Table 7: Emissions and levelised costs of heat pump solutions by country

		Unit	Denmark	Finland	Iceland	Norway	Sweden
Waste water	Cost	€/MWh	55	32	24	23	34
	Emissions	$kgCO_2/MWh$	67	38	3	3	4
Seawater	Cost	€/MWh	58	35	28	26	37
	Emissions	$kgCO_2/MWh$	66	37	3	3	4
Solar thermal	Cost	€/MWh	63	56		53	56
	Emissions	$kgCO_2/MWh$	20	11		1	1
Data centre waste heat	Cost	€/MWh	64	40	34	33	41
	Emissions	$kgCO_2/MWh$	52	29	2	2	3
Geothermal	Cost	€/MWh	52				
	Emissions	$kgCO_2/MWh$	39				

could also be used to reduce the use of biomass, this does not provide emission reductions from direct emissions point of view and we have not assessed this potential.

We have applied the following limitations to the solutions.

Waste water:
- Not scaled further in networks where waste water is already known to be used
- Maximum production of 8% of network heat demand (share in Turku)
- Maximum production together with existing ambient heat[31] of 63% of network heat demand

Seawater:
- Only applied to networks next to sea
- Maximum production of 67 GWh
- Maximum production together with existing ambient heat of 63% of network heat demand (current share in Drammen)

Solar thermal:
- Maximum production of 12.4 GWh
- Maximum production of 50% of network heat demand (share in Marstal)
- Maximum production together with existing ambient heat of 63% of network heat demand

Data centre waste heat:
- Maximum production together with existing ambient heat of 63% of network heat demand
- Average expected new data centre capacity by 2025 in the Nordic countries (2,580 MW; Nordic Council of Ministers, 2018) is allocated to countries based on historical allocation (Finland 17%, Sweden 44%, Norway 17%, Denmark 21%, Iceland 1%; Cloudscene). Note that the waste heat is treated as zero-emission and we have not assessed the emission implications of the electricity use by the new data centres
- New data centres assumed to be a minimum of 15 MW each (as in Mäntsälä), which according to the Mäntsälä benchmark equals 20 GWh of available district heat

Geothermal heat:
- No technical potential in Finland, Sweden or Norway or in the cold areas in Iceland
- 376 MW potential in 28 networks in Denmark (Ea energianalyse, 2015); this does not represent all Danish potential, but it is the best assessment available

The fuel use by network is available from Finnish Energy, the Swedish Energy Market Inspectorate, Norsk Fjernvarme and Iceland's National Energy Authority. There are some differences between these and official total district heating fuel use statistics, and we have scaled the fuel use by network to match the total fuel use. However, Dansk Fjernvarme only shares total heat production by network, not by fuel. We could pinpoint where coal CHP is used in Denmark, but the distribution of gas and oil between

31 Heat from heat pumps, excluding industrial waste heat.

Table 8: Emissions and variable costs of district heating incumbents by country

			Separate heat production		CHP		
		Unit	Gas	Oil	Coal CHP	Gas CHP	Peat CHP
Net efficiency		%	90	90	86	88	84
Net electricity production efficiency		%			30	48	28
Variable O&M cost		€/MWh fuel	0.8	0.8	1.9	0.8	1.3
Taxes	Denmark	€/MWh heat	29	29	19		
	Finland	€/MWh heat		27	17	8	2
	Norway	€/MWh heat	11	32			
	Sweden	€/MWh heat		48	33	14	0
Resulted total variable costs	**Denmark**	**€/MWh heat**	**60**	**71**	**42**		
	Finland	**€/MWh heat**		**69**	**41**	**46**	**32**
	Norway	**€/MWh heat**	**42**	**74**			
	Sweden	**€/MWh heat**		**90**	**56**	**51**	**30**
Resulted emissions		**kgCO_2/MWh heat**	**221**	**317**	**388**	**226**	**461**

Energy method used for CHP. See Table 3 for fuel price and emission assumptions and Table 2 for EU ETS allowance price assumption.

the networks was not possible for us to determine. We have then assumed that all networks have some gas, and this can result in overestimation of the emission reduction.

For some networks, summing up all the solutions can replace more than there are fossil fuels left or exceed the limit of 63% of ambient heat. To assess the total combined emission reduction and cost, we have in these cases applied the solutions in cost order: waste water, seawater, data centre waste heat and solar thermal. In Denmark, this assessment by network was not possible, but we have capped the total reductions so that they do not exceed the total fossil fuel use within all the networks.

