# Clean district heating - how can it work?

**Highlights:**

- **Fossil fuels in district heating systems can be replaced mainly by a combination of wind power, heat pumps and heat storages.**
- **Such district heating and cooling systems also help to balance the increasing shares of variable wind and solar power in the energy system.**
- **Clean electricity production must increase significantly to replace the use of fossil fuels in the heating sector.**

***This discussion paper aims to illustrate, how fossil fuel-free district heating and cooling networks can be achieved by the electrification of the heating system. We describe, how district heating systems can operate mainly with heat pumps using wind power and ambient heat as primary energy sources. Biofuels in combined heat and power production will serve as the main complementary energy source. We also explain how the variability of electricity production and peaks in the demand of energy can be managed with heat storages, demand response and flexible production.***

***This is a major transition that affects all parts of the energy system. In the end of this paper we list some challenges that need to be resolved in the transition period; and point out how the social acceptance of wind energy can be promoted.***

***We hope this discussion paper will enrich the ongoing discussion in Finland about the decarbonization of the district heating systems, about the policies needed to enhance this transition and the ways how Finland could better benefit from it.***

## Content

# Electrification of the heating and transport sectors enables the replacement of fossil fuels

In Finland 40% of the total energy consumption including electricity, heating, transport and industry (Figure 1) is still based on fossil fuels.[1] Apart from transport and industry, many district heating networks in Finland are major users of fossil fuels.[2] As all fossil fuels should be phased out before 2040[3], new solutions for district heating are needed.

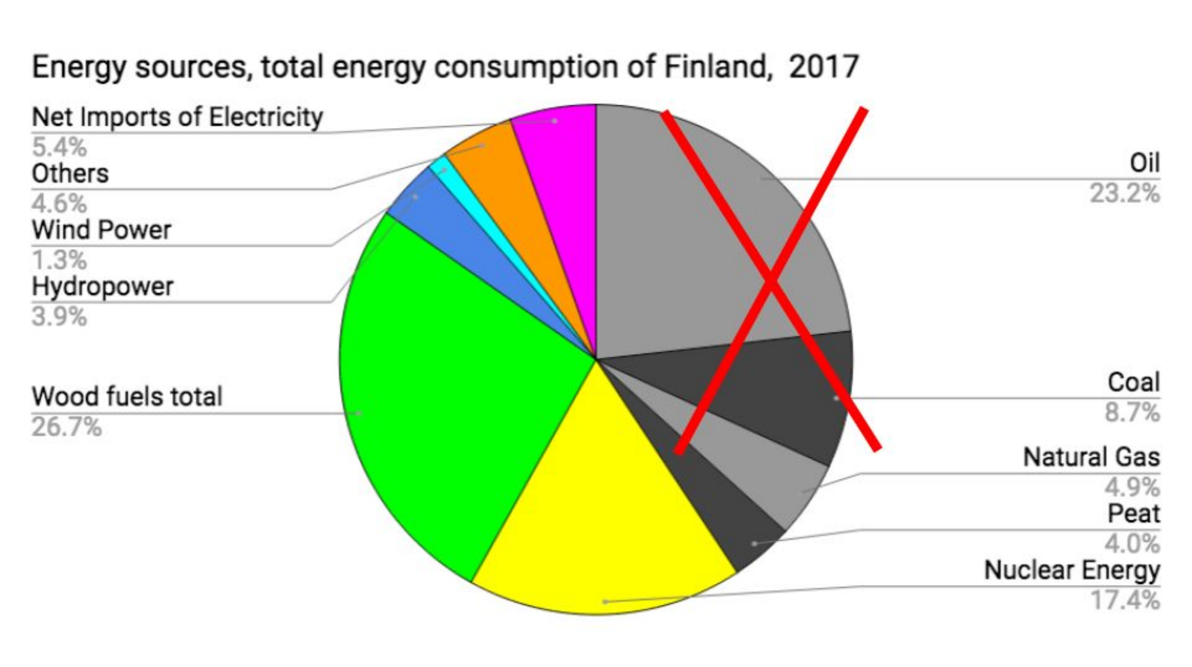


**Figure 1: Primary energy sources in Finland 2017. All fossil fuels should be replaced by clean energy sources.**

[1] Official Statistics of Finland: Energy supply and consumption [e-publication]. ISSN=1799-7976. Statistics Finland [referred: 16.11.2018]. Available: http://www.stat.fi/til/ehk/tup_en.html
[2] Finnish energy (2018). Kaukolämpötilasto 2017. Available: https://energia.fi/ajankohtaista_ja_materiaalipankki/materiaalipankki/kaukolampotilasto.html#material-view
[3] Seppälä Jyri (2018). Presentation: Suomen päästövähennyspolku hiilineutraaliksi jo 2035? Available: https://www.ilmastopaneeli.fi/tiedotteet/suomen-ilmastopolitiikalle-lisaa-kunnianhimoa-15-asteen-tavoitteeseen-suomen-ilmastopaneelin-seminaari-9-11-2018/

The Finnish Government aims to ban coal in power and heating production by 2029[4] as one step towards carbon-neutrality.

Fossil fuels can be replaced mainly by electricity-generating technologies using wind, solar, biofuels and nuclear as primary energy sources. This means that a higher degree of electrification is needed in both heating and transport sectors. Heating systems are increasingly integrating with electricity systems and markets. Therefore, after presenting the clean district heating and cooling system vision, which builds mainly on wind power, heat pumps and heat storages, we also present - for discussion - a 100% fossil fuel-free energy scenario for the whole energy system.

**The falling price of clean technologies is the main driver disrupting the fossil-fuel based energy system, in addition to climate change mitigation and environmental policies.**

# Clean district heating and cooling system - how can it work?

The following concept for clean district heating and cooling consists of multiple renewable energy sources, co-generation of heating and cooling, as well as energy storage technologies in both the district heating network and in buildings. The envisioned system is summarized in Figure 2. Already today, IT systems with smart control and automation functionalities can connect renewable energy units, storages and buildings in a way that allows total phasing-out of fossil fuels from the heating systems of cities even in the Nordic region.

[4] Ministry of Employment and the Economy, 2018. Press release: Legislative proposals: coal ban in 2029, more transport biofuels and more biofuel oil for heating and machinery. Available: https://tem.fi/en/article/-/asset_publisher/lakiehdotukset-kivihiilikielto-2029-lisaa-biopolttoaineita-liikenteeseen-seka-biopolttooljya-lammitykseen-ja-tyokoneisiin

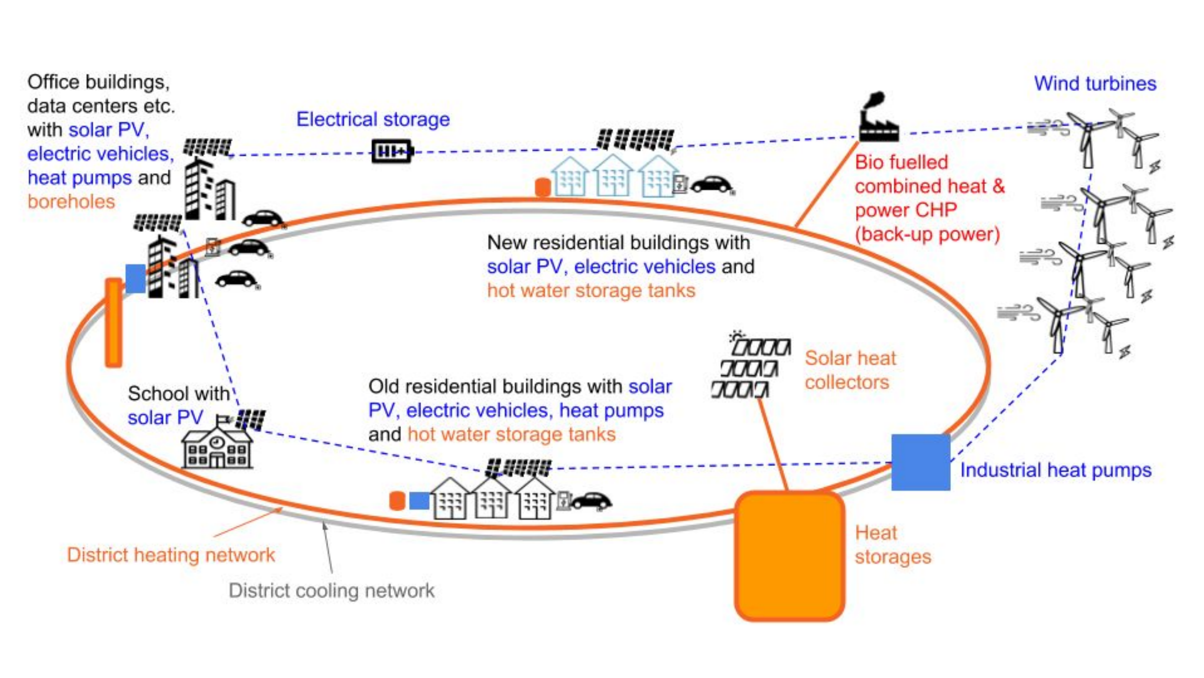


**Figure 2: Fossil fuel-free district heating and cooling system**

In the following section the main components of the 100 % fossil fuel-free district heating and cooling system are described. The system is based on a high level of electrification. It has flexibility solutions to solve the seasonal, weekly and daily mismatch of energy production and demand, sufficiently high temperature supply for the buildings, and balancing the electricity and heat markets.

## Technologies and solutions

### Heat pumps

Heat pumps are power-to-heat conversion technologies. Their size can vary from industrial to various building-scale solutions. Heat pumps can simultaneously produce both heating and cooling and thus feed both heating and cooling networks. This is essential in today's cities where many buildings, such as offices, schools, restaurants, cinemas and shopping malls, often require cooling also during the winter due to high internal heat gains. During summers, simultaneous heating and cooling are needed for sanitary hot water and space cooling.

Heat pumps consume electricity for approximately 15-50% of the heat or cooling produced. Also other parts of the system such as electric resistances, pumps and valves require electricity. Heat pumps produce fossil fuel-free heating, if this electricity is produced without fossil fuels, as is the case with wind, solar, hydro, nuclear or biomass-based power.

