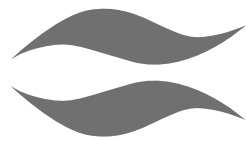




Aalto University



Sector Coupling

Outlook and practical application

The Greenlink group

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This report is an outcome of the teamwork during the Advanced Energy Project L (AAE-E3000) course. The project is focusing on the sector coupling opportunities for Finland to reach carbon neutrality by 2035.

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Preface

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Abstract

Climate change currently poses the biggest threat to humanity, therefore rapid decarbonization of the whole society is needed to sustain the life quality on the planet. Sector coupling is considered as a good strategy to utilize resources efficiently and advance decarbonization while maintaining cost-efficiency of the energy systems. Sector coupling opportunities are various but so are the barriers in current regulations and taxation, therefore for the most efficient decarbonization, the taxation should be based only on life-cycle emissions. Excess electricity from various sectors can be utilized in many ways, for example, the production of gaseous and liquid fuels (power to x), generation of heat (power to heat) or storage. Waste heat from different industries could be used to produce biogas and alcohols (heat to x), whereas low heat sources could be further explored by the heat pumps. Additionally, a surplus of heat could be sorted and utilized again in winter times. Various sustainable materials and waste streams can be refined to renewable liquid fuels (x to x) or used directly to produce heat and power (x to power). The examples of sector coupling from the literature review, as well as from the already implemented real case examples, such as widespread utilization of electric heat pumps in households and some larger scale in district heating and industry, such as those utilizing waste heat of data centers are presented. The question studied in this research was how to most efficiently utilize sector coupling in Finland. To address this problem, besides the literature review a system modeling was conducted using long-range energy alternatives planning system (LEAP), to investigate which sources are the ones that cause most of the emissions. A large waste heat resource was identified in condensing power plants, such as nuclear power plants, and putting that in use in nearby areas where the heat is needed would reduce emissions considerably. The results indicate that the transportation sector contributes strongly to the total emissions in the system and is the most difficult sector to be electrified. Additionally, the demand for transportation grows rapidly, and the current fleet average life is long. Therefore, as a conclusion, new game-changing approaches such as the substitution of the fossil-fuels with renewable drop-in liquid fuels and accelerated electrification of the light-duty passenger vehicles is highly recommended. Additionally, new regulations and incentives to reduce transportation emissions are necessary to achieve carbon-neutral Finland by 2035.

Keywords: sector coupling, energy efficiency, renewable energy, sustainability, interlinking sectors, waste utilization.



Highlights

Sector coupling is an excellent way to utilize resources efficiently and advance decarbonization.

Transportation sector demand grows rapidly and the current fleet average life is long, therefore bringing large quantities of renewable liquid drop-in fuels in to the market is necessary to offset the emissions.

Conversion of condensing power to co-generation and obtaining maximum energy efficiency is identified as an important way to reduce the primary energy consumption and emissions.

Utilization of sector coupling paths to most efficient decarbonization requires more collaboration between different sectors and new collaborations within the whole value chain of energy resources.

Electrification is considered as a good tool to decarbonize other sectors, such as heating or transportation. As electricity demand grows in new sectors, more carbon neutral electricity production is needed.

New regulations and incentives to reduce the transportation emissions are necessary to accelerate the transition. Very important is the change of taxation mechanisms, that should be based on the life cycle environmental impact instead of tank-to-wheel.

Sector coupling examples already exist in the energy industry. Further implementation of sector coupling methods in practice requires changes in regulations concerning the taxation and emissions.

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Symbols and abbreviations:

BAU	Business as usual scenario
C	Commercial
CAES	Compressed air energy storage
CC	Carbon Caps scenario
CN	Carbon Neutral Finland by 2035 scenario
E	Electric motor
E85	Fuel (85% ethanol and 15% gasoline)
EVs	Electric Vehicles
FAME	Fatty Acid Methyl Esters (biodiesel)
FC	Fuel Cell
FP	Fuel production
FT	Fischer–Tropsch process
GHGs	Greenhouse gases
H2H	Heat to heat
H2X	Heat to X
HFO	Heavy Fuel Oil
HTL	Hydrothermal liquefaction
HVO	Hydrotreated Vegetables Oil
I	Industry
IC	Internal Combustion
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
LCOS	Levelized cost of storage
LFG	Landfill gas
LNG	Liquefied Natural Gas
MDO	Marine Diesel Oil
MSW	Municipal Solid Waste
P2X	Power to X
PCM	Phase Change Materials
PV	Photovoltaic
R	Residential
SC	Sector Coupling
T	Transport
V2G	Vehicle to Grid
X2P	X to Power
X2X	X to X – conversion of one form of chemical material into another.

1 Introduction

1.1 About sector coupling

Sector coupling can be defined by two overlapping strategies. Sector coupling can either be seen interpreted as **end-use sector coupling**, which mainly deals with the electrification of the end-use sectors and providing balancing services to the power sector. The other strategy is to also include further coupling of the energy, mainly through coupling electricity and gas, by introducing supply-side integration. This is referred to as **cross-vector integration**. These two strategies combined, are very similar to that of energy system integration. The electrification of end-use sectors is the most cost-effective way to decarbonize the energy system, but the further integration of energy supply sectors can provide additional flexibility (European Parliament 2018). Since it is currently most cost-effective and technically most feasible to use the electricity from renewable sources directly as electricity, rather than convert it to fuels or heat, a large amount of GHG emissions does not originate from the power sector, but from other sectors, such as industry, transport and buildings. However, simply electrifying these sectors would pose significant challenges, due to additional needed flexibility capacity and reinforcement and extension of transmission and distribution networks in the power sector. Therefore, while renewable electricity would still play an important role, other energy vectors such as renewable gas, hydrogen and renewable liquid fuels based solutions would be used for applications, where electrification is difficult. Sector coupling between electricity and gas and between demand and supply would lead to more energy and cost-efficient energy system. It would also lead to a larger utilization of the existing gas infrastructure. Therefore, the combination of end-use sector coupling with cross-vector integration is preferable, especially in situations where renewable energy is abundantly available (European parliament 2018). Sector coupling also increases flexibility in the electricity system. High shares of intermittent renewable energy cause instability and uncertainty to the electricity supply, when the ratio of generated power and load varies highly. This has even led to situations, where the price of electricity has gone negative. Sector coupling can help with these problems, by introducing flexibility to the energy system through various means, such as energy storage technologies, power-to-X applications and demand response (European parliament 2018).