Ground source heat pumps

Abatement

Ground source heat pumps (GSHPs) can replace oil or gas boilers or direct electric heating to reduce emissions. The emission reduction is the difference between the replaced alternative and the emissions related to the electricity use of the heat pumps, determined by the grid emission factor (see Table 2). For oil and gas, we have used the default fuel efficiencies from Statistics Finland (oil 78%, gas 90%). GSHPs have been assumed to have an average COP of three. The resulted emissions and GSHP abatement against each incumbent are presented in Table 9.

Cost

As the systems to be replaced are already in place and are not likely to have resale value, we compare the total levelised cost of the heat pump system to the fuel cost of the replaced alternative. Maintenance costs we assume to be lower or the same for heat pumps as for the incumbents and exclude them from the comparison.

The investment cost for GSHPs varies a lot depending on different factors. We assume an investment cost of approximately 1 € per kWh of annual heat production, a 20-year lifetime and a 4% interest rate. See Table 2 for the assumed electricity, gas and oil prices. The resulted costs and GSHP abatement cost against each incumbent are presented in Table 9.

Scaling up

In Stockholm, a third of detached houses have a ground source heat pump. We estimate that of the houses not connected to the district heating network the share is 36%, and this we use as our benchmark.

Based on household energy use data from Statistics Finland, the Swedish Energy Agency, Statistics Norway, the Danish Energy Agency and Iceland's National Energy Authority as well as default efficiency values and available estimates of heat pumps, electric heating share and appliance electricity use, we have estimated the heating type shares presented in Table 10. Based on these we estimate the baseline share of houses not connected to the district heating with a GSHP. This is 25% for Sweden, 5% for Finland and 7% for Denmark. For Norway, there is no recent data available on GSHPs, and we use the same value as for Finland. In Iceland we assume there are no GSHPs yet.

When scaling the GSHP share up to 36% in houses outside of district heating, we first replace oil heating, then gas heating and then direct electric heating.

Public transport in urban areas

Abatement

We assume the increased use of public transport to replace average urban car travel. As Helsinki purchases green electricity for rail transport, we do not account any emissions from that, and the emissions from public transport come from the diesel use of buses. The Helsinki public transport operator HSL reports that in 2017 the bus emissions were 60 gCO_2 per passenger-kilometre. Buses accounted for 35% of passenger-kilometres, so the total average emissions were 21 gCO_2/passenger-kilometre. We recognize that the applicability of different public transport modes varies by location but assume that the same emission intensity can be reached in areas where we scale the solution.

Average urban car travel data was only available for Finland (VTT/Lipasto), and therefore we have used the same values for all Nordic countries. Average fuel consumption in urban driving is 9 l/100km and related emissions 202 gCO_2/km. Average occupancy in urban driving 1.3 passengers per car, which translates into average emission of 155 gCO_2/passenger-kilometre.

Cost

HSL shared their total costs for this report. Including operational costs, overhead, infrastructure costs and the 10% VAT passengers pay on tickets, the total cost per passenger-kilometre equals 0.33 euros. This includes all costs to HSL and the municipalities, but government's support to investments is excluded.

We compare this to the total cost of average urban car travel in Finland. The average price (including purchase taxes) of a new car purchased in Finland

Table 9: Heating emissions and costs per MWh of heat by type and country

		Unit	Denmark	Finland	Iceland	Norway	Sweden
Ground source heat pump (GSHP)	Emissions	$kgCO_2$/MWh	69	39	3	3	4
	Levelised cost	€/MWh	143	107	96	105	116
Oil boiler	Emissions	$kgCO_2$/MWh	337	337		337	337
	Fuel cost	€/MWh	163	112		129	135
	GSHP abatement	**$kgCO_2$/MWh**	**268**	**298**		**335**	**333**
	GSHP abatement cost	**€/tCO_2**	**–73**	**–16**		**–72**	**–57**
Gas boiler	Emissions	$kgCO_2$/MWh	221	221			221
	Fuel cost	€/MWh	97	123			129
	GSHP abatement	**$kgCO_2$/MWh**	**152**	**182**			**217**
	GSHP abatement cost	**€/tCO_2**	**303**	**–86**			**–63**
Direct electric heating	Emissions	$kgCO_2$/MWh	208	117	9	8	12
	Electricity cost	€/MWh	222	114	80	108	139
	GSHP abatement	**$kgCO_2$/MWh**	**138**	**78**	**6**	**5**	**8**
	GSHP abatement cost	**€/tCO_2**	**–567**	**–91**	**2,710**	**–555**	**–2,859**