**Industrial heat pumps**

District heating can be supplied by industrial heat pumps, which can collect their main energy from the ground, lake, sea, air and from different excess heat sources like wastewater treatment plants, data centers, industrial processes, large bakeries, supermarkets and buildings. This allows the reuse of low temperature excess heat, which until now has mostly been wasted. For example, in the Finnish municipality of Mäntsälä, the excess heat from the Yandex data center produces after the ongoing upgrade[5] up to 80% of the district heating annually.[6]

**Heat pumps in buildings**

Various types and sizes of heat pumps can be installed in buildings depending on the end-use. The following examples illustrate the versatility of heat pumps.

Ground source heat pumps (GSHP) can be installed in shopping malls and large office buildings for supplying cooling and heating directly to the building during the opening hours. During weekends and holidays the heating and cooling can be produced to district networks.

Heat pumps for public buildings and housing companies can be designed sufficiently large to produce heat also to district heating and cooling networks in a two-directional way. In this case the boreholes can also be used as heat storages, storing heat during the summertime cooling.

Exhaust heat pumps can be installed in old buildings, where the ventilation system has only outtake channels, as auxiliary heating source. Air to air heat pumps can be installed in residential buildings, nurseries, stores etc. for cooling and auxiliary heating. Air to water heat pumps can be installed in all kinds of buildings for water heating.

[5] Gigabit. 8.5.2018. Article: How Yandex is heating a Finnish city with its data centre's surplus energy. Referred 22.11.2018. Available: https://www.gigabitmagazine.com/company/how-yandex-heating-finnish-city-its-data-centres-surplus-energy#
[6] Porkka Antti, Calefa Oy (2018). Interview 30.10.2018.

**FREQUENTLY ASKED QUESTION:**

**“Can heat pumps provide a sufficiently high temperature to district heating networks and old buildings?”**

Currently the temperature of district heating water in the supply pipe varies according to the weather between 65 and 115 ºC and in the return pipe usually between 40 and 60 °C.[7] In southern Finland the temperature stays 85% of the time below 85 °C in the supply pipes.[8] During very cold days, the temperature in district heating networks may need to be raised up to 120 ºC.[9]

High output temperature is technically possible for heat pumps, but it decreases the efficiency of the heat pumps. The efficiency - or coefficient of performance (COP) value - of the heat pumps depends on the difference of temperature of the heat source and the required heating temperature. If the temperature difference is small, the heat pumps can work very efficiently with COP value 7 using electricity only for 15% of the heat produced. Viceversa, if the output temperature needs to be very high, the heat pump’s efficiency decreases to COP value 2 and it needs 50% of electricity. Heat pumps can supply heat to approximately 90 °C, when the temperature of the heat source is round 10 °C degrees. For example, the temperature increase of about 70 °C from seawater, can be achieved efficiently with an approximate COP value of 2,8[10].

High temperature heat pumps can produce heating to high temperature district heating networks, but lowering the temperature of the network would benefit the whole energy system improving the overall resource and cost efficiency. Excess heat reuse improves energy efficiency on a system level[11]. Therefore, it is advantageous to aim at lower temperatures in the district heating networks over time.

Several solutions exist to resolve the challenge of providing sufficient heating for the old buildings, if the network temperature is lower. For example, the supply temperature can be boosted in the buildings with heat pumps and hot water tanks equipped with smart electric resistances.

[7] Finnish Energy (2018). Article: Almost 15,000 km of district heating networks. Referred 22.11.2018. Available: https://energia.fi/en/energy_sector_in_finland/energy_networks/district_heating_networks

[8] Porkka Antti, Calefa Oy (2018). Presentation: Reuse of Data Center Waste Heat Case Mäntsälä. Available: https://www.slideshare.net/SmartEnergyTransition/reuse-of-data-center-waste-heat-case-mnstl

[9] Lauri Laaksonen (2018). Diplomityö: KAUKOLÄMMÖN MENOVEDEN LÄMPÖTILAN TALOUDELLINEN OPTIMOINTI. Saatavissa: https://lutpub.lut.fi/bitstream/handle/10024/158481/Diplomityo_laaksonen_lauri.pdf?sequence=1&isAllowed=y

[10] More info in e.g. Arpagaus C, Bless F, Uhlmann M, Schiffmann J & Bertsch S S (2018). High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. Energy 152, 985-1010. Available: https://www.sciencedirect.com/science/article/pii/S0360544218305759

[11] Mikko Wahlroos et. al. (2017). Utilizing data center waste heat in district heating – Impacts on energy efficiency and prospects for low-temperature district heating networks. Energy. Available: https://www.sciencedirect.com/science/article/pii/S0360544217314548

## Wind and solar power

The electricity needed by the heat pumps can be produced mainly by wind power. During the summer when cooling is needed, solar photovoltaics (PV) can be used to feed electricity to the heat pumps. Solar PV panels can be installed both in public and residential buildings mainly designed in a way to allow the use of the produced electricity on site. Also utility scale installations can emerge following the trend of declining solar PV prices and evolving business models around solar energy utilization[12].

These production methods balance the seasonal variation somewhat: solar energy production is higher during the summer and wind production is usually higher during the winter (Figure 3). The mismatch between solar PV production and daily demand curve of electricity is not as severe as often assumed.

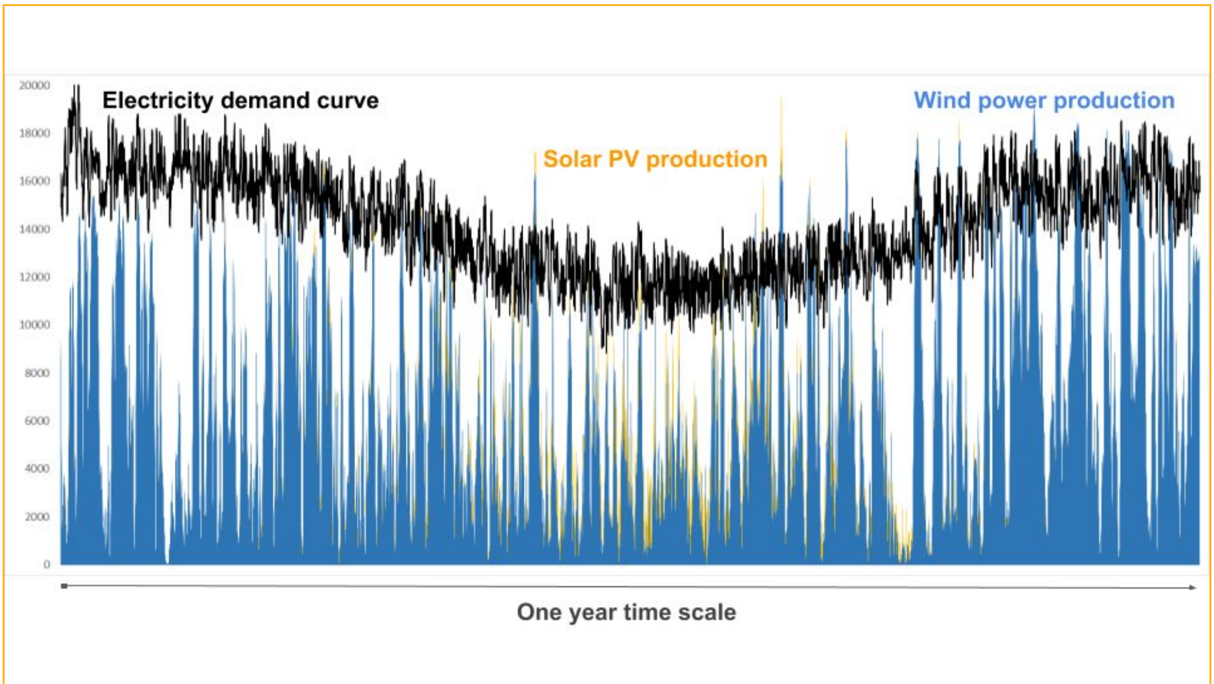


**Figure 3: Wind and solar production complement each other during a year, as there is more wind during the winter and more sun during the summer**

## Heat storages and demand response automation

Heat storages are essential in the fossil fuel-free district heating system due to the variable wind and solar power production, and the fluctuation of electricity prices. These variations have different rhythms - from seconds to months - and therefore different storages and demand response solutions are needed (Figure 4).

[12] IEA PVPS (2018). Trends 2018 in Photovoltaic Power Applications. Available: www.iea-pvps.org

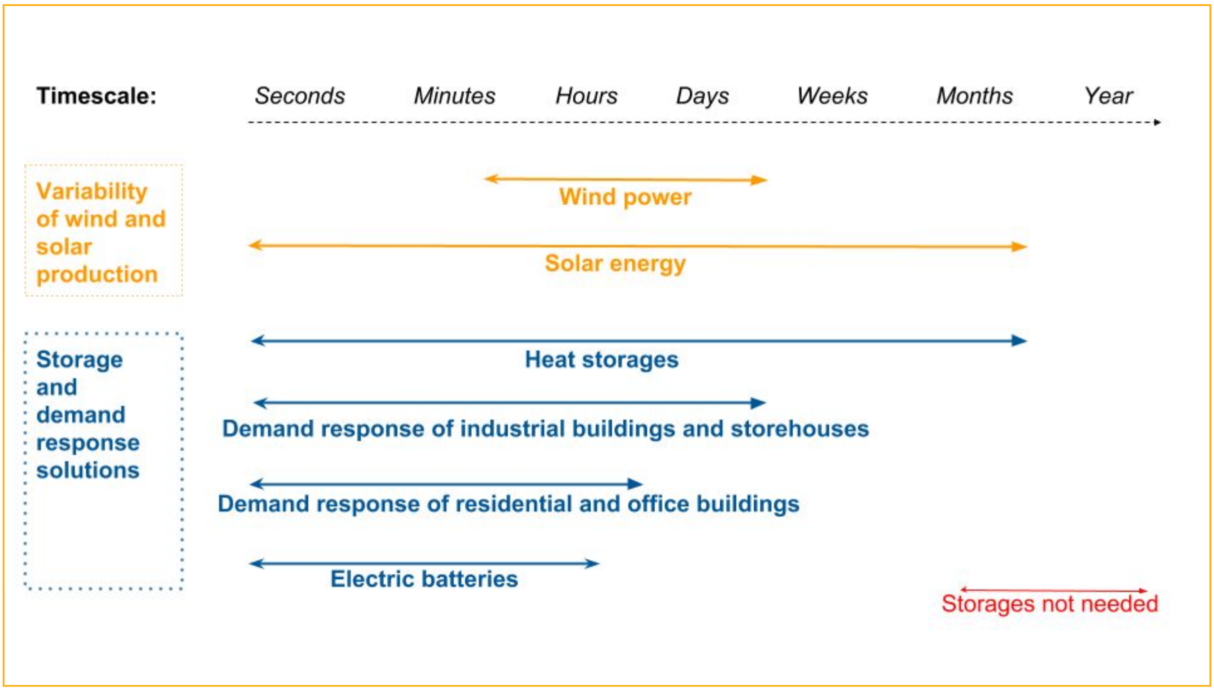


**Figure 4: Different storages and demand response solutions offer the flexibility needed because of the variable wind and solar power production**