1.2 Opportunities for sector coupling.

Sector coupling is generally perceived as a tool in decarbonization, which can be used to improve the efficiency and flexibility of the energy system and this way reduces the costs of decarbonization. Furthermore, the benefits of sector coupling are considered to include increased reliability and adequacy of energy resources. The main objectives of EU Energy Climate policy are sustainability, the security of supply, and competitiveness, which are aimed to achieve via the most important sector coupling strategies such as electrification, deployment of low-carbon energy sources, gas-electricity sector coupling, and using a broad mix of energy technologies with a technology-neutral stance. Electrification is considered as the most important tool in decarbonization, as currently most of the decarbonization progress has been achieved in the electricity sector, as carbon-free nuclear and variable renewables comprised 51% of the net electricity generation in EU-28, even though combustible fuels still comprised 49% (Eurostat, 2018). Other sectors, such as transport, heat, and industry are even more dependent on fossil fuels. However, some countries have already achieved a

nearly fossil-fuel-free electricity generation mix, e.g. Finland where 79% of the electricity generation was carbon-neutral in 2018, with the mix of renewables and nuclear (Finnish Energy, 2019). Other examples are Norway 98%, Sweden 97%, and Denmark 63% of carbon dioxide neutral electricity. As well as the costs of wind and solar have reached good competitiveness compared to conventional energy sources, they are a cost-efficient way to decarbonize energy demand. Big opportunities of electrification are seen in end-use sectors, such as passenger transport or heating of buildings, as the efficiencies of electric motors (>90%) or electric heat pumps (200-400%) are significantly superior to the conventional internal combustion engines (<30%) or fossil-fired boilers (60-80%). The electrification of heat and transport sectors can also improve the flexibility of the electricity system by optimizing the use of electricity during periods of low demand. Some sectors are more challenging to electrify, such as industrial energy demand and some parts of the transport sector. In this context sector coupling and deployment of carbon-neutral gas are seen in a complementary role via power-to-gas technologies, energy storage, and gas-to-power technologies, which are also seen as a way to ensure the system stability and security of supply with large amounts of variable renewable electricity production. Deployment of renewable and other carbon-free technologies can also be advanced by sector coupling. For heating and cooling in buildings and industry, which consumed around half of the final energy consumption in EU in 2015, end-use sector coupling methods include heat pumps and electric boiler and cross-vector integration through combined heat and power or district heating, where renewable energy sources can also be used directly via geothermal or solar heat, or indirectly via electric heat pumps and renewable heat sources.

1.3 How can sector coupling be achieved

As said in previous chapters electrification plays a big role in the EU Commission's sector coupling vision. Heat pumps are a viable solution to the electrification of low-temperature heat but for high-temperature heat (>200°C) there is still no commercially available heat pump option. The electricity required to electrify as many sectors as possible is assumed to be mainly from intermittent renewables, nuclear facilities and biomass/renewable gas. A large portion of intermitted renewables in the energy mix is inevitable if the time of production deficit is wanted to be minimal. This will lead to occasional surplus production which is not wanted to be curtailed in order to make the most profit out of the capacity. For the purpose of evading the waste of energy from curtailment, the surplus electricity could be used to convert water into hydrogen via numerous methods of electrolysis. This hydrogen is thus considered to be renewable, and it could be used in many sectors, such as chemical industry, transportation, and gas grids. Hydrogen is widely used, as a feedstock in manufacturing different chemicals, to produce high-temperature heat for processes and as a reductant in steelmaking. As of now, hydrogen is often made in the steam reforming process which uses fossil methane as a feedstock, therefore this is one great opportunity for applying sector coupling. In the long run, renewable synthetic fuels could play a bigger role in aviation and marine sectors, which are difficult to electrify. Using algae as a feedstock of biofuel production could become a viable option in order to reduce the competition of land area between food and energy sectors. Sector coupling can be achieved through demand-response technologies, such as smart charging. The battery capacity of electric vehicles can be used to balance the electricity demand between surplus and deficit periods. Other home appliances, such as fridges or heating, can be used for the same purpose. Other possibilities for maintaining grid balance include pumped hydro, geothermal storage and conversion to gases or fuels. Implementation of all these technologies will make the high penetration of intermittent renewable technologies more plausible.

1.4 Barriers to sector coupling in the short and medium-term

There are several techno-economical barriers to sector coupling. The biggest barrier to sector coupling can be seen to be the need for further innovation in technologies to improve the techno-economical feasibility. This includes various supply, demand, transmission, distribution and storage technologies. As renewable electricity production is variable by its nature, it needs back-up in some form. While the combination of renewable electricity production and local energy storage is not yet competitive with other existing solutions, more innovation needs to take place. Converting electric energy into gas, like hydrogen or methanol, is estimated to be 20% more expensive than fossil fuels even in 2050 unless taxation is considered. The same kind of examples can be found for other modern technologies as well. This is why impacting on the cost and performance in sector-coupling technologies by innovations would be feasible, in the same way as biomass-based CCS (carbon capture storage) depends on the efficiency of CCS technologies. (European Parliament 2018). In the infrastructure side, the power transmission capacity and utilization need to be further monitored and controlled. Adequate infrastructure for energy carriers such as power, gas, heat or CO₂ is a major barrier. For example, heat networks will require larger investments comparable to electricity or gas infrastructures. For electricity and gas investments it is estimated to require €114bn investments in Europe by 2030. These kinds of large investments are making new technologies like renewable-based district heating uncompetitive with decentralized technologies. Also, the existing standards and regulations need adaptation e.g. to enable injecting hydrogen into the gas grid. Market conditions can restrict the development of new technologies or those with limited resources like hydrogen. Reliable and financially predictable frameworks for new business models are therefore needed. The limited availability of resources of biomass feedstock and biomass production is hindering the sector-coupling opportunities in some areas. The effective use of solar steam reforming of hydrogen is also limited in high-solar radiation areas such as Southern Europe and Northern Africa. The local climate conditions are also relevant for the effectiveness of air-source heat pumps. Hence the most effective technologies in sector coupling are varying by region and application according to available resources, market conditions and performance of the technologies. There are also several political and regulatory barriers to sector coupling. A major barrier is the lack of integrated planning and operation of the synergy potentials of energy sectors. These can be seen as long-term barriers. These kinds of barriers would have to be overcome by an integrated, forward-looking approach that requires co-operation between all energy sectors and all levels. These scenarios would need future-proof investment planning and corresponding enabling regulations since the climate and energy policies affect sector coupling by impacting the enabling technologies. (European Parliament 2018)

2 Stakeholder analysis

Finnish Energy (Energiateollisuus) is the political advocacy of the Finnish Energy sector. It represents the companies that produce, transmit, supply, sell or buy electricity, natural gas or district heating and cooling. It negotiates on the collective labor agreements and provides information and feedback between the authorities and the business sector. The figure below indicates how the participants (Government, Energy companies, energy-intensive industries and Energiateollisuus) interact with each other in terms of information, regulation and money. ((ET) 2019)

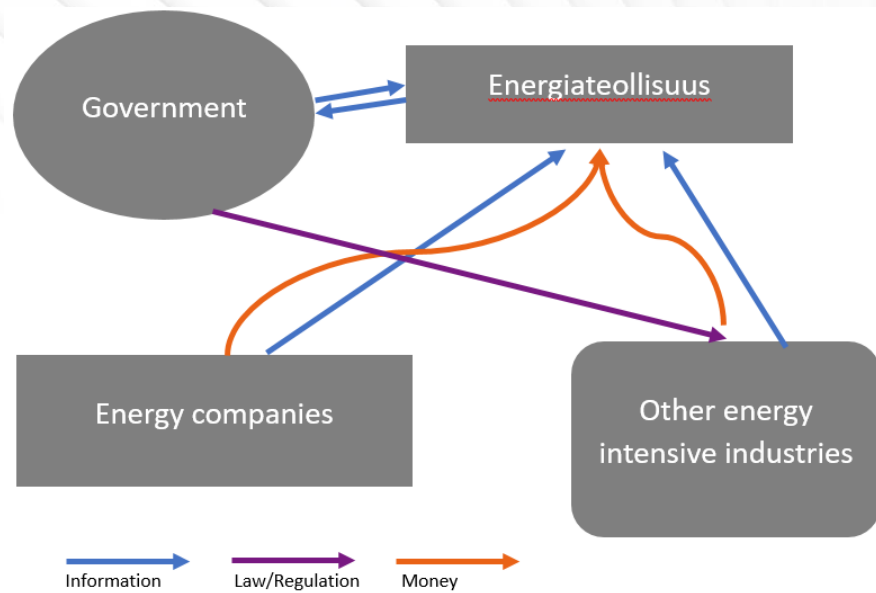


Figure 1. Stakeholder analysis – Energy Finland.