Table 10: Estimated heating shares for detached houses by country

	Unit	Denmark	Finland	Iceland	Norway	Sweden
Heat pumps (all types)	%	14	21	0	37	53
GSHPs	%	5	5	0	not available	22
Direct electric heating	%	7	33	3	48	19
Oil	%	6	10	0	4	1
Natural gas	%	17	0.3	0	0	1
Biomass	%	25	25	0	11	14
District heating	%	31	11	97	0	13
Total	TWh	31	24	5	25	42

has been very stable since 2008 at 34,000 euros and the average car lifetime is 20.6 years and average annual mileage 14,000 kilometres. We apply the same interest rate of 5% that HSL does for their own investments in order to make the results comparable. We assume insurance, maintenance costs and taxes to amount to 1,400 euros per year and fuel to cost 1.45 €/l (Statistics Finland, petrol). In urban driving the resulting cost is 0.42 €/km and 0.32 €/passenger-kilometre, making the abatement cost 80 €/tCO_2.

The data needed to calculate the abatement cost for each Nordic country was not available, so we use the same abatement cost for all. Note that Finnish car ownership costs are the cheapest of the Nordic countries due to the cheapest fuel, longest lifetime and annual mileage and below-average purchase price, so the abatement cost is on the conservative side for other countries.

Note also that the infrastructure cost for private cars is excluded from the comparison, as we assume that infrastructure to already be in place, whereas the required public transport infrastructure is assumed to be additional.

Scaling up

In Helsinki area 21% of travelled distance is made by public transport (Finnish Transport Infrastructure Agency, 2018), and we use this as our benchmark. We scale public transport use further only in functional urban areas (OECD, 2019).

Based on Trafikanalys (2017) travel survey and population weighting based on Sveriges Kommuner och Landsting (SKL) and Statistics Sweden, the public transport share in Stockholm, Malmö and Gothenburg areas is already 22%, which is slightly above the benchmark. Therefore, we scale the public transport further only in other functional urban areas in Sweden. Table 11 presents the baseline estimates.

Electric vehicles

Abatement

To determine the abatement and cost effect of electric vehicles, we try to eliminate all other variables and compare two vehicles of a same model with a different powertrain, the Volkswagen e-Golf with a 36 kWh battery and Volkswagen Golf Comfortline 1,5 TSI EVO 96 kW (130 hp) BLUEMOTION DSG automatic. We compare the production-based emissions, i.e. the tailpipe emissions of the gasoline Golf (6 l/100 km and 135 gCO_2/km in WLTP test) and the emissions related to the grid electricity consumed by the e-Golf (15.9 kWh/100 km; Volkswagen, 2019a). See Table 2 for electricity emission factors and Table 12 for the resulted emissions by country.

The lifecycle emissions of electric vehicles are often discussed, so we looked at them too for comparison. Volkswagen's (2019b) certified life cycle assessment states that the manufacturing emissions of a Golf TDI (Diesel) are 29 gCO_2/km, and the manufacturing emissions of an e-Golf 57 gCO_2/km, making the electric powertrain's additional emissions 28 gCO_2/km, when assessed for a lifecycle mileage of 150,000 km (Volkswagen, 2014). On the other hand, a lifecycle analysis must also take into account the emissions from extracting, refining and transporting the fuel needed for the use phase. For gasoline the lifecycle emission is 93 tCO_2/TJ (Edwards et al.,

Table 11: Population, daily travel distance and estimated baseline share of public transport in areas where public transport use is scaled up

	Unit	Denmark	Finland	Iceland	Norway	Sweden
Population in functional urban areas	thousand	3,120	3,000	223	2,460	1,680 (excl. Stockholm, Malmö and Gothenburg)
Average daily travel distance in urban areas	km/ person/ day	39	38	19	38	42
Current share of public transport in urban areas	%	4	15	4	8	13
Sources and notes		Transport DTU, OECD (2019). Daily distance and public transport share are national values, as urban values were not available.	Finnish Transport Infrastructure Agency (2018), OECD (2019)	Daily distance received from City of Reykjavik, based on Reykjavik's travel survey. 4% is public transport modal share, but we use it to approximate maximum share of distance. Population from Statistics Iceland.	TØI (2014), OECD (2019), population weighting based on Statistics Norway	Trafikanalys (2017), OECD (2019), population weighting based on SKL and Statistics Sweden. Distance and share in urban areas excluding Stockholm, Malmö and Gothenburg.