Earth pits, old oil caverns, borehole fields, large water tanks etc. can be used as heat storages offering a significant backup potential. In general, one cubic meter of water stores 40 kilowatt hours of heat (kWh/m$^3$). Heat storages can be constructed for example in parks (underground), industrial zones, and city suburbs. The heat storages in district heating networks offer affordable flexibility potential for the clean energy system, as the cost of heat storage capacity is approximately e.g. 4000 euros/MWh,[13] and even lower if the storage infrastructure already exists[14]. The electric battery capacity costs can be, for example 400 000 euros/MWh (400 euros/kWh) or even much more[15]. (The output energy price of the storages is the capacity cost divided by the amount of cycles during the storage's lifetime.)

Both energy storage forms are needed, but they have very different roles in balancing the energy system (Figure 3). Due to the high, but declining prices of electric batteries, we assume in the scenario that most of the electric battery capacity will emerge from the electric vehicles.

[13] D. Mangold, T. Schmidt (2010). The next Generations of Seasonal Thermal Energy Storage in Germany. Available: http://www.solites.de/download/literatur/07-Mangold_ESTEC%202007.pdf
[14] Helen Oy (2018). News: JÄTTIMÄINEN LUOLALÄMPÖVARASTO TOTEUTETAAN HELSINGIN MUSTIKKAMAALLE. Accessed 25.11.2018. Available: https://www.helen.fi/uutiset/2018/mustikkamaa_toteutus/
[15] Helen Oy (2015). News: HELSINKIIN POHJOISMAIDEN SUURIN SÄHKÖVARASTO. Available: https://www.helen.fi/uutiset/2015/helsinkiin-pohjoismaiden-suurin-sahkovarasto/ and example from electric battery in detached house size class: Photovoltaic4all (2018). Axitec AXIstorage Li 7s lithium-ion storage. Referred 25.11.2018. Available: https://www.photovoltaik4all.de/axtec-axistorage-li-7s-lithium-ionen-speicher?number=AXI25573

Large and centralized heat storages[16], as well as short term heat storages in buildings, can be charged when the electricity price is negative or very low for example during peak wind power or solar energy production periods. The heat storages are then discharged during peak heat and electricity demand times. Short term heat storages in buildings and electrical storages with demand response automation will allow renewable energy to be shifted several hours, solving the daily mismatch of demand and production curves. Large heat storages can solve the mismatch of demand and production curves during days, weeks or even months.

### Solar heat collectors

Additional heat sources for the clean district heating system are solar heat collectors, which are most favourably built as plants next to the seasonal heat storages in places where the value of the land is low. Solar heating plants can charge the heat storages during summer time. The solar heat can also be directly delivered to heat pumps supporting them to reach sufficiently high temperature for direct supply into the network.

### Combined heat and power (CHP) production fuelled with biomass

During the low wind power production moments, dispatchable back-up power and heat production is needed. Bio-based heat and power production (CHP) operates in those moments, when also the price of electricity is high since the price is based on the marginal cost of the currently running most expensive production method. When the electricity price is high and heat demand is low, then the excess heat also from the CHP plant can be stored in the heat storages. This way heat storages can maintain and improve the overall efficiency of the CHP plants when it takes turns with variable wind production. The system efficiency has in principle its maximum when all heat is produced with either heat pumps, CHP or by utilising excess power or heat.

### Digital platform

District heating and cooling network operators need automation systems to connect and control the production and storage units as one virtual power plant. For this, various IT solutions are already commercially available and new solutions continue to develop (Figure 5).

[16] Bayon et. al (2010) Review of seasonal heat storage in large basins: Water tanks and gravel–water pits. Applied Energy. Available: https://doi.org/10.1016/j.apenergy.2009.06.033
Felderhoff, Urbanczyk, Peil (2013). Thermochemical Heat Storage for High Temperature Applications – A Review. Available: https://doi.org/10.1515/green-2013-0011

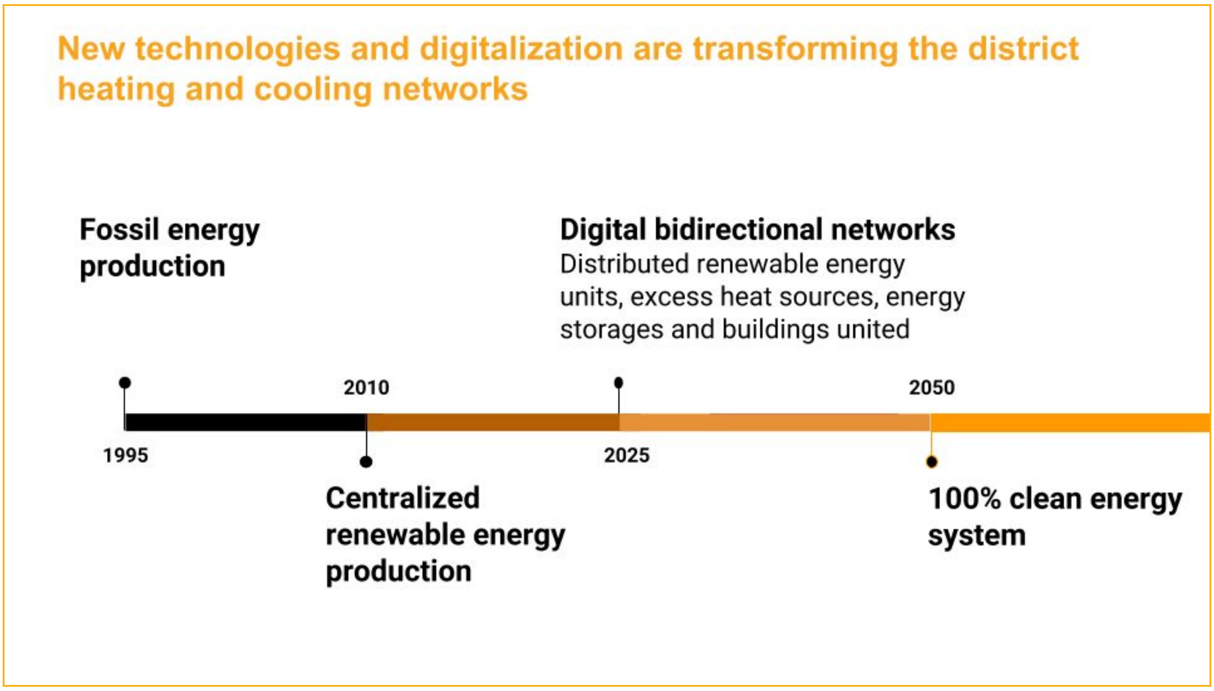


**Figure 5. New technologies and digitalization continue to transform the district heating and cooling networks.**

# Fossil fuel-free energy scenario for Finland

The following scenario for a 100% fossil fuel-free Finnish energy system includes all sectors of energy use. It has been made simulating clean energy production technologies and storages using EnergyPLAN-simulation program[17], that aims to balance power and heat production and consumption hour by hour[18]. The simulation is made in a deterministic way, trying to minimise the total fuel input in the system with optimization.

## Energy sources and installed capacity in the 100% fossil fuel-free energy scenario

The simulation shows that the Finnish energy system can be made 100% fossil fuel-free. 95% of the energy sources are resolved in the simulation as they can be produced at moderate cost, with proven technologies as well as readily available renewable energy sources and nuclear power. The remaining 5% are liquid or gas fuels needed in long

[17] Energyplan (2018). Advanced energy system analysis computer model. Available: https://www.energyplan.eu/.
[18] Energiateollisuus ry (2018). Hourly electricity production statistics. Available: https://energia.fi/ajankohtaista_ja_materiaalipankki/materiaalipankki/sahkon_tuntidata.html#material-view

distance transportation, aviation and to a smaller extent also in the most flexible part of peak power production. These fuels can be produced with wind, solar, biomass or nuclear.

The primary energy sources in the scenario are summarized in Figure 6 and Table 1.