3 Literature review - the examples of successful sector coupling.

Presently Sector Coupling is globally applied in transportation, heat and electricity, energy storage and conversion of various materials. This chapter focuses on the possibilities for SC that could be successfully applied to optimize various systems.

3.1 Transport

The transport sector including all modes is responsible for 29% of the Total Final Energy Consumption (TFEC) in the world, whereas in Europe it accounts for about 33%. According to the International Energy Agency (IEA), global carbon dioxide emissions resulting from fossil fuel combustion were equal to 32.3Gt of CO₂ in 2015, While the transport sector is responsible for 24% of those emissions. Sector Coupling in transportation has big opportunities for decarbonization, especially when looking at the present and future fleet of various powertrains. Nevertheless, dependent on the mode of transportation, there are certain limitations for SC in terms of alternative solutions. Understanding the need for liquid fuels versus electrification potential in the transport is essential for further development of relevant solutions with SC. Figure 1 summarizes those relations in different modes and indicates possible options for SC. The Renewable Energy Source (RES), means either electricity, heat or feedstock such as biomass. Power to X (P2X), means the conversion of electricity to another form of energy, such as the energy stored in the chemical bonds of various molecules, for example, the case of power-to-gas (P2G). P2G can be further upgraded into liquids, and that technology is known as Gas to Liquids (GTL). The second option is Heat to X (H2X), various streams of heat could be utilized to provide the necessary environment for reactions of gas and liquid fuels production. On the P2X pathway, electro-fuels so-called efuels and synthetic fuels are produced, whereas H2X leads to the production of biofuels. When speaking about the utilization of electricity in transportation, options generally assigned to X to Power (X2P) and direct utilization of electricity (peak shaving) are possible

in the SC. When speaking about X2P, various RES and waste streams of energy could be converted to electricity for propulsion.

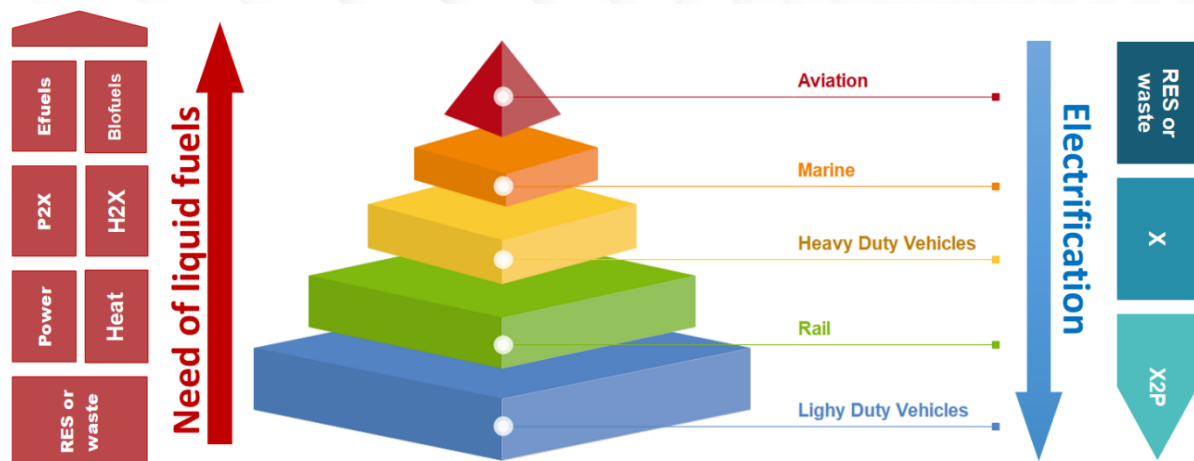


Figure 2. Electrification vs need for liquid fuels in the transport sector.

As presented above, there are large possibilities for sector coupling in transportation. Globally there are many successfully applied cases of SC that are continuously decarbonizing the sector. Sustainable electricity or its excess could be used for electrolysis of water to produce hydrogen fuel. Hydrogen together with electricity and carbon dioxide could be further used in the methanation process to produce methane. Hydrogen and methane are excellent fuels for fuel cell (FC) applications, but also for internal combustion (IC). Methane can be produced while utilizing the waste streams of heat – heat to x (H2X). The benefit of this option is that the process of digestion requires low temperatures, around 20 – 70 degrees Celsius, dependent on the type of bacteria. Which is an excellent occasion for the management of the waste heat streams from industrial processes. H2X could be also considered in fermentation processes for alcohols production. In order to provide sustainable electricity for propulsion in transportation, X2P brings promising solutions for SC (Robinius, 2017). Production of electricity, by combustion in IC engines or electrochemical conversion via FC, are suitable options for the utilization of various gaseous, liquid and solid energy carriers. The third and industrially very applicable solution for SC in transportation is X2X, which means the conversion of one form of molecules into another, such as in the case of gas to liquid (GTL). However, even heavier molecules can be effectively converted into longer chains including not only regular alkanes but many more compounds.

3.2 Heat and electricity

Energy consumption for heating and cooling purpose is playing a major role in GHG emissions. It is also one of the greatest energy end-uses in the EU: around half of the final energy demand was used for heating in 2015. This consists of space heating and industrial process heating.

Sector coupling technologies for combining heating or cooling and electricity are direct use of renewable energy sources like geothermal energy for heating, direct solar heat, using biomass for heating, and electric heat pumps. Some technologies, such as solar, are of course dependent on the geographical location. Electric heat pumps can be considered as the option with the best technical

performance, as their coefficient of performance is rather high (even around 3). (European Parliament 2018)

Heat and electricity sectors have been coupled for a long time through combined heat and power production (CHP) in some countries e.g. Finland, Sweden. The waste heat from conventional power production has been used in district heating since the 1960s. Originally it was a big improvement in general energy and cost efficiency when the heat from power plants was no longer wasted and replaced the property-specific heating and fuel needs in the buildings. Currently, the next energy transition problem to solve in these kinds of countries that already have applied widely district heating is the fact that conventional CHP plants still produce emissions that have to be reduced.

The electrification of the heating sector is one way to reduce the emissions of heating. It has been already done in a few district heating networks by installing industrial-scale heat pumps for district heating and cooling production. Examples of these are Katri Vala heat pump plant in Helsinki, Suomenoja heat pump plant in Espoo, Värtan Ropsten Heat pump plant in Stockholm. Additionally, the cooling sector is also coupled with heat and electricity through heat pumps, as a heat pump always produces simultaneously heating and cooling while using electricity.

Additionally, more direct power-to-heat solutions, which do not require a heat source, are also applied in district heating. One example of this is a new power-to-heat facility (120MW) in the Reuter West power plant in Berlin, which is aimed to be using excess electricity generated from variable renewable sources and can also be used as to store heat.