2017), which adds 38 gCO_2/km to the gasoline car emissions. Thereby, after manufacturing and fuel cycle emissions have been accounted for, the lifecycle emission reduction of an EV is 10 gCO_2/km larger than the production-based emission reduction.

Assessments of electricity lifecycle emissions are not readily available for the Nordic countries, but the additional emissions from electricity lifecycle are unlikely to make the EV lifecycle emission reduction much smaller than the production-based emission reduction. Based on international assessments, lifecycle emissions of the most common electricity production methods in the Nordic countries are around 26 gCO_2/kWh for hydro and wind, 29 gCO_2/kWh for nuclear and 45 gCO_2/kWh for biomass (World Nuclear Association, 2010). To bridge the 10 gCO_2/km gap between lifecycle and production-based comparison, the additional average electricity lifecycle emissions should be over 63 gCO_2/kWh.

Cost

We compare the total cost of ownership (TCO) for the two vehicles with different powertrains. We include a home charging station and an expected EV battery change in countries where the average lifetime of a car is above 15 years. We assume that a home charging station costs on average 3,000 € and that the battery cost will fall to 110 $/kWh by the time the battery change would be needed between 2025 and 2030 (Sitra & McKinsey, 2018). We use an interest rate of 4%. Cost assumptions are presented in Table 12.

Note that this assessment does not take into account any public infrastructure cost – we have assumed that public charging infrastructure can be operated profitably like the current transport fuel distribution infrastructure is.

Scaling up

12% of Oslo's car fleet in 2018 were battery electric vehicles (Statistics Norway). We scale the share of EVs in the vehicle fleet in each country to 12%. Baseline shares (Autoalan tiedotuskeskus, Statistics Sweden, Statistics Norway, Statistics Denmark, Statista, direct contact to Iceland Transport Authority) are presented in Table 12.

Table 12: Cost assumptions for petrol* and electric VW Golf, average car lifetime and mileage and current share of EVs in the Nordic countries

		Denmark		Finland		Iceland		Norway		Sweden	
	Unit	Petrol	BEV	Petrol	BEV	Petrol	BEV	Petrol	BEV	Petrol	BEV
PURCHASE COSTS											
Import price	€	19,774	34,089	19,774	34,089	19,774	34,089	19,774	34,089	19,774	34,089
VAT	%	25	25	24	24	24	0	25	0	25	25
Registration tax	€	10,586	0	3,334	1,102	36	0	6,361	0	2,627	2,627
Scrapping tax	€	0	0	0	0	0	0	248	248	0	0
Commodity tax	%	0	0	0	0	14	0	0	0	0	0
Home charger	€	0	3,000	0	3,000	0	3,000	0	3,000	0	3,000
Interest rate	%	4	4	4	4	4	4	4	4	4	4
USE											
Use taxes	€/a	319	88	135	141	91	91	300	300	67	34
Insurance	€/a	600	600	600	600	600	600	600	600	600	600
Maintenance	€/a	811	426	811	426	811	426	811	426	811	426
Battery change halfway through lifetime	€		3,470		3,470		0		3,470		3,470
Emissions	gCO_2/km	135	33	135	19	135	1	135	1	135	2
Average car lifetime	years	15.1	15.1	20.6	20.6	13.4	13.4	17.8	17.8	18	18
Average mileage	km/a	12,882	12,882	14,000	14,000	12,730	12,730	12,390	12,390	12,000	12,000
END OF LIFE											
Scrapping cost	€	–295	–295	0	0	3	3	0	0	0	0
BASELINE											
Current share of EVs	%		0.3		0.1		1.2		7.1		0.3
RESULTED TCO AND EMISSION REDUCTION											
Total cost of ownership per km	**€/km**	**0.47**	**0.46**	**0.34**	**0.35**	**0.43**	**0.39**	**0.44**	**0.38**	**0.39**	**0.41**
Emission reduction per vehicle	**tCO_2/car/a**		**1.3**		**1.6**		**1.7**		**1.7**		**1.6**

See Tables 2 and 3 for petrol and electricity cost and emissions assumptions
* Volkswagen Golf Comfortline 1.5 TSI EVO 96 kW (130 hp) BLUEMOTION DSG automatic

Cycling in urban areas

Abatement

Cycling does not produce emissions. We assume that 50% of the increased cycling comes from urban car travel, which emits on average 155 gCO_2/passenger-km (see the section for public transport). The other half we assume to replace public transport and walking, which we don't assume to reduce emissions here but simply to reduce the occupation rate of public transport. Thereby a cycled kilometre reduces emissions on average by 78 gCO_2/km.