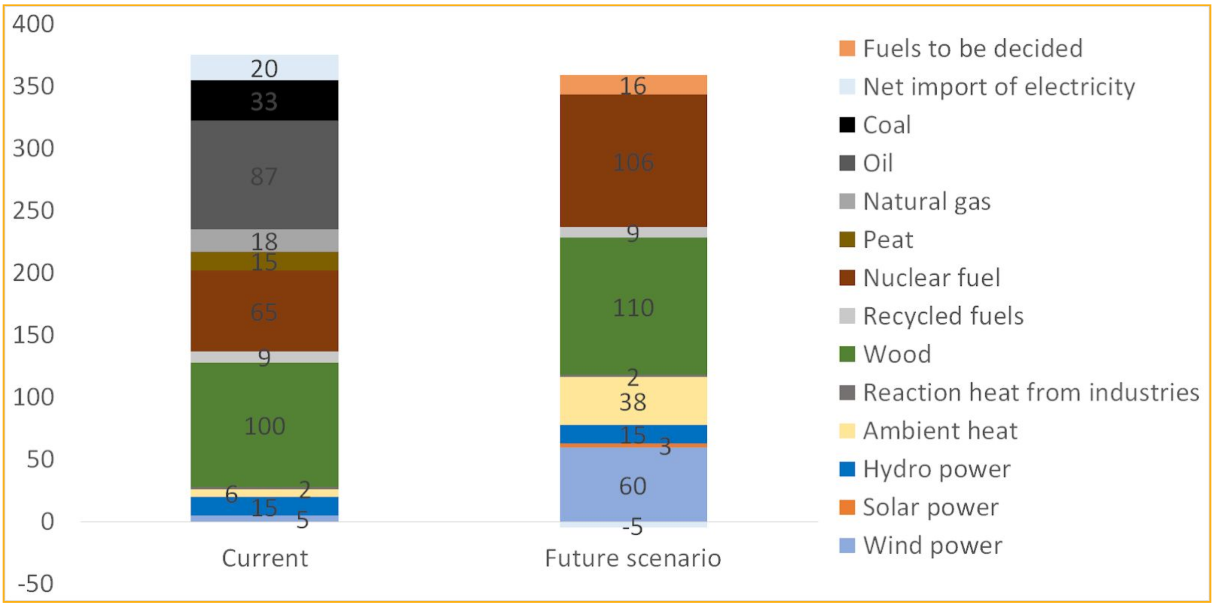


**Figure 6. Primary energy sources in 2017 (375 TWh)[19] and in 100% fossil-free energy scenario (359 TWh). Unit is TWh/year.**

**Table 1. The primary energy sources in Finland 2017 and in 100% fossil fuel-free scenario for comparison. Hydropower 15 TWh, recycled fuels 9 TWh and reaction heat from industries 2 TWh are assumed to remain on the level of 2017, and therefore not included in the table.**

| Energy sources | Consumption in Finland, 2017 | Consumption in 100% fossil-free scenario |
|---|---|---|
| **Wind power** | 5 TWh | 60 TWh |
| **Ambient (ground, sea, air, geothermal) and excess heat** | 6 TWh | 38 TWh |
| **Biomass** | 100 TWh | 110 TWh |
| **Nuclear fuels, uranium** | 65 TWh | 106 TWh (36 TWh power) |
| **Solar power** | 0 TWh | 3 TWh |
| **Alternative clean fuels** | | 16 TWh |
| **Net imports or exports of electricity** | 20 TWh imports | 5 TWh exports |
| **Fossil fuels** | Natural gas 18 TWh, oil 87 TWh, coal 33 TWh and peat 15 TWh | - |

[19] Tilastokeskus (2018). Annual statistics of energy production and use in Finland: Energia. Available: http://stat.fi/til/ene.html

## Energy sources and assumptions in 100% fossil fuel-free scenario

**Wind power** is assumed to increase and it will be the largest single source of electricity. This is considered realistic as wind power is currently the cheapest energy source in Finland with a production cost of 30-35[20] eur/MWh and very large growth potential. The capacity factors of the new wind turbines have recently increased to over 40%.[21]

**Ambient and excess heat** includes heat taken from the sea, lake, river, air, ground, geothermal sources and various urban excess heat sources like wastewater and exhaust air, and used by heat pumps. This can also be very deep geothermal heat.

**Biomass** is already now a major source of renewable energy in the Finnish energy system. The scenario assumes only minor growth of biofuels originating i.e. from the enhanced collection of logging residues, and agricultural residues. The Finnish economical biogas potential is approximately 10 TWh and main sources are various agricultural residues.[22] Since the availability of sustainable biomass is limited, biofuels must be used sparingly. Therefore, we suggest using biomass in combined heat and power plants (CHP) for maximal efficiency.

**Nuclear fuels** include the energy content of the nuclear fuel used: the level of uranium use in 2017 and that of the Olkiluoto 3 EPR reactor, which is under construction. 106 TWh uranium use in the scenario translates to 36 TWh power production.

**Hydropower** production is assumed to remain at the current level.

**Solar energy** and, in particular solar photovoltaics (PV) will significantly increase in buildings especially to meet their cooling demand. Solar electricity production also complements wind power production during summers. Solar thermal heating is not part of this scenario because, according to hourly simulation, seasonal heat storages were not yet an optimal solution. Solar heating potential can, however, grow in the future depending on the development of the electric and heat storage solutions.

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[20] Joint view of Market-based wind production working group, Finnish wind power association. 2018. Production price doesn't include interest or profit rates, lifetime 30 years.

[21] Wind power production, see e.g. the manufacturer brochure for model V150: http://nozebra.ipapercms.dk/Vestas/Communication/Productbrochure/4MWbrochure/4MWProductBrochure/?page=18

[22] Marttinen S., Luostarinen S., Winquist E., Timonen K. (2015). Rural biogas: feasibility and role in Finnish energy system. Available: http://bestfinalreport.fi/files/Rural%20biogas%20-%20feasibility%20and%20role%20in%20the%20Finnish%20energy%20system.pdf

**Alternative clean fuels** not specified in this scenario include liquid and gas fuels that are needed for example in long-distance road transportation, aviation, peaks of electricity and heat production, and some industrial processes. These fuels can be biofuels requiring additional biomass use on top of the 110 TWh assumption in this scenario, or liquids or gases converted from renewable or nuclear electricity[23]. Renewable electric energy can be transformed into storable methane via electrolysis and subsequent methanation. For example, biogas can be used as carbon dioxide source in power to gas (PtG) process chain and higher methane content can be achieved.[24] Some of these technologies are still under development. In this paper, the energy sources of the fuels are left open for discussion.

**Imports and exports of electricity.** A small amount of imports, about a third of the amount of 2017, and exports is allowed as an assumption in the simulation. The electricity is assumed to be transmitted without limits inside Finland. In the scenario Finland will turn to be a net exporter of electricity, exporting approximately 5 TWh of electricity to Nord Pool or Russian power markets annually. The amount of imports is very low compared to the situation in 2017. The international electricity transmission grid and European electricity markets should be taken into account, but since the imports and exports are quite limited in our scenario, we don't discuss this topic in more detail in this paper.

## Installed energy capacity and assumptions in 100% fossil fuel-free scenario

Wind and solar power capacity grows significantly. The amount of district heating CHP capacity will reduce to about half of the 2017 level, due to the decommissioning of plants which can only or mainly use coal or natural gas. The remaining district heating CHP plants with fluidized bed boilers can quite easily be converted to 100% biomass.

[23] Graves et al. (2011). Sustainable hydrocarbon fuels by recycling CO2 and H2O with renewable or nuclear energy. Renewable and Sustainable Energy Reviews. Available: https://doi.org/10.1016/j.rser.2010.07.014

[24] Manuel Gotz et. al. (2015). Renewable Power-to-Gas: A technological and economic review. Renewable Energy 85 (2016) 1371e1390. Available: https://www.journals.elsevier.com/renewable-energy

Heat pump capacity will be built to the district heating networks and industry, and it will also replace oil combustion and 5 TWh (out of 17 TWh) of small scale wood use, in the residential sector.

Heat only boilers are covering heat demand peaks in district heating networks with CHP. Electric boilers are used to convert peaks of excess electricity to heat. Condensing power in the fossil fuel-free scenario consists of condensing tails and auxiliary coolers of bio-CHP plants, i.e. not separate thermal power plants. Condensing power production is used in the scenario only as minor backup, as separate thermal power inefficiently wastes about 50-70% of the fuel. Existing gas turbines in Fingrid's power reserves are assumed to remain in the scenario.

We also assume that the system contains 10 terawatt hours (TWh) of flexible demand: 5 TWh in electric vehicles and another 5 TWh in heating, especially in detached houses. In addition, the heat storages will grow from the current 0,02 TWh to 0,1 TWh in the scenario.

Table 2 shows the changes in the installed power and heating capacities in Finland 2017 and in the 100% fossil-free scenario. Industrial CHP 2900 MW and hydropower 2700 MW are assumed to remain the present level, and therefore they are not included in the table.

**Table 2. Differences in installed energy production capacity in Finland between year 2017[25] and 100% fossil-free scenario.**

| Energy production capacity | Installed capacity in Finland, 2017 | | Installed capacity in 100% fossil-free scenario | |
|---|---|---|---|---|
| | Electricity | Heat | Electricity | Heat |
| **Wind power** | 2 000 MW | | 19 000 MW | |
| **Solar power** | 70 MW | | 4 000 MW | |
| **CHP, district heating** | 3 200 MW | 4 600 MW | 1 500 MW | 2 300 MW |
| **Nuclear power** | 2 700 MW | | 4 300 MW | |
| **Heat pumps in district heating networks** | | 250 MW | | 6 000 MW |
| **Heat only boilers** | | 12 000 MW | | 4 000 MW - 12 000 MW |
| **Condensing power** | 2 000 MW | | 1 600 MW | |
| **Electric boilers in district heating networks** | | | | 1 000 MW |

[25] Energiavirasto (2018). Voimalaitosrekisteri. Available: https://www.energiavirasto.fi/voimalaitosrekisteri

# Electricity in the 100% fossil fuel-free scenario

## Electricity production increases massively replacing fossil fuel combustion

For the replacement of fossil fuels, the share of electricity will increase by about 50% in the fossil fuel-free energy scenario for Finland (Figure 7). More electricity will be needed to supply power for the heat pumps in district heating networks and buildings, and electric vehicles in the transport sector. Also steel industry and other industries need clean electricity in order to replace fossil fuels in the heating and the industrial processes.