Electrification of heating of buildings is quite far already in Finland, as electricity and heat pumps cover 32 % of the building heating needs. The rest is covered by district heating (traditionally mainly CHP) 46%, wood 13%, oil 8%, and others 1%. (Official Statistics of Finland, 2018)

3.3 Energy Storage (and gas)

Storing energy to be used at a later time has always been in the interest of energy system operators, and there have been several different ways of doing so for quite some time already. Most commonly, energy has been stored in fuels, such as oil and gas, and there are even some regulations regarding storing energy. For example, EU members are obliged to uphold oil storage worth of 61 days of consumption or 90 days' worth of oil imports, depending on which figure is the largest. Furthermore, the EU sustains gas storage with the total capacity equivalent of 23% of annual gas demand, in order to prepare for unexpectedly cold winter months. (European parliament 2019)

However, the vast majority of 97% of the total storage capacity in the EU, is done by using pumped hydro technology. Pumped hydro is already used in sector coupling, as it is used to store excess amounts of electricity, e.g. from Danish wind power, by pumping water into reservoirs in Norway. The major setback of this technology is that there are practically no suitable sites left to converted into reservoirs. Therefore, this storage method doesn't offer great opportunities for sector coupling as the existing capacity is already being utilized (European parliament 2019)

A similar principle, as in pumped hydro, is applied in Compressed Air Energy Storages (CAES). This storage technology relies on potential energy through the air's ability to compress and expand controllably. The potential sites for CAES are, for example, decommissioned salt mines and other large rock caverns. (De Samaniego Steta 2010) The existing Compressed Air Energy Storages' capacities vary from tens of megawatts up to 330MW in power and 2860MWh depending on the use case. For

example, in 1978 a CAES plant was built in Huntorf, Germany, with a capacity of 290MW and 580MWh giving it a run time of two hours with full power. In order to make CAES low-carbon technology, either renewable electricity or biogas must be used in heating the expanding air while discharging. Currently, gas turbines that use fossil gas are often used and large amounts of heat is released to the atmosphere. Technologies, such as Advanced Adiabatic Compressed Air Energy Storages (AA-CAES) have been developed to address these issues. Other barriers to this technology include the lack of feasible sites regarding environmental sustainability. (IRENA 2017)

A more modern electricity storage solution are batteries, such as Lithium-Ion batteries, that store the energy in chemical bonds. These kinds of electricity storages are used widely from electric devices to peak shaving and grid control. An example of utility-scale batteries is energy company Fortum's so-called 'Batcave', which is the largest Li-ion battery in the Nordic countries with a capacity of 2MW/1MWh. Needless to mention, this technology doesn't offer a longer-term storage solution, but it has a place in demand response and grid control. One worrying part of this technology is the global distribution of material resources and manufacturers, as only 3% of Li-ion batteries are made in the European Union. The second and even more concerning fact is that the materials needed in batteries are usually rare and fossil by nature, therefore making the obtaining of them to be extremely stressful to the environment.

Flywheels store energy in the angular momentum of rotating masses. They are charged by spinning the mass with a motor, and when discharging, the rotating uses the engine acting as a generator. Flywheels are very useful for applications, where instantaneous power is required, but their low energy storage capacity remains a problem. Also, flywheels have rather large standby losses and can have dangerous failure modes. Flywheels are however very durable, able to last hundreds of thousands of charging cycles. (Evans, Strezov and Evans 2012) However, according to Finnish startup Teraloop, their flywheel electrical energy storage (EES) prototype is scalable enough to suit different use cases such as peak-shaving and frequency control. Teraloop's pilot project is planned to be 5MW in size and the company even received the EU Horizon 2020 SME program's grant of 2,4 million euros for further development. (Teraloop 2019)

Power-to-gas solutions could play a complementary role since in addition to storing energy, gas products can be used in applications that are difficult to electrify. The most obvious option is to use hydrogen as the energy carrier, since it can additionally be processed to react with CO or CO₂, which would then produce synthetic methane or synthetic liquid fuels, which could also be used in other sectors, such as transportation. However, these technologies are not yet competitive with fossil natural gas. (European parliament 2019)) There are some new technologies to achieve Power-to-gas, which have the potential to make this viable. A reversible Solid Oxide Cell reactor-based system for both electricity storage and sector coupling has been researched. This system, which was hydrogen or methane-based, achieved roundtrip system efficiencies of 53%. (Santhanam 2018)

Heat storage can be used to a couple of different kinds of power generation together. For example, Denholm et al propose in their paper that Nuclear and renewable power generation could be coupled together with the help of heat storage attached to the nuclear power plant. In this research paper (Denholm, et al. 2012), Denholm et al propose attaching heat storages to nuclear power plants, so a variable amount of electricity could be generated using the heat storage while allowing the nuclear power plants to run at a constant load. The efficiency of heat storage is up to 95%, so this would not cause too large losses. Storage mediums such as molten salt are proposed. The paper does recognize that any such solutions would increase the design and operation costs of the reactors and would require significant attention to the selection of the storage medium and heat exchanger design.

3.4 Materials and Conversion

Waste can be separated into two main categories: Municipal waste and industrial waste. Both include multiple material streams that need to be handled in a circular economy manner. In the EU waste hierarchy, recycling is considered the best option. It means separating useful materials from the waste stream for re-use. Waste to energy (WtE) technologies are considered second-best options for waste management while landfilling is the last resort option. In EU 43% of municipal solid waste (MSW) is recycled, 31% landfilled and 26% incinerated. 3/4 of incineration is located in Sweden, Germany, France, Italy, Netherlands and the UK. From the waste management point of view, skepticism exists toward WtE technology, as it undermines recycling. From the renewable energy point of view, WtE plays a key role, as biomass and waste account for 63.1% of renewable energy in Europe. (Malinauskaite et al 2017)

From a sector coupling point of view, it is of interest to find ways new ways to utilize the material streams in the waste. Possible solutions include innovative material recovery and WtE. Currently, WtE technology is focused on incineration using a grate or fluidized bed boilers. For example, in Norway, an incentive exists to increase biofuel production from waste, because they already have enough renewable electricity. Norway has set a target to increase the production of biofuel from waste to 24 TWh until 2020. (Malinauskaite et al 2017)

Several promising processes for advanced biofuel production exist. For example, the production of high-quality biofuel from various biomass sources is possible through thermochemical liquefaction. Especially hydrothermal liquefaction can process feedstock with water content up to 90%, which makes it a promising technology, even though it is in the pilot stage. (O.K.M Ouda et al 2015)

One specific source of biomass in Finland is the pulp and paper industry. As a side product of cellulose production, a big amount of lignin is dissolved, as 25% of the tree is lignin. It can be converted to biofuels. Possible pathways include gasification, pyrolysis or hydrothermal liquefaction. These processes can lead to various end products such as ethanol, bio-gasoline, upgraded hydrocarbons and bio-crude. (O.K.M Ouda et al 2015) Another study in Linköping university suggests using benzenediols from lignin for carbon-neutral electricity production with an organic fuel cell (Che et al 2018).