Cost

The cost of increased cycling is assumed to be the cost of cycling infrastructure and other cycling-related initiatives. Investments in cycling-related initiatives in Copenhagen were DKK 2.07 bn between 2004-2017 (Cycling Embassy of Denmark, 2016a), or 20 m€ per year. In Copenhagen the inhabitants cycle on average 3 km per day (Cycling Embassy of Denmark, 2016b), making the cost of cycling 0.03 €/km.

We assume that cycling does not fully replace car ownership, and in the cost comparison we only account for the cost of fuel saved by cycling. In urban car travel the fuel consumption is 9 l/100 km, or 6.9 l/100 passenger kilometres with an occupancy of 1.3 (see the section for public transport). We assume 60% of replaced driving to use petrol and 40% to use diesel, see Table 2 for fuel prices. As half of increased cycling is assumed to replace something else than car travel and not to bring any savings, the savings from the replaced alternatives are on average 0.05-0.06 € per kilometre cycled, depending on the fuel prices in each country.

Scaling up

We use Copenhagen's 3 km of cycling per person per day as a benchmark. We scale cycling in functional urban areas (OECD, 2019), similarly to the public transport solution. Table 13 presents the baseline.

Electric ferries

Abatement

The abatement is calculated by comparing the emissions related to the electricity used by the electric ferries with the avoided diesel combustion. Ampere uses 150 kWh of electricity per 5.7 km crossing (BBC 4 April 2017) and displaces 1 million litres of diesel in a year (Ship Technology), corresponding to 810 tonnes. Ampere has 34 crossings per day, and assuming that is every day of the year, Ampere uses 1.9 GWh of electricity per year. This means that 1.9 kWh of electrical propulsion is needed to replace one litre of diesel. This is less than the actual energy content of diesel, because electric ferries are significantly lighter than traditional diesel ferries and electric motors have better energy efficiency compared to combustion engines.

Siemens (2015 and 2016) has assessed that Norway has 84 and Denmark 39 ferries that would be more profitable if replaced with electric ferries. In Norway an

Table 13: Population and estimated baseline distance of cycling in areas where cycling is scaled up

	Unit	Denmark	Finland	Iceland	Norway	Sweden
Population in functional urban areas	thousand	3,120	3,000	223	2,460	5,440
Current cycling in urban areas	km/ person/ day	1.8	0.8	0.6	0.9	0.6
Sources		Cycling Embassy of Denmark, OECD (2019), population weighting based on Statistics Denmark	Finnish Transport Infrastructure Agency (2018), OECD (2019)	Cycling data unavailable for Iceland, we use the same baseline as for Sweden. Population from Statistics Iceland.	TØI (2014), OECD (2019), population weighting based on Statistics Norway	Trafikanalys (2017), OECD (2019), population weighting based on SKL, Statistics Sweden

average diesel displacement per ferry is 1060 tonnes/a and in Denmark 487 tonnes/a, presumably due to shorter connections or smaller capacities in Denmark.

Cost

Siemens (2015 and 2016) has calculated that the additional investment needed per electric ferry compared to a diesel ferry is 4.6 m€ in Norway and 1.4 m€ in Denmark. We assume the lifetime of the ferries to be 50 years and use an interest rate of 4%. The diesel that ferries use is tax free. Electricity for ferries is fully taxed in Finland and in Sweden, in Norway ferries pay the industry tax rate and in Denmark ferries do not pay taxes except for the PSO levy. See Table 2 for the resulted diesel and electricity prices by country. The maintenance costs are lower for electric than for diesel ferries and we exclude them from the comparison.

Scaling up

Siemens (2016) states that connections below 60 minutes and 2,000 kWh of average energy consumption are suitable for electrification.

We only consider the electrification of ferries that carry cars. Sweden has 70 ferries (Trafikverket, 2019), and based on crossing distances and times (Färjerederiet) they are all suitable for electrification. In Finland we estimate there are 41 ferries suitable for electrification (Finferries). In Iceland there are two suitable connections. Some of these have already been electrified (see Table 14). The crossings in Sweden, Finland and Iceland are on average significantly shorter than for Ampere, so we assume that the Danish average diesel displacement and investment is better suited to their estimation than Norway's.