**The electricity consumption increases 50% from current levels replacing fossil fuel combustion in heating, transport and industry.**

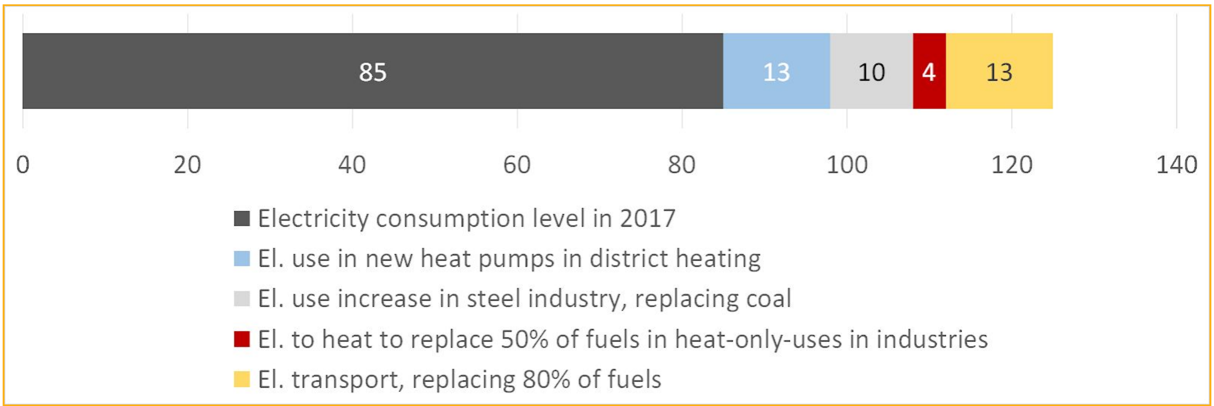


**Figure 7. The electricity consumption is assumed to increase from 85 TWh[26] in 2017 to 125 TWh/year, because electricity use will replace fossil fuel combustion in heating, transport and industry.**

The increasing electricity will be supplied largely by wind power, which will represent half of the annual electricity production in the 100% fossil-free scenario (Figure 8). In other words, the amount of wind power production will then be ten times as high as in 2017. Solar power production is assumed to be about 5% of the wind power production but its role will be to even out the daily variation of electricity demand. It also matches well with space cooling, which may strongly increase.

[26] Official Statistics of Finland (OSF): Production of electricity and heat [e-publication]. ISSN=1798-5099. 2017. Helsinki: Statistics Finland [referred: 2.11.2018]. Access method: http://www.stat.fi/til/salatuo/2017/salatuo_2017_2018-11-01_tie_001_en.html

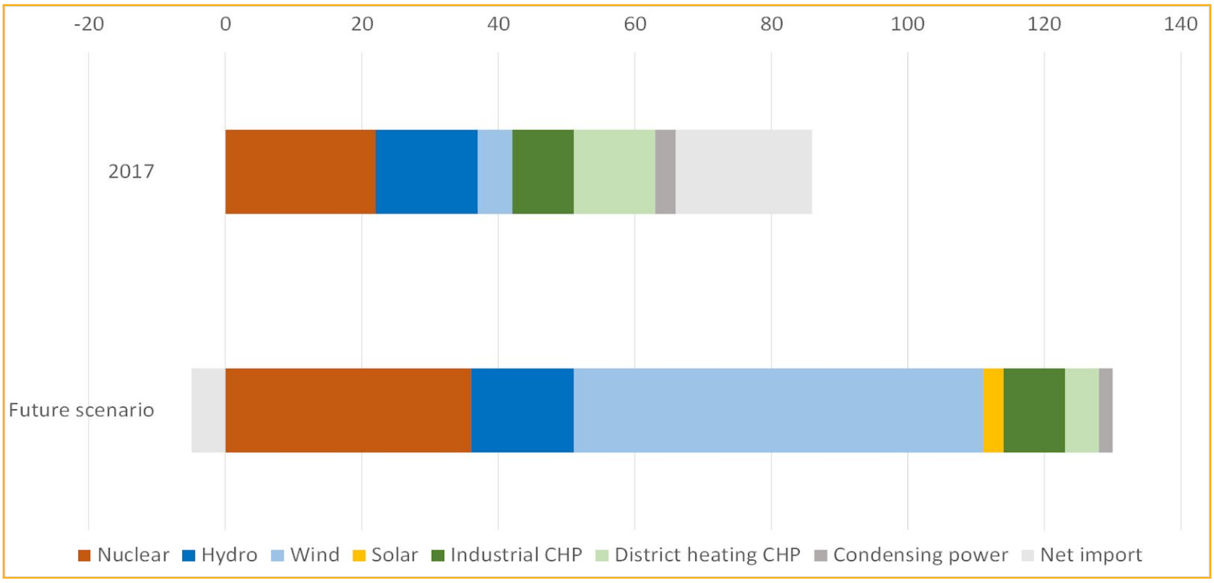


**Figure 8. Electricity production in 2017 and in the 100% fossil-free scenario.**

### Power balancing in the energy system with high shares of variable wind and solar power

A high share of wind power causes high production peaks, as the nearly constant nuclear power production pattern remains with the new Olkiluoto 3 plant. However, these peaks in power production can be utilised in many ways. For example, by converting electricity into heat for the district heating networks or increasing industrial processes with demand response automation. Also various technologies for the conversion of power to fuels are developing.

In our scenario, an hour by hour balance for both heat and electricity demands is sought for (Figure 9).

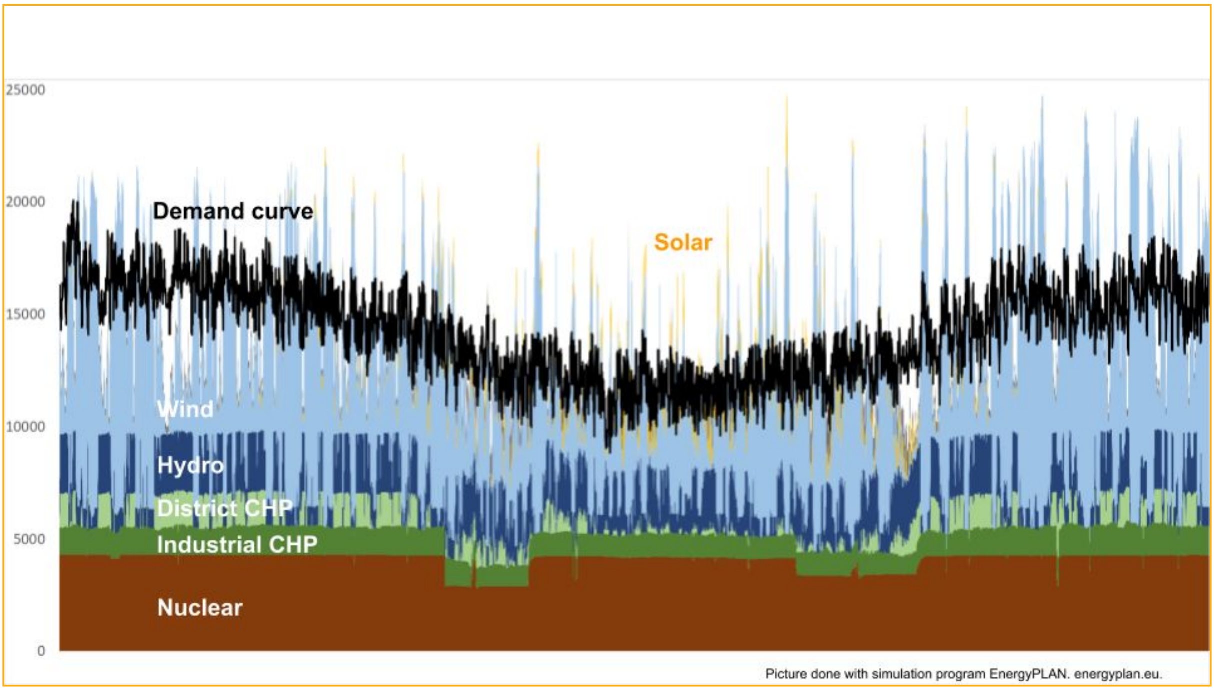


**Figure 9. Estimated hourly electricity production in Finland during one year, with a 60 TWh capacity of wind power. Hydro power, combined heat and power (CHP) production in district heating networks and electricity imports are used to even out the power fluctuations. In practice the CHP production curve is smoother than in the picture, due to the e.g. flexible power consumption.**

We assume that the hourly industrial CHP production remains as it was in 2017. The production timing of hydro power has a new shape to fit into the variable production of wind power. District heating CHP will also depend on the wind energy production pattern, aiming at filling the occasional gaps in the electricity production. Bio-CHP plants can operate as backup power supported by other flexibility solutions; demand response automation, flexibility of the heat pumps and storages enable several hours of time for the bio-CHP plants to adapt to the fluctuating wind power production and the power needs of heat pumps. In the scenario the peak load time of the bio-CHP plants is approximately 3500 hours annually. Total running hours are more since the plants run also in partial power. This way, it should be feasible to upgrade existing CHP plants with fluidized bed boilers for 100% bioenergy. CHP plants with condensing tails or auxiliary coolers can also provide separate power production, when there is no need for the heat, but electricity is needed and it cannot be imported. This kind of utilisation of bio-CHP plants is less expensive than separate condensing power plants.

FREQUENTLY ASKED QUESTION:

**“How to secure sufficient heat and electricity supply during very cold winter days, when the wind is not blowing?"**

The low wind periods hardly ever last more than few days. At worst it can be one week, which happens extremely rarely. Therefore in the 100% fossil-free scenario the needed heat storage capacity covers approximately one week of heat demand.

During the cold days’ peak demand, the electricity prices are high if the wind is low at the same time. Figure 10. shows how the electricity system works when there is lack or excess of electricity production.