The steel industry is one of the most energy-intense industries, causing high CO₂ emissions. There is a project by SSAB and Vattenfall called Hybrit, which aims to reduce emissions from the steel industry drastically. The basis is the direct reduced iron process, where coke is replaced with hydrogen as a reducing agent. Required hydrogen for such processes can be produced with PEM electrolysis using renewable energy from wind or sun to separate hydrogen from water. (European parliament 2019)

Soletair project by VTT takes a step further promising it is able to produce any hydrocarbons by producing the required hydrogen with PEM electrolysis and the required carbon with direct air capture. Fischer-Tropsch synthesis is used to produce natural gas, liquid fuels or wax components, depending on the reaction conditions and catalyst of the Fischer-Tropsch reaction. (Vidal Vazquez et al 2018).

3.5 Unified table - opportunities for sector coupling.

The following table represents possibilities for sector coupling while utilizing electricity, heat and various materials. In the table, one can find various options for conversion and end-use in the transport (T), industry (I), residential (R), commercial (C) and fuel production (FP). Additionally, representative approximate efficiencies and costs were found in the literature and linked to the relevant pathway.

Table 1. Opportunities for sector coupling while utilizing electricity, heat and various materials.

Energy source		Option		Feedstocks or additions	Conversion		Total	Examples of costs	End product	End-use		
Examples	Generation				General	Infrastructure	Efficiency	CAPEX				
Wind Solar PV Hydro Biomass Nuclear Hydrogen FC Peak shaving MSW	Electricity	P2X	Power to Gas	H2O	Electrochemical	Electrolysis	70 - 95%	750 - 1200 €/kW	H2	T, I, FP		
				CO2, H2, heat	Chemical	Methanation	70 - 80%	800 - 1200 €/kW	Methane	T, I, R, C, FP		
		P2H	Power to heat	Heat source	Mechanical	Heat pump	200-700%	610 k€/MW	Heat	I, R, C, FP		
				-	Electrical	Large electric	>99%	190 k€/MW				
		Storage	Potential energy	Infrastructure	Mechanical	Pumped hydro	75-85 %	150 €/kWh	Electricity	T, I, R, C, FP		
				-		CAES	70-89 %	400 - 1200 €/kW				
				-		Flywheels	93-95 %	500 – 2 000 €/kW				
			Kinetic	Electrolyte	Chemical	Industrial batteries	70-90 %	1000 - 3000 €/kW				
						Vehicle to Grid	70-90 %	0,05 €/kWh (el)				
Air Geothermal Waste Metal refining Chemical industry Food industry Nuclear Solar thermal Biomass	Heat	H2X	Heat to gas and liquids	Biomass	Biochemical	Digestion	20 - 70%	8-100 €/kWh	Methane	T, I, R, C, FP		
						Landfill gas (LFG)	50 - 99%		Bioethanol	T, I, C, FP		
						Fermentation	80 - 90%		Heat	I, R, C, FP		
		H2H	Heat to heat	Electricity	Thermal	Heat pump	200-700%	610 €/kW	Heat	I, R, C, FP		
		Storage	Sensible heat	H2O	Thermal (change of	Liquids	50 - 90%	0.1-10 €/kWh	Heat	I, R, C, FP		
						Solids						
			Latent heat	Phase Change Materials (PCM)	Thermal (phase change)	PCM: Solids-Liquid	75 - 90%	10-50 €/kWh				
						PCM: Liquid-Gas						
Hydrogen Methane Hydrocarbons Biomass Lignin Vegetable wastes Cellulose Starch MSW	X (materials)	X2P	Gas to Power	H2, CH4	Thermal and electrochemical	Fuel cells	25 - 35%	6000 €/kW	Electricity and propulsion	T, I, R, C		
			iquid to Powe	Liquid fuels		Combustion	20 - 51%	500 k€/MW				
			Solid to Power	MSW, biochar		Combustion	30 - 80%	1m€/MW	Electr.and heat	T, I, R, C		
		X2X	X to biocrude	biomass, H2	Thermochemical conversion	Gasification	75%	625 €/ton (annual)	Gaseous, liquid and solid fuels	T, I, R, C, FP		
						Pyrolysis	35 - 40%	815 €/ton (annual)				
						HTL	30 - 40%	560 €/ton (annual)				
			X to biodiesel	CH3OH	Physiochemical	Transestrification	60 - 95%	124 €/ton (annual)	FAME	T, I, FP		
			X to alcohols	Yeasts or bacterias	Biochemical	Fermentation	80 - 90%	150 - 5597 €/ton (annual	Bioethanol	T, I, FP		
			X to biogas	Bacterias		Anaerobic digestior	20 - 70%	430 €/ton	Methane	T, I, R, C, FP		

4 Research question: How to most efficiently deploy sector coupling in Finland?

In this chapter, the most important means to execute sector coupling will be answered. The answer is divided into five parts: Electricity, heat, energy storage, materials and transport. Table 4 gives a nice view of several technical solutions that can be utilized for the purpose. The intention of this chapter is to give a practical viewpoint of the solutions that could be implemented in Finland already today.

4.1 Electricity

Electricity will play a major role in the system level decarbonization since it can be seen as a clean form of energy when produced from renewable sources. In addition, the efficiency of electrical applications is rather high. Hence, with growing electrification in the future, the demand for electricity will increase as well. To cover that change and to reach carbon neutrality by 2035, there is a need for sustainable production of electricity and a strong reduction of fossil fuels in the electricity mix. In addition, considering the relatively cheap price of electricity in Finland, the expenses should stay at a reasonable level. The electricity pool in Finland 2018 was roughly Nuclear 32%, hydro 19%, biomass 19% and wind 9% and others, like peat, oil, natural gas, coal and solar, 21%. The total share of carbon-neutral was 79% with 47% renewable production (Energiategollisuus 2019). According to the Finnish wind power association; there would be room for almost three times the current wind energy in the electricity markets. The modern wind turbines go over 7MW per unit in power and are usually built as wind parks because of the scale economics. When building on the ground, the investment costs are around 1,5M€ / MW. However, the production of electricity being free in terms of fuel cost makes the investments feasible. When building offshore, the investment costs are 20-50% more. The Finnish government has proposed to reduce the property tax of offshore wind parks to make them economically more feasible. (Suomen Tuulivoimayhdistys ry 2019) The excess power generated by modern wind turbines could be used for electrolysis to produce hydrogen. The hydrogen can then be used e.g. for fuel in transportation. Other probable solutions for more modern and climate-friendly energy production are rooftop-solar installations in houses and apartment buildings, modular sized nuclear power plants, increased use of biomass combustion instead of oil-based fuels and CHP.

4.2 Heat

In the heat sector, there is a need to replace fossil fuel combustion with other heat production technologies that do not require combustion, both in district heating and industrial heat production. One way via sector coupling is heat production using electricity as a fuel, with technologies such as heat pumps and electric boilers. Using electricity as a heat production fuel has the advantage of very high efficiency with heat pumps, but there exist still barriers, such as electricity tax that is still very high compared to fossil fuel taxes in heat production. Suggestions to reduce emissions via sector coupling in the heat sector are following:

- Utilization of available waste heat sources in the nearby areas for district heat or industry heat
- Direct utilization of higher temperature waste heat, such as from condensing power plants e.g. nuclear power plants
- Identification of waste heat sources and nearby heat demand areas: eg. Oulkuoto: Pori, Rauma, Turku, Hanhikivi: Oulu, Raahel, Loviisa: Loviisa, Kotka, Porvoo, Capital region
- Utilization of lower temperature waste heat with the aid of heat pumps
- For example, Kilpilahti oil refinery's waste heat utilization with heat pumps in the capital region, and other industrial waste heat sources and utilization in nearby cities' district heating networks

- Utilization and development of high-temperature heat pumps for industry heat production (currently up to 120°C) and heat recycling
- Utilization of electric heat pumps with ambient heat sources
- Large-scale heat pumps using geothermal or water as a heat source in district heating or industry
- Small-scale heat pumps using the ground, water, or air in households
- Utilization of electric boilers when heat pumps are not applicable (no heat source available or very intermittent production need)
- Power-to-heat and heat storage using excess electricity from variable renewables, when the heat is more economical to store than electricity
- Need to develop other low-carbon high-temperature heat sources for industry heat (e.g small modular nuclear).