Table 14 presents the emission reduction and levelised cost difference per ferry as well as ferries remaining to be electrified by country.

Biogas from food waste

Abatement

We assume the abatement effect of biogas to come from the replacement of fossil transport fuels and the avoided methane emissions when compared with landfilling the biowaste. Anaerobic digestion with gas upgrade (i.e. transport biogas production), composting and incineration for energy we assume not to cause emissions or abatement on their own.

However, it should be noted that depending on the technology used, there are in fact varying amounts of methane leaks in biogas plants, most notably from the digestate during storage and the upgrading process of biogas, and the greenhouse gas balance is also affected by the energy used by the process. According to EUR-Lex Document 32018L2001, the typical life-cycle emission reduction of biogas compared to fossil transport fuels is between 43% (open digestate storage, no upgrading off-gas combustion) and 86% (closed digestate storage and upgrading off-gas combustion).

In 2013 the Oslo biogas plant received 7,300 tonnes of biowaste and produced 700,000 Nm^3 or 6.9 GWh

Table 14: Emission reduction, cost and ferries remaining to be electrified by country

	Unit	Denmark	Finland	Iceland	Norway	Sweden
Average electricity use	GWh/ ferry/a	1.1	1.1	1.1	2.4	1.1
Average diesel displacement	t/ferry/a	487	487	487	1,060	487
Average emission reduction	tCO_2/ ferry/a	1,136	1,237	1,359	2,957	1,355
Average levelised cost difference between electric and diesel ferry	k€/ferry/a	–149	–143	–153	–290	–128
Ferries suitable for electrification	pcs	39	41	2	85	70
Existing electric ferries	pcs	0	1	1	8	0
Ferries remaining to be electrified	pcs	39	40	1	77	70

of transport grade biogas and 1,200 tonnes of biofertiliser (City of Oslo Waste-to-Energy Agency). A tonne of biowaste can therefore produce 927 kWh of transport biogas. We assume the efficiency of gas to be 82% of the diesel efficiency as fuel. Thereby each kWh of biogas cuts emissions from diesel by 194 gCO_2 and each tonne of biowaste processed into biogas cuts emissions by 180 $kgCO_2$. Note that we exclude the biofertiliser emission reduction effect from this calculation.

In Iceland, biowaste is still landfilled but combined with a landfill gas capture and vehicle fuel upgrade system. Each tonne (wet weight) of biowaste on average has the potential to produce 204 Nm^3 of biogas, of which 63% is methane (Swedish Gas Technology Centre, 2012), a greenhouse gas that on a 100-year time horizon has a global warming potential of 28 times that of CO_2 (IPCC AR5). We assume that 70% of the landfill gas is captured (VTT, 2002), of which 43% is flared and rest upgraded to transport fuel (Álfsnes landfill in Reykjavik; Nordic Council of Ministers, 2014). In total 40% of the produced methane or 497 kWh per tonne of biowaste ends up as a transport fuel and reduces transport emissions by the abovementioned 194 gCO_2/kWh or by 97 $kgCO_2$/tonne of biowaste. The methane emissions of the uncaptured 30% of landfill gas amount to 772 $kgCO_2e$/tonne of biowaste. In total, landfilling with gas capture and upgrade produces emissions of 676 $kgCO_2e$/tonne of biowaste.

Cost

Sund Energy (2010) estimates that the production, upgrading and distribution cost of biogas from semi-liquid waste with complex technology is 0.76-1.5 SEK/kWh, the average being 0.11 €/kWh or 99 €/tonne of biowaste. Østfoldforskning (2019) states that compressed biogas price after production and distribution costs in Norway is 0.56-1.49 NOK/kWh, the average being 0.11 €/kWh or 98 €/tonne of biowaste. The income for biofertiliser we assume to be 30 €/tonne of biofertiliser (Aui, 2018), or 5 €/tonne of biowaste. The total net cost of biogas production is therefore –4 €/tonne of biowaste, including the income from end products.

Hogg (2002) estimates that the cost of composting is 53 €/tonne of biowaste while the income from the sale of compost is 10 €/tonne of biowaste, making the total net treatment cost 43 €/tonne of biowaste. For incineration with energy recovery Hogg estimates a cost of 121 €/tonne of biowaste and an income of 16 €/tonne of biowaste, making the total treatment net cost 105 €/tonne of biowaste.