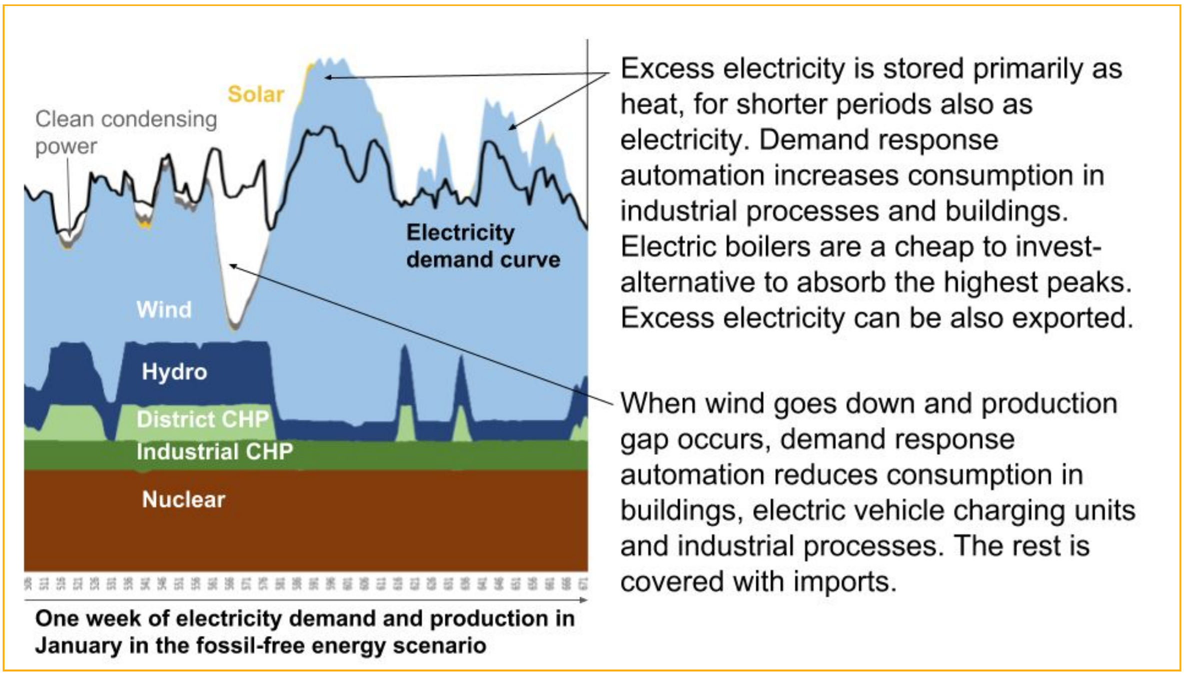


**Figure 10. During the coldest days of the year different energy sources, energy storages, demand response solutions, and imports and exports of electricity help to balance the electricity production and demand curves. The amount of imports in the 100% fossil fuel-free scenario is however low, only about third of 2017 year’s levels.**

In the district heating networks, heat storages are discharged, when wind energy supply is low. This helps the heat pumps to run with high efficiency and low electricity consumption. District bio-CHP is used actively as back up power and heat.

In case of a threat of power shortage, mainly existing gas turbines or engines are used. The fuels used are currently fossil oil or gas, but in the future clean fuels can be used. The annual energy consumed by the gas turbines and motors is not high, currently and also presumably in the future, less than 0,1 TWh/year. This kind of capacity is and will be however needed. For example, the capacity in Fingrid’s reserve power plants is currently over 1200 MW[27].

[27] Fingrid (2018). Reserve power plants. Referred 22.11.2018. Available: https://www.fingrid.fi/en/electricity-market/reserves_and_balancing/reserve-power-plants/

## Transport in the 100% fossil fuel-free scenario

The scenario assumes significant electrification of vehicles as well as various measures for the reduction of mobility[28]. The energy use of transportation fuels is now 50 TWh; which is not assumed to be replaced by liquid biofuels. Biogas could be used in trucks and buses.

The fuel choices for transport must be made considering the whole energy system. For instance, the developments in the traffic sector regarding the use of biofuels, electrification and reduction of transport, e.g. through mobility service development, will impact the electricity and heating sectors. For example, the demand of transport biofuels may reduce the availability of limited biomass for the heating and electricity production. On the other hand, the batteries in electric vehicles can offer demand response and electric storage capacity. Transport is not the focus of this study, but we recommend that the future choices of the transport sector will be discussed taking its dependence of the whole energy system into account.

**The energy choices in the transport sector will impact the whole energy system.**

## Heating in the 100% fossil fuel-free scenario

The electrification of the heating sector requires 45 TWh of electricity assuming that fossil fuels are replaced in the industry, and also in large and small district heating networks. In addition, it is assumed that heat pumps will also replace small scale oil heating, and partly wood burning outside of the district heating networks following the ongoing heating choice trend in the residential sector[29].

To illustrate the scale of the transformation to fossil fuel-free district heating and cooling system, the annual shares of district heating methods were estimated for the whole Finland (Figure 11).

[28] Hiiletön liikenne 2045 - polkuja päästöttömään tulevaisuuteen. Liikenteen ilmastopolitiikan työryhmän väliraportti. Liikenne- ja viestintäministeriön julkaisuja 9/2018. Available: http://urn.fi/URN:ISBN:978-952-243-555-2.
[29] Kimmo Rautiainen, Pientaloteollisuus (2018). Presentation 22.11.2018: Minkälaisia ovat uudet omakotitalot?. Available: https://koulutuskalenteri.adato.fi/eTaika_Tiedostot/2/TapahtumanTiedostot/1701/OhjelmanTiedostot/388/Kimmo%20Rautiainen%20Uudet%20omakotitalot.pdf

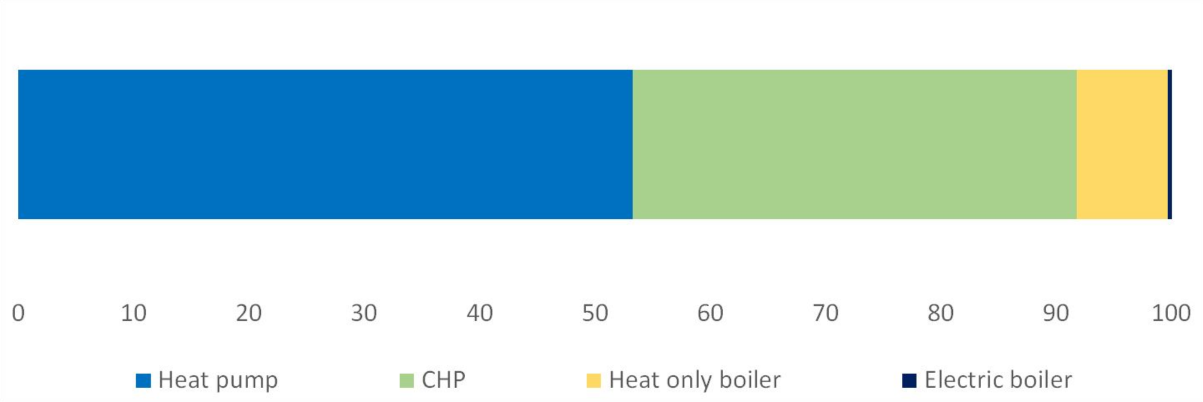


**Figure 11. The annual shares of district heating production methods in Finland in the 100 % fossil fuel-free scenario. These shares with combined heat and power (CHP) production concern larger district heating networks, that account for about 75% of the district heating use in Finland.**

Different cities can have different clean energy mixes, but with the shares presented in the figure above the national power balance can be achieved. The role of cities with district heating networks are very important for the electricity balance of the whole Finland. Also, a single city system has a best resilience against high volatility of electricity prices, when there is both heat pumps and combined heat and power (CHP) production in the system. The volatility of electricity prices is expected to increase in the future due to the fluctuations in the electricity production and consumption balance.

**FREQUENTLY ASKED QUESTION:**

**“How much does the fossil fuel-free heating cost?"**

The production cost estimation of the clean heating would be approximately 31 euros/MWh (3,1 snt/kWh) when taking into account the investment, fuel and maintenance costs of the heat pumps, wind power farms and heat storages, new bio-CHP plants, updating old CHP plants to burn 100% biomass and a small amount of new heat only boilers. This rough production cost estimation is based on the costs presented in Table 3 of the main technologies needed, with assumptions of 25 years investment lifetime and 5% interest rate including the cost of capital, but excluding profit and electricity tax.

Please note that new power capacity investments indicated here are needed for the heat production. The costs of existing electricity production (e.g. nuclear power) are not included.

**Table 3: Production cost estimation based on main new capacity investments and their annual costs for producing 45 terawatts (TWh) of electricity for the heating sector in the 100% fossil-free scenario.**

| Technologies | Needed capacity / volume | Technology prize, euros / installed megawatt | Investment price, million euros | Total annual cost, interest 5%, million euros |
|---|---|---|---|---|
| **Wind power** | 3200 MW electricity | 1 300 000 €/MW | 4 200 M€ | 298 M€ |
| **Bio-CHP, new capacity** | 250 MW electricity | 2 000 000 €/MW | 500 M€ | 36 M€ |
| **Existing CHP, update to 100% bio** | 1250 MW electricity | 400 000 €/MW | 500 M€ | 36 M€ |
| **Heat pumps** | 6000 MW heat | 2 400 000 €/MW | 7 200 M€ | 512 M€ |
| **Heat only boilers (new)** | 500 MW heat | 400 000 €/MW | 200 M€ | 14 M€ |
| **Heat storages** | 100 000 MWh heat | 4 000 €/MWh | 400 M€ | 28 M€ |
| | | | | **+ variable costs:** |
| **Variable costs** | | **Production volume / year,** MWh | **Operation & maintenance costs,** euros/MWh | **Total variable cost,** M€ / year |
| **Industrial heat pump maintenance cost** | | 30 000 000 MWh | 1 €/MWh[30] | 30 M€ |
| **Biomass + maintenance cost** | | 10 000 000 MWh | 30 €/MWh | 300 M€ |
| **Maintenance of windmills** | | 10 000 000 MWh | 7 €/MWh | 70 M€ |
| **Electricity transmission** | | 10 000 000 MWh | 10 €/MWh | 100 M€ |
| | | | **Sum of annual costs, estimation** | **= 1 417 M€** |

If the total estimation 1400 M€ is divided by the 45 TWh/year of the electricity needed for the heat production, the **heat production price is approximately 31 eur/MWh**

The consumers' end price is higher, as value added tax (VAT) and service fee with company profit expectancy rates would be added to the production price. In addition there is the cost of district heating network use, which is approximately 25% of the district heating price. The district heating end customer prices to, for example to Finnish housing companies, are in average 75-80 eur/MWh[31].

[30] Mika Luoma, Calefa Oy, haastattelu 23.11.2018.
[31] Finnish energy (2018). Kaukolämmön hintatilasto. Kaukolämmön hinnat 1.7.2018 (XLS). Available: https://energia.fi/ajankohtaista_ja_materiaalipankki/materiaalipankki/kaukolammon_hintatilasto.html

This way the customer price of the 100% fossil-free production would be approximately the same as today. If the price of fossil fuels get higher, then clean district heating and cooling becomes relatively cheaper. This shows, that 100% fossil-free production mix is an economic option compared to today's combustion-based district heating.