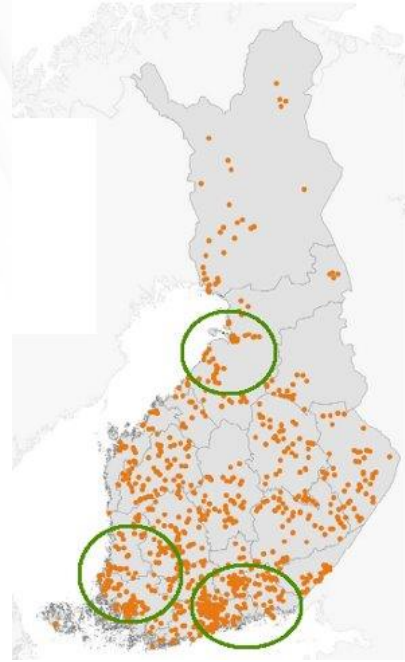


Figure 3. Local district heating network areas marked with orange and large condensing nuclear power plant heat sources in the green-circled areas on the map.

4.3 Energy storage

Employing energy storages could help the energy producers to get rid of curtailment, i.e. restricting profitable generation at times of low demand. This can be done in Finland in numerous ways, such as utilizing rock caverns as thermal storages or constructing megawatt-scale batteries, as Helen has already done in Helsinki. Finland's geographical profile does not allow building dams and reservoirs required for pumped hydro storage, and 10+ megawatt batteries would be extremely capital intensive, so there are not many options for economical large-scale electricity storage. However, compressed air energy storage could still be considered viable for the context of Finland, as Finland has a lot of base rock that would be suitable for such systems. At least in theory, a CAES facility with capacity from 50 MW to 300 MW could be built in an old mine shaft, etc. (Salameh 2014). The environment center of Finland has a list of all decommissioned mines in the country, out of which several are underground and therefore fill the preliminary criteria for CAES (Anna Törnivaara 2018). Although batteries might be considered expensive amongst the variation of electricity storage options, they still have multiple lucrative use-cases in the energy industry. One clear use-case is to help balance the grid when intermittent renewable capacity increases in the system. For example, in the year 2018, Finland had a wind power capacity of 2041 MW, but there is nearly 16500 MW worth of capacity being planned and 1305 MW is already under construction (Suomen Tuulivoimayhdistys ry 2019). This means a lot of poorly predictable generation that needs to be balanced with the demand in hand. Some energy producers are now mitigating this problem by incorporating Lithium-ion batteries in the wind power parks. E.g. Tuulivoima Oy is building a record-breaking 6 MW battery to its 4,2 MW production site in Viinamäki. Finland's TSO Fingrid considers this development as a positive one since it brings relief to the task of balancing the grid and therefore creates savings in its grid development (Jouko Kyytsönen 2019). In the context of batteries, there is also a new and more progressive development rearing its head. Finland's national Energy and climate strategy for 2030 states that an amount of 250 000 electric vehicles (EV) can be predicted, all of which will contain a battery within a capacity range of 25-100 kW (Government 2016). Not every EV of

this fleet will be equipped with Vehicle-to-Grid (V2G) technology, but a large share can be assumed, nevertheless. For illustration, if only 2500, in other words, 1%, of those 250000 EVs would be connected to V2G charger with 10kW at the same time during a workday in Helsinki, that would create a controllable load for peak shaving and 25 MW temporary battery for further demand response. Discharging citizens' EVs would, of course, have to be compensated, and the utility would have to pay each customer at least the current SPOT-market price, which in Finland would be under 0,05 €/kWh. For complementary short-term electricity storage demand, there are still a couple of cards yet to be turned for the Finnish power system. Ultracapacitors, for say, have high roundtrip efficiency of 90-95% whereas their capacity is often limited to 0,3 MW and run-time up 1 minute. This still makes feasible for grid balancing purposes, which is an increasingly important issue. The same goes for flywheels, which also have high efficiency but small capacity and short run time. Although, it needs to be noted that they could run up to 15 minutes. (Evans, Strezov and Evans 2012) However, they both possess the same major flaw of having quite a large capital expenditure cost, 67627 €/kWh for ultracapacitor and 10470 €/kWh for flywheels (K. Mongrid 2019). At the beginning of this chapter, Helen's thermal storage plans were mentioned. In essence, Helen is turning old oil storage reserve caves into sensible thermal storages which use water a medium, in order to store up to 4 days' worth of heat for Helsinki citizens (Marina Galkin-Aalto 2018). Unfortunately, feasible rock cavities near enough to the consumptions, are quite unique and therefore not all heat storage demand can be satisfied with this solution. Another way, than to just heat water, is to use latent thermal energy storage by storing energy via phase change of the medium rather than increasing its temperature. In this case, the medium is usually a miscibility gap alloy which changes phase from solid to liquid state without a notable increase in temperature, when the heat is added and vice versa. The third option is to store heat using chemical reactions such as hydrating and dehydrating salt. Here, heat is used to vaporize water from a solution in an endothermic reaction, and the absorbed heat is released again when water is added back. In addition, there are multiple ways of storing heat in the markets, such as molten salt storages and heated rock masses, but all other than water-mediated sensible thermal storages tend to be either too inefficient or too expensive to be lucrative choices for Finnish industry. (Sebarchievici 2018)

Table 2. Energy storage properties (Evans, Strezov and Evans 2012) (Watt-Logic 2017). X=number of EVs.

Energy storage technology	Storage capacity	Type	Runtime	Maturity	Efficiency	Storage case	LCOS
Sensible water	0,001-120 MW _{th}	Thermal	Hours-months	Mature	50-90%	Intra-day	1-10 €/kWh
Phase-change material	0,001-1 MW _{th}	Thermal	Hours-months	Demonstration	75-90%	Seasonal	10-50 €/kWh
Chemical reactions	0,01-1 MW _{th}	Thermal	Hours-days	Demonstration	75-100%	Intra-day	8-100 €/kWh
Pumped Hydro	100-5000 MW _{el}	Mechanical	1-24h	Very mature	75-85 %	Seasonal	0,14-0,18 €/kWh
CAES	5-400 MW _{el}	Mechanical	1-24h	Mature	70-89 %	Seasonal	0,11-0,13 €/kWh
Batteries	0,1-40 MW _{el}	Chemical	Seconds-hours	New	70-90 %	Intra-day	0,17-0,92 €/kWh
Fuel Cells	0,1-50 MW _{el}	Chemical	1-24h	New	20-50 %	Seasonal	0,02-0,57 €/kWh
Ultracapacitor	0,3 MW _{el}	Electrical	ms-60s	New	90-95%	Grid balance	1820-10000 €/kWh
Flywheels	0,25-5 MW _{el}	Mechanical	ms-15min	Demonstration	93-95 %	Grid balance	0,31-1,14 €/kWh
Heat storage	120 MW _{el}	Thermal	Hours-days	Mature	50-90%	Intra-day	0,1-10 €/kWh
Vehicle-to-grid	0,01-0,1 MW _{el} * X	Chemical	Seconds-hours	Demonstration	70-90 %	Grid balance	0,05 €/kWh