Landfilling cost Hogg estimates as 29 €/tonne of biowaste. VTT (2002) estimates that the cost of landfill gas capture is 3.4-4.5 €/MWh. Nordic Council of Ministers (2014) estimates that the annualised cost of Álfsnes gas upgrading plant is 307,000 € with an annual production of 2,000,000 Nm^3. Distribution cost is 0.2 SEK/kWh according to Sund Energy (2010). In total the cost per tonne of biowaste is 50 € and the income from biogas is 53 €, making the total

Table 15: Cost and emissions of different biowaste treatment alternatives

	Unit	Composting	Incineration with energy recovery	Landfilling with gas capture and upgrade	Anaerobic digestion and gas upgrade
Treatment cost	€/tonne of biowaste	53	121	50	99
Income	€/tonne of biowaste	10	16	53	103
Net cost	€/tonne of biowaste	43	105	–3	–4
Emissions	$kgCO_2$/tonne of biowaste	0	0	676	–180
SWITCH TO ANAEROBIC DIGESTION AND GAS UPGRADE					
Emission reduction	**$kgCO_2$/tonne of biowaste**	**180**	**180**	**856**	
Abatement cost	**€/tCO_2**	**–260**	**-604**	**–1**	

net cost −3 €/tonne of biowaste. Table 15 presents a summary of the costs and emissions of different biowaste treatment alternatives.

This calculation assumes that switching to biogas vehicles does not bring net costs or savings. Biogas vehicles are somewhat more expensive than conventional ones, but biogas as a fuel brings savings, particularly if the fuel is exempt from taxes like it is in the Nordics, bringing the cost to the same level. However, it tends to be necessary for a public transport operator to build their own refuelling station, which can raise the costs.

Scaling up

In Oslo, 45% of household food waste is separately collected and processed into biogas (City of Oslo, waste and recycling statistics). We use this as our benchmark. When scaling, we first redirect the separately collected food waste to biogas production and then increase the share of biowaste that is separately collected. We estimate that in Finland and Sweden the separately collected biowaste share is already around 50%, and the increased share of biogas is thus assumed to come from current composting. In Norway, Denmark and Iceland, separate collection of biowaste must be stepped up to reach Oslo's 45% share, and thus also the current incineration practices and landfilling in the case of Iceland will be reduced. Table 16 presents the estimated current and scaled biowaste treatment shares and associated costs and emissions.

Reduction of retail food waste

Abatement

Avoided food waste reduces emissions, if less food is produced because of it. We assume that the emission reduction of avoided food waste equals the climate impact of that food. We also assume that the donated food follows the distribution of average grocery consumption and that the grocery consumption patterns are similar in all Nordic countries. We have used Finland's distribution for all. Table 17 presents the consumption distribution and the climate impact of each food product group.

Before the Shared Table model the food donations in the capital region amounted to 2.3 kg per person (Nordic Council of Ministers, 2014b). Now they are on average 3.3 kg per person in Vantaa, meaning an increase of 1 kg (Halme et al. 2018).

Cost

We compare the costs of the food collection and distribution with avoided biowaste fees and avoided need to buy the same food. The average prices of food product groups are presented in Table 17.

Vantaa has invested 500,000 € in a terminal where the food is collected and distributed to different organisations. In addition, the yearly costs of the operation are 550,000 €. An average of 725,000 kilos of surplus food have been delivered annually. The savings in biowaste fees to the donating stores are 100,00 €/a. (Halme et al. 2018)

We have assumed an interest rate of 4% and a lifetime of 30 years for the terminal. Per delivered kilo the capital costs are 0.04 €, operational costs 0.76 €, biowaste fees savings 0.14 € and avoided food cost 2.47 €, totalling savings of 1.81 € per kilo.

Scaling up

Donation data from other municipalities or countries is not available, and we simply assume that everyone can decrease their food waste by one kilo per person.