# Clean district heating - case Helsinki

The following estimations are calculated based on the 100% fossil fuel-free scenario for Finland, reflected to the 630 000 citizens of Helsinki representing 12% of the total population of 5,5 million. Therefore, the estimations do not necessarily reflect the real energy need of the City of Helsinki. This scenario aims at giving an idea of a clean energy mix that diverse players including new producers, flexibility providers, prosumers etc. could provide in cooperation with Helen Ltd to phase out fossil fuels from the capital city of Finland.

Helen Ltd., a utility company fully owned by the City of Helsinki, is a producer of district heating, power and district cooling. Helen supplies heat to 90% of the heated building stock in Helsinki.[32] Therefore Helen Ltd's production portfolio and installed capacities in 2017 are used in this discussion paper as "baseline reference" in order to point out the necessary changes in the energy sources and technologies when heading towards a 100% fossil-free Helsinki. Helen Ltd produces about 20% of the district heating in Finland.

Given the considerations presented above, if the City of Helsinki would make a transition to a 100% fossil fuel-free scenario the needed energy sources for heating would be as presented in Figure 12 and the needed capacities in Table 4.

[32] Euroheat and power (11. 9.2018). News: Helsinki energy company Helen to go climate neutral. Referred 22.11.2018. Available: https://www.euroheat.org/news/helsinki-energy-company-helen-go-climate-neutral/

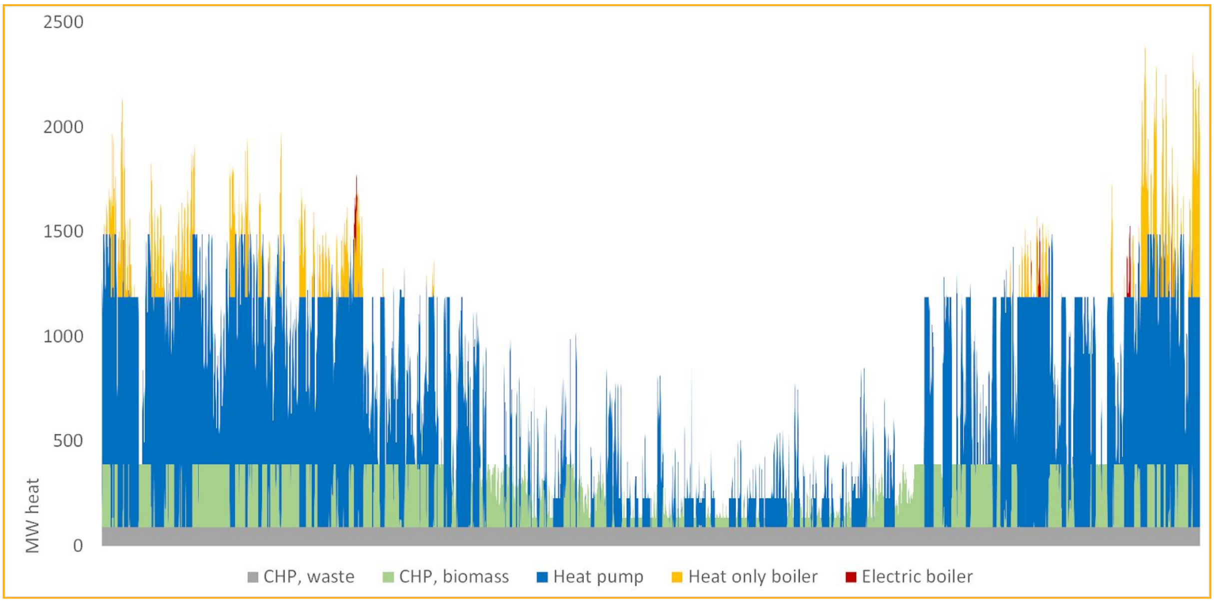


**Figure 12. The district heat production in Helsinki hour-by-hour based on 100% fossil-free energy scenario during a year. In reality the running patterns are significantly smoother than in this figure drawn with EnergyPLAN simulation tool.**

The production shares and timing presented in Figure 12 can be scaled for district heating systems of different sizes. Even though the curve shape does not reflect the real heat demand of Helsinki, we have run simulations with different heat consumption profiles and the curve shape is not that important for the final results. The exact dimensioning and technical solutions need to be tailored case by case depending on the real heat demand.

**Table 4. Installed heat production capacity by Helen Oy in 2017 and capacities and energy sources in 100% fossil-free scenario for the City of Helsinki**

| Energy production capacity | Installed heat capacity by Helen Oy, 2017 | Installed heat capacity and energy sources used in Helsinki in 100% fossil fuel-free scenario |
|---|---|---|
| **Heat pumps** | 100 MW | 1 100 MW, using ambient and waste heat and mostly wind power |
| **CHP, district heating** | 1 300 MW | 300 MW (+ 200 MW power), using biomass |
| **Heat only boilers** used for peak heat demand | 2 000 MW | 1 100 MW, using liquid fuels or synthetic gas made from clean electricity (wind, solar, nuclear) or biomass |
| **Electric boilers** used to convert peaks of excess electricity to heat | | 200 MW, using mostly wind power |
| **Heat storages** | 0,002 TWh | 0,015 - 0,03 TWh - with upcoming heat storage of 0,014 TWh in Mustikkamaa[33] the system can already work well |

If Helsinki would become self-sufficient for the part of the electricity required to run the heat pumps, 700 megawatts (MW) of wind power would be needed. Furthermore, 400 megawatts of solar power could be added. However, it is not as important as wind power. The estimated wind power amount is calculated taking into account that wind power production is used for many different purposes, of which 700 MW is needed as extra capacity to take care of the heating needed in this scenario. The possibility to use electricity for heating especially when there is a surplus of electricity, will reduce the required capacity. In other words, storages in combination with wind power, heat pumps and bio-CHP, will increase the system efficiency.

In the 100% fossil fuel-free district heating scenario for Helsinki, we assume less bio-CHP than the national average would suggest. The transportation of domestic biomass to Helsinki can be a challenge and the required storage space of the biomass may be a problem, because of high land prices. Moreover, the current CHP plants in Helsinki are technically difficult to convert to use biomass. For these reasons, we assume, that bio-CHP will be used more in other district heating networks of Finland for the national power balancing needs, while heat pumps are more numerous in Helsinki.

[33] Talouselämä (12.10.2018). News: Helen valjastaa Mustikkamaan vanhat öljyluolat vähentämään hiilidioksidipäästöjä. Referred: 22.11.2018. Available: https://www.talouselama.fi/uutiset/helen-valjastaa-mustikkamaan-vanhat-oljyluolat-vahentamaan-hiilidioksidipaastoja/4b4432b2-5923-35f4-afad-aae4c50a4af5

**FREQUENTLY ASKED QUESTION:**

**“How many wind turbines and heat pumps would be needed in Helsinki to phase out coal?"**

Helen Ltd used in 2016 6,9 TWh of coal, 4,6 TWh of natural gas and 0,2 TWh of oil for the production of district heating and power.[34] Most of these fossil fuels could be replaced with 1100 megawatts of heat pumps presented in the scenario. That would require additional 950 MW of heat pump capacity on top of the upgraded Katri Vala’s 123 MW[35] and Esplanade park’s 22 MW[36] heat pump stations. So the required increase in heat pump capacity (950 MW) could be covered with approximately ten new large heat pump stations or 19 000 units of 50 kW heat pumps in buildings.

1100 megawatts of heat pump capacity require approximately 400 megawatts of electric power. Due to the variability of wind power, in practise this requires 700 MW of wind power capacity, which is equal to 170 units of four megawatt wind turbines.

The 100% fossil-free scenario shows, that different production technologies - together with flexibility solutions - interact in such critical ways, that they must be modelled together in order to get a correct understanding of the technologies needed.

The wind farms do not need to be located next to the district heating networks, as electricity grids can transmit wind power from distant locations. For instance, the wind turbines providing electricity for the heat pumps in Helsinki can be located in the Pohjanmaa or Lapland regions, which have good wind resources.


However, wind farms as well as other renewable energy power plants impacting local communities, need to be developed according to the principles of procedural and distributive justice to minimize public opposition. Procedural justice in renewable energy development means that citizens and local communities should be actively involved in the decision-making processes regarding wind farms planning and situating. Distributive justice instead refers to the issue of who really benefits from wind power projects. Wind farms can offer a great opportunity for local economic development in rural areas. Therefore,

[34] Finnish energy (2018). Kaukolämpötilasto 2017. Available: https://energia.fi/ajankohtaista_ja_materiaalipankki/materiaalipankki/kaukolampotilasto.html#material-view ;

[35] Helen Oy (2018). News: HELSINKIIN RAKENNETAAN JÄLLEEN UUSI LÄMPÖPUMPPU. Referred 22.11.2018. Available: https://www.helen.fi/uutiset/2018/uusilampopumppu/

[36] Helen (2017). News: LARGE HEAT PUMPS ARRIVE IN HELSINKI. Available: https://www.helen.fi/en/news/2017/large-heat-pumps-arrive-in-helsinki/

community ownership or joint ownership with project developers can be encouraged to create a win-win situation in which both citizens living in rural and urban areas can benefit from wind energy. The dramatic reduction in the costs of wind power generation as demonstrated by the recent PPA (Power Purchase Agreement) deal[37] signed by Google to buy renewable energy from wind farms in Finland, creates new opportunities for local communities to co-invest in wind energy.

# Towards clean district heating and cooling networks - key challenges to be solved

In order to phase out fossil fuels and to secure the transition from the current district heating systems, which are unidirectional and based on combustion technology, towards bidirectional and electrified district heating and cooling systems, we need to solve the following challenges:

## Profitability of clean energy investments

The recent IPCC report emphasized the need to reduce greenhouse gases as fast as possible to avoid the most severe impacts of climate change on ecosystems, human health and well-being.[38] Whereas wind and solar power[39], energy storages, and heat pumps are becoming cheaper, the price of coal and emission allowances (eur/t$CO_2$) have been increasing in the market[40]. Despite these favourable market developments, it is important to further increase the carbon price in order to promote a faster transition to clean energy. The carbon price that would reflect the cost of climate change mitigation, is estimated to be 42-85 eur/t$CO_2$ by 2030[41].