4.4 Materials

Finland has a huge potential as a producer of lignin-based products. The production of pulp in Finland is 11.65 Mton/year (Metsäteollisuus ry 2018), generating approximately 81.55 Mtons of weak liquor as a side product. Around 10% of this is organic solids, which contain around 40% of lignin. This leads to the production potential of 3.262 Mton/year for lignin, which could be utilized in form of multiple products: As a substitute for fossil phenols in paint and glue production, or raw material for carbon fiber, which can be utilized for many purposes. One possibility is to produce high-quality liquid biofuels from lignin, substituting fossil alternatives (Tekniikka ja talous, Ligniinistä kehitetään hiilikuituja ja muovin korvaajia 2016). Utilizing the whole 3.262 Mton of lignin for renewable fuel production with hydrothermal liquefaction could provide 1.5 billion liters of renewable fuel for 1\$/liter price (Lilu T. Funkenbusch et al. 2018). In comparison, the consumption of gasoline is 1.9 billion liters per year in Finland (STT 2018). Therefore, lignin-based renewable fuel could substitute around ¾ of gasoline. The steel industry is changing rapidly, as several manufacturers are piloting solutions that could drastically reduce the emissions of production processes. SSAB Hybrit is a project which aims to reduce the emissions of steel production close to zero by substituting fossil fuel with hydrogen. SSAB factory in Raahe emits 4.2 Mton of CO₂ alone, so by transforming the process to fossil-free alternative the total emissions in Finland could be cut out by 7% (Tekniikka ja talous 2019).

4.5 Transport

The energy sector is responsible for around 74% of total emissions in Finland, 28% of which is caused by transportation (Land, water and air). The total emissions of transport are 11.5 MtonCO₂-ekv/year (2017), most of which is caused by land transport. (Tilastokeskus 2018). Electrification is a key point of the EU sector-coupling scheme. Most of the emissions (10.7 MtonCO₂-ekv) is caused by land transport, 55% of which is caused by passenger cars. However, the life cycle environmental impact of EVs is higher than internal combustion passenger vehicles powered by renewable liquid fuels (Figure 4). Therefore, both EVs powered by renewable electricity and ICEV powered by renewable fuels should contribute hand-in-hand; and complete each other to achieve the climate targets.

Life-cycle emissions

- E85 premium from Agroetanol (80 % CO₂ reduction)
- HVO waste cooking oil (91 % CO₂ reduction)

Cars:

- Average European car
- 2017 Peugeot 208 1.6
- 2017 Nissan Leaf (30 kWh)

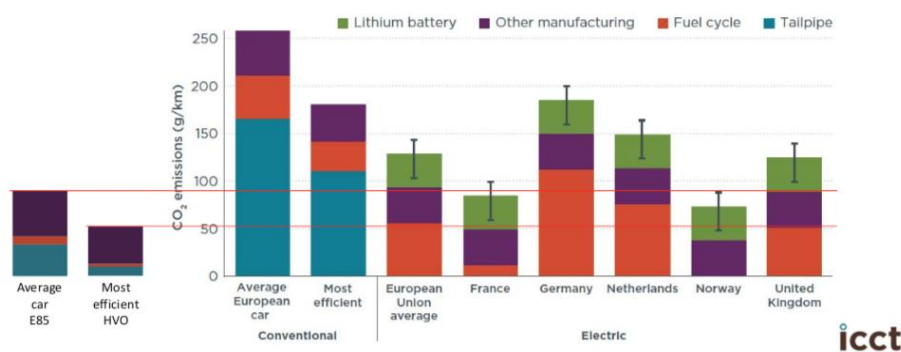


Figure 4. Comparison of life cycle emissions (over 150 000 km) of electric vehicles and internal combustion vehicles powered by renewable liquid fuels in Europe 2015. Source: International Council of Clean Transportation (ICCT) (Andersson 2018).

When considering the emission reduction possibilities in transportation, another important factor to take into account is the lifetime of cars. Currently, the average age of Finnish cars is 11.8 years (Keskisuomalainen 2017). If the average age will be constant, approximately half of the stock of cars will recur in 11.8 years. Therefore, it can't be assumed that the sector will change very rapidly if no strong political actions are implemented in favor of EVs (such as financial support for EV purchase).

Therefore, large quantities of renewable drop-in liquid fuels in all modes of transportation will be necessary to meet the climate target. Good examples are renewable diesel (Hydrotreated Vegetable Oil – HVO) and renewable/synthetic gasoline or E85 for dedicated powertrains.

5 Methodology

5.1 System boundaries – Finland

In the very beginning of the project in hand, the group discussed internally and together with Energiategollisuus, what system boundaries would be interesting to perform analysis within. After considering two options, the capital region and the whole country, the group came to the conclusion that the whole of Finland should be included, even though the capital region could have sufficed as well. This was due to the fact that the capital region is already quite coupled regarding the energy sector, and therefore the most viable opportunities lie in the untapped areas scattered all around the country. This report's physical boundaries are therefore selected to be in line with the borders of the Republic of Finland, as shown in figure 5 below. On the technology side, the group decided to set the boundaries for sector coupling to include heat and electricity production, transport, energy storage, energy-intensive industry, and households.

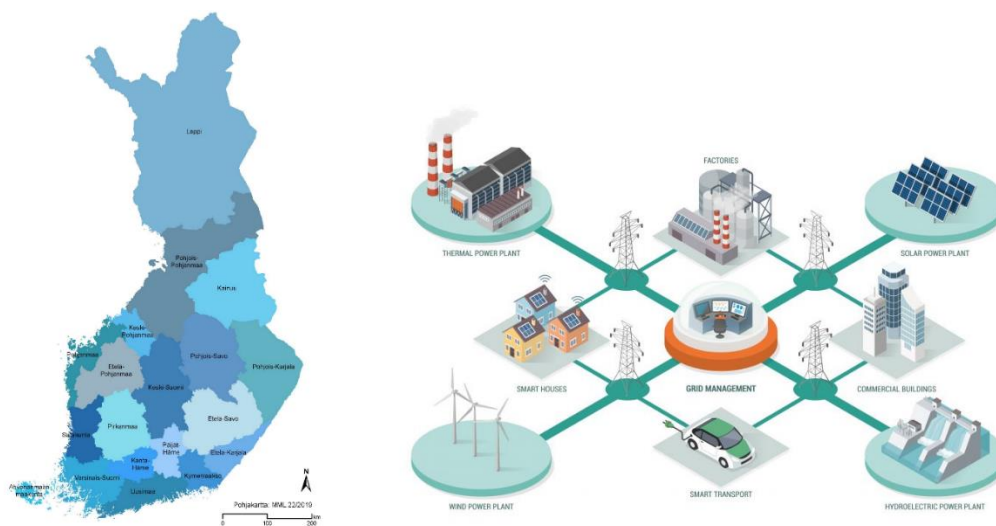


Figure 5: Physical boundaries illustrated by a map of Finnish municipality division (Varsinais-Suomen Liitto n.d.) & technological boundaries illustrated by sector coupling graph (Euractiv 2019)

5.2 The present state of the system and target

This is an overview of the data of the present state of the Finnish energy system. Modeling of the baseline – year 2016 was completed using the data from Statistics Finland's (Statistics Finland 2019).