Table 16: Estimated current and scaled biowaste treatment shares and associated costs and emissions by country

	Unit	Denmark	Finland	Iceland	Norway	Sweden
CURRENT						
Total household food waste	kt/a	674	830	40	481	888
Share separately collected	%	6	52	0	42	49
Share included in mixed household waste	%	94	48	100	58	50
Share anaerobically digested	%	6	16	0	24	39
Share composted	%	0	32	0	16	10
Share incinerated with energy recovery	%	94	52	0	60	50
Share landfilled	%	0	1	100	0	0
Emissions	$ktCO_2/a$	–7	–19	27	–21	–63
Net cost	m€/a	66.5	56.0	–0.12	33.2	49.5
SCALED UP TO OSLO'S LEVEL						
Share separately collected	%	45	52	45	45	49
Share included in mixed household waste	%	55	48	55	55	50
Share anaerobically digested	%	45	45	45	45	45
Share composted	%		2		0	4
Share incinerated with energy recovery	%	55	52		55	50
Share landfilled	%		1	55		
Emissions	$ktCO_2/a$	–55	–63	12	–39	–72
Net cost	m€/a	37.7	44.6	–0.14	26.9	47.1
Sources for total food waste and current treatment shares		Statistics Denmark, Environmental Protection Agency (2017). Distribution of composting and digestion not available, we assume all digested	Statistics Finland, Suomen Kiertovoima (biowaste share in mixed waste 33%). Includes all municipal biowaste.	Statistics Iceland. Share of food waste not available, we assume 33% of household waste	Statistics Norway. Total amount of household food waste not available, we assume the same as for Oslo (89 kg/ person/a)	Naturvårdsverket (2018). Includes all municipal food waste (not sewage). Assumed that share digested or composted is separately collected.

Table 17: Consumption distribution, climate impact and price of each food product group

Product group	Consumption	Share of consumption	Climate impact	Price
	kg/person	%	kgCO_2e/kg	€/kg
Milk	156	28	1	1.0
Cheese	26	5	13	14.2
Butter	4	1	3	6.1
Sugar	29	5	1.1	0.8
Meat	81	14	5	4.3
Grains	79	14	0.5	2.9
Potatoes	46	8	0.2	0.9
Fruits	65	12	0.2	1.6
Vegetables	65	12	0.2	0.9
Eggs	12	2	2.5	3.4
Total	**563**	**100**	**1.9**	**2.5**
Source	Natural Resources Institute Finland		Nissinen et al. (2010)	Statistics Finland

Appendix II: Project background

The Nordic Green to Scale for Cities and Communities project was launched by the Finnish Innovation Fund Sitra (sitra.fi/en). Sitra served as the project secretariat and contributed both financial and in-kind resources.

Core funding was kindly provided by the Nordic Council of Ministers (NCM) Climate and Air Pollution Group KoL. The project is also included in the Nordic Prime Ministers' Initiative, Nordic Solutions to Global Challenges.

The project steering group consisted of representatives of Nordic partner institutions: Frode Longva from CICERO Centre for International Climate Research, Jarl Krausing from CONCITO, Anna Maria Gran from NCM Nordic Climate and Air Pollution group, Oliver Johnson from Stockholm Environment Institute, Brynhildur Davíðsdóttir from the Institute for Sustainability Studies at the University of Iceland and Mikkel Petersen from C40 Cities. NCM Climate and Air Pollution Group doubled as an advisory council to the project, providing further guidance.

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Nordic Green to Scale for Cities and Communities builds on three earlier phases of the project. In 2015, Green to Scale analysed the potential of 17 climate solutions globally. In 2016, Nordic Green to Scale looked at applying 15 Nordic climate solutions in comparable countries around the world. In 2018 Nordic Green to Scale for Countries focused on applying the Nordic solutions to specific countries: Estonia, Latvia, Lithuania, Poland, Ukraine, Kenya and Ethiopia.

Reports, other material and further information can be found online at greentoscale.net. If you would like to know more, do not hesitate to contact the project secretariat (greentoscale.net/#contact-us). Please also let us know if you are interested in exploring possibilities for co-operation.

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Nordic Green to Scale

Green to Scale is a series of analysis projects that have highlighted the potential of scaling up existing climate solutions. Nordic Green to Scale for Cities and Communities analyses proven climate solutions from Nordic cities and municipalities. This report presents the emission reduction potential of 14 selected solutions. The study highlights the costs, savings and co-benefits of implementing the solutions as well as makes policy recommendations for capturing the potential. The project was carried out by the Finnish Innovation Fund Sitra, together with its partners CICERO, CONCITO, Stockholm Environment Institute, Institute of Sustainability Studies at the University of Iceland and C40 Cities. The project is part of the Nordic Council of Ministers' Prime Ministers' Initiative Nordic Solutions to Global Challenges.