[37] Reuters (2018). Google buys into new Finnish wind energy in renewables search. (Accessed 15.11.2018). Available: https://www.reuters.com/article/us-alphabet-renewables-finland/google-buys-into-new-finnish-wind-energy-in-renewables-search-idUSKCN1LR1OG
[38] Intergovernmental Panel on Climate Change IPPC (2018). Report: Global Warming of 1.5 °C. Available: http://www.ipcc.ch/report/sr15/
[39] Deloitte (2018). Global renewable energy trends. Accessed 13.11.2018. Available: https://www2.deloitte.com/insights/us/en/industry/power-and-utilities/global-renewable-energy-trends.html.
[40] Markets Insider (2018). Coal commodity price https://markets.businessinsider.com/commodities/coal-price and CO2 European emission allowances price https://markets.businessinsider.com/commodities/co2-emissionsrechte. Accessed 13.11.2018
[41] The Carbon Pricing Leadership Coalition (2017). Report of the HIGH-LEVEL COMMISSION ON CARBON PRICES. Available: https://www.carbonpricingleadership.org/report-of-the-highlevel-commission-on-carbon-prices/

## District heating market and partnership models

The recovery of excess heat, distributed energy solutions and demand response automation require the integration of energy users and buildings into the district heating system. The current natural monopoly model of the district heating companies that manage both the production assets and distribution networks, is not supportive for handling multi-directional markets or attracting energy users to participate. There is a need for a a system integrator who can run the district heating and cooling networks as a virtual power plant and establish attractive partnership models for clean heating and flexibility producers.

## Electricity market model


Electricity market model 2.0 is needed to enable high shares of wind and solar power production.[42] The current electricity market model is based on the marginal cost of the most expensive production method used in the power production in a certain hour. This highest marginal cost is then the price of all electricity sold in that hour. The challenge that needs to be solved in the long term, is how to enable market-based investments for capacity, when fuel costs are no more the scarcity factor in the market. Wind movements on the earth and solar radiation from the sun do not cost anything, so the only variable cost of wind and solar power plants is their maintenance cost under 10 euros/MWh. Demand response mechanisms also reduce the need for the most expensive production and thus reduce electricity prices eating up its own profitability to some equilibrium point. The mechanism is the same: the first implementation of demand response system has the best profitability, when it replaces the most expensive production, but the second one is a bit less profitable since the price got already lower and so on.

The fewer hours the expensive condensing power is needed, the cheaper the electricity becomes for consumers, due to the low marginal cost and the mentioned market price setting principle. In the scenario, the annual average electricity price remains very low with the current price setting mechanism, as bio-CHP with relatively low marginal cost, becomes almost the only power production method based on combustion. The low marginal price of electricity does not cover the cost of investments in 100% fossil-fuel free scenario. The income from the power market therefore does not turn the needed clean capacity or demand

[42] Ahola et al. (2017). Keskustelupaperi: Kohti sähkömarkkinamallia 2.0. Available: http://smartenergytransition.fi/fi/keskustelupaperi-kohti-sahkomarkkinamallia-2-0/

response automation investments profitable. Thus, a new market model, in which the energy users pay for the clean capacity, in addition to low marginal cost, will be needed.

## Social acceptance

In order to complete a rapid transition towards a sustainable energy system, the number of wind farms as well heat pumps in both industrial sites and buildings need to considerably increase. Current experience with wind power development in Finland has showed that although citizens in general are supportive of wind energy, often they oppose the deployment of this technology in their neighborhood[43]. This phenomenon is often referred to as NIMBY, which stands for "Not In My Back Yard" and it depends more on local factors, such as participation and decision-making procedures, than on general attitudes. Therefore, social acceptance of wind energy is a crucial challenge that needs to be addressed.[44]

A large number of studies has demonstrated that providing incentives for local citizens to invest in wind projects as well as inviting them to participate in planning procedures, can strongly influence public acceptance. More specifically, research suggests a strong positive correlation between community ownership and acceptance of wind power projects. For instance, in a survey carried out in Sweden it was found that public support for wind farms grows when they are located away from recreational areas and they are fully or partly owned by local communities. In addition, the same study also revealed that consumers in Sweden would be willing to pay more for electricity generated by wind power schemes in which the local population were involved in the planning of the wind farms[45].

Community-based organizations such as cooperatives, village development associations or trusts have played an important role in the development of wind power projects in countries like Denmark, Scotland and Germany. In these countries, deliberate policies have ensured

[43] Akordi (2017). Tuulivoiman hyväksyttävyys ja sosiaalinen toimilupa. Accessed on 12.11. 2018. Available: https://akordi.fi/?p=1959
[44] Toke et al. (2006), Warren and McFadyen (2010), Zoellner et al. (2008), Jobert et al. (2007), Barry and Chapman (2009), Devine-Wright (2005), Toke (2005), Enevoldsen and Sovacool (2016), Loring (2007), Boon and Dieperink (2014), Wirth et al. (2018), Slee (2015), Toke et al. (2008), Perlaviciute and Steg (2014), Bolinger (2001), Ruggiero et al. (2014), Berka and Creamer (2018).
[45] Ek, K., Persson, L., (2014). Wind farms — Where and how to place them? A choice experiment approach to measure consumer preferences for characteristics of wind farm establishments in Sweden. Ecological Economics, 193-203.

that local communities could directly benefit from wind power projects and, therefore, despite the high number of wind farms, there has been limited public opposition. Research has shown that community ownership can be a significant tool for local economic development and a greater opportunity for economic regeneration than benefit packages offered by project developers[46].

In Finland, wind power projects do have consultation processes but they are often controlled by the project developer and do not provide a two-way communication[47]. Moreover, although some wind power projects have offered monetary compensations to local communities, they can create further problems when it is not clear who will benefit from these compensations. Therefore, in Finland there is a need for promoting participation of local communities 1) in the decision-making process and situating of wind farms and 2) in the sharing of the benefits of wind energy through community ownership.

## How can Finland gain more benefits from its cleantech sector?

Clean technologies and service-based solutions represent a huge business opportunity. New companies are emerging and also actors from the fossil industry are seeking ways to get involved in the clean energy business in various novel networks (Figure 13). The estimated volume of global investment in clean power generation capacity  is 11 500 billion dollars between 2018 and 2050[48]. Therefore, phasing out fossil fuels can also benefit the economy.

There is an enormous demand for clean heating and cooling solutions in the global energy markets. Therefore, the export potential of Finnish clean energy expertise[49] is considerable and Finland should take better advantage of that by improving export programmes and international marketing strategies.

[46] Munday, M., Bristow, G., Cowell, R., (2011). Wind farms in rural areas: How far do community benefits from wind farms represent a local economic development opportunity?. Journal of Rural Studies. 1, 1-12.
[47] Janhunen, S. (2018). Determinants of the local acceptability of wind power in Finland. Ph.D. thesis, Lappeenranta University of Technology.
[48] Bloomberg NEF. 2017. New Energy Outlook 2018. Available: https://about.bnef.com/new-energy-outlook/#toc-download
[49] Smart Energy Transition (2018). Database: UUDEN ENERGIAN YRITYKSET. Available: http://energiamurros.fi/

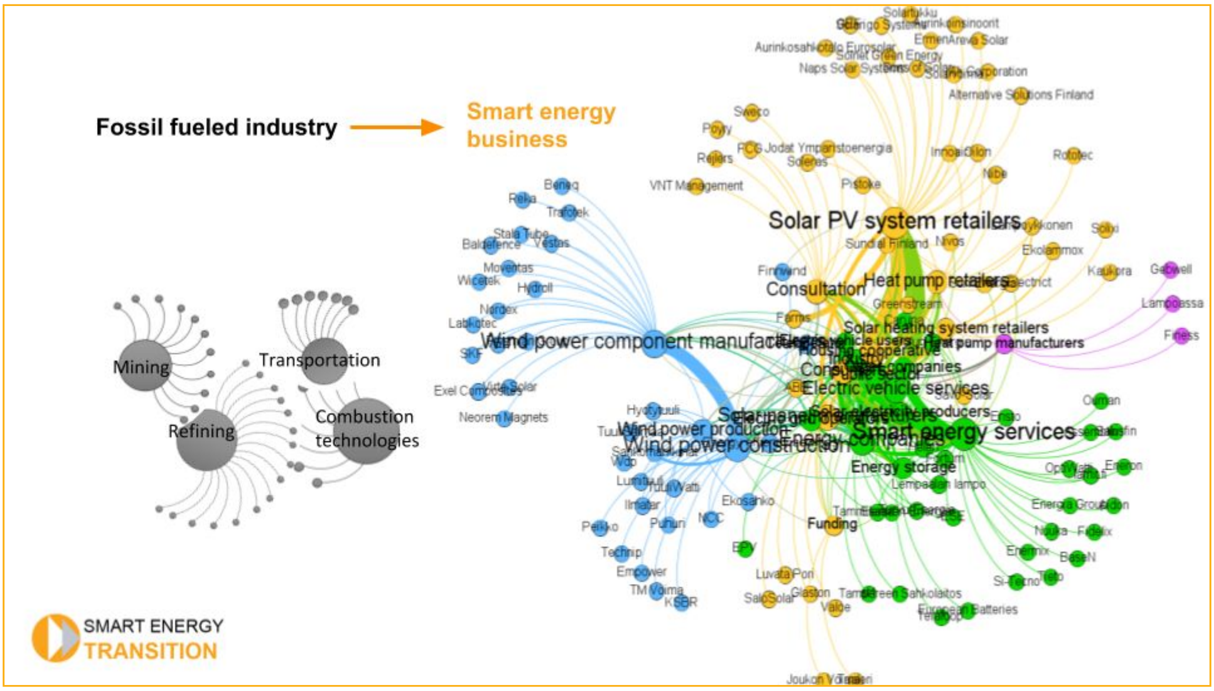


**Figure 13: New business emerge from technology disruptions. Companies can profit from the ongoing energy disruption by actively participating in the development of new market, technology and service solutions.**

In conclusion, we hope that this discussion paper serves as a first step in better understanding the existing challenges in transitioning to fossil fuel-free district heating and cooling systems as well as the opportunities for Finland to reap the benefits of the energy transition.

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