5.2.1 Energy production by feedstock fuels and GHG emissions

The energy outputs by feedstock fuels are presented in figure 6. The first sector is heat-only production, which is around half based on wood combustion since Finland is traditionally a forestry nation. A considerable part of the heat-only production is produced with natural gas from Russia and with coal mainly along the coast due to easier coal supply by ships. Oil refining uses mainly crude oil as its feedstock but nowadays also vegetal wastes that are converted into biodiesel and ethanol for road transport. The third bar is electricity and combined cycles. This production is quite diverse in Finland, the largest part of which is nuclear power from Loviisa and Olkiluoto powerplants. Biomass, hydropower, wood, coal and natural gas are almost equal in shares of the total feedstock.

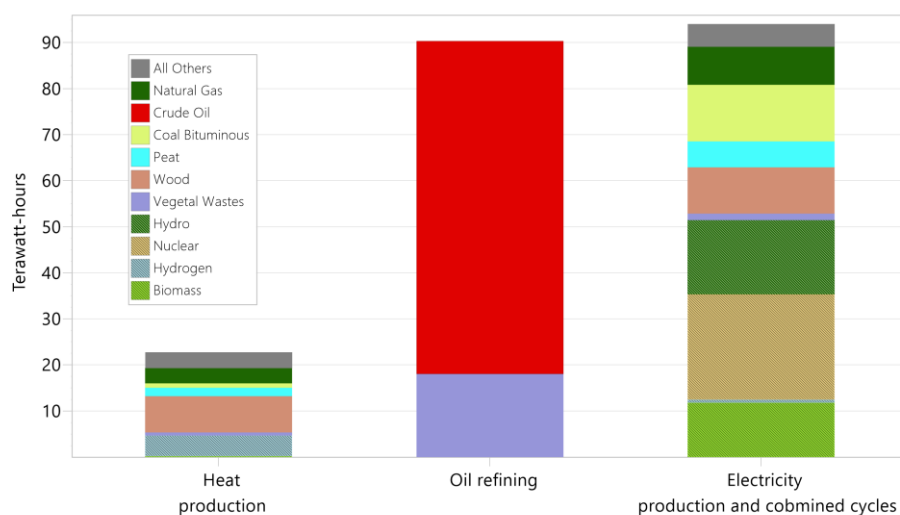


Figure 6: Transformation demand for primary energy carriers - Finland 2016.

Electricity production and combined cycles have, by far, the highest global warming potential of the three at around 6.5 Mt of CO₂ equivalent emissions while heat production and oil refining are almost equal to each other at a little under 3 Mt of CO₂ equivalent emissions. The biggest source of emissions in this sector is the use of coal, the second one is crude oil, the third one is peat, and after that comes natural gas and oil.

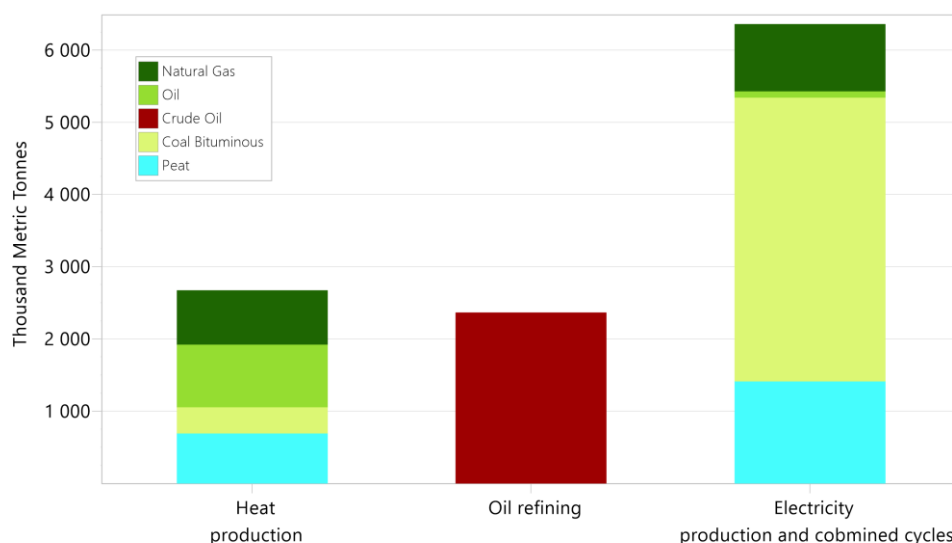


Figure 7: Transformation related GHG emissions – Finland 2016.

Finnish electricity production is currently dominated by CHP, nuclear and hydro, which are the traditional centralized power plants. In the last years, condensing power has diminished, as electricity price has been exceptionally low for a long time. A good example is Inkoo condensing power plant, which was demolished in 2019 after being shut down a few years ago. The future trend is also that the CHP plants using fossil fuels will be shut down at some point and the share of wind power will increase strongly.

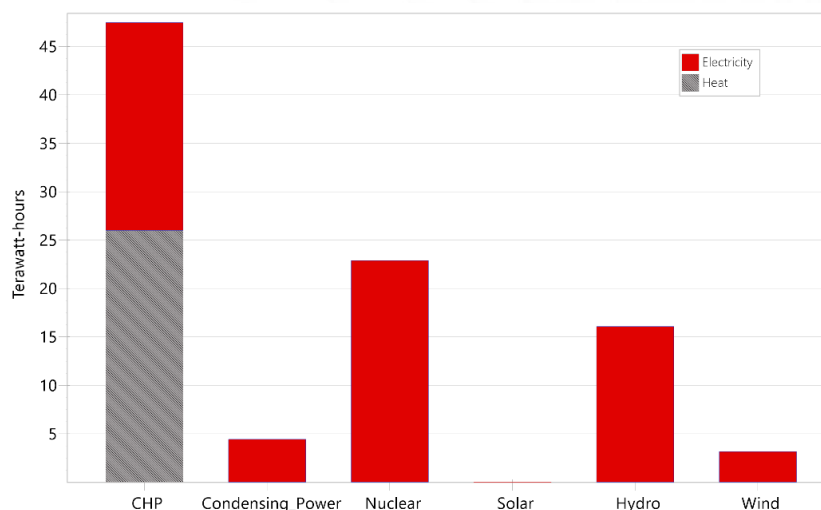


Figure 8: Electricity production and combined cycles - Finland 2016.

5.2.2 Energy demand and GHG emissions by end-use sectors

The industry is, by far, the largest consumer of energy in Finland using almost 140 TWh of energy. A significant part of industrial energy demand is met with the usage of wood. Coal, oil, heat and electricity also play a major role. High demand is explained by large traditional production plants such as wood and paper, metal refining and chemical production. Residential has the second highest energy demand after industry with nearly 80 TWh demand using mainly electricity and heat but also wood and oil. Third, the largest is transportation with approximately 60 TWh demand using diesel, jet kerosene and gasoline. Commercial buildings have the smallest demand of the four, with only 35 TWh demand. The commercial sector uses electricity, heat and oil as energy sources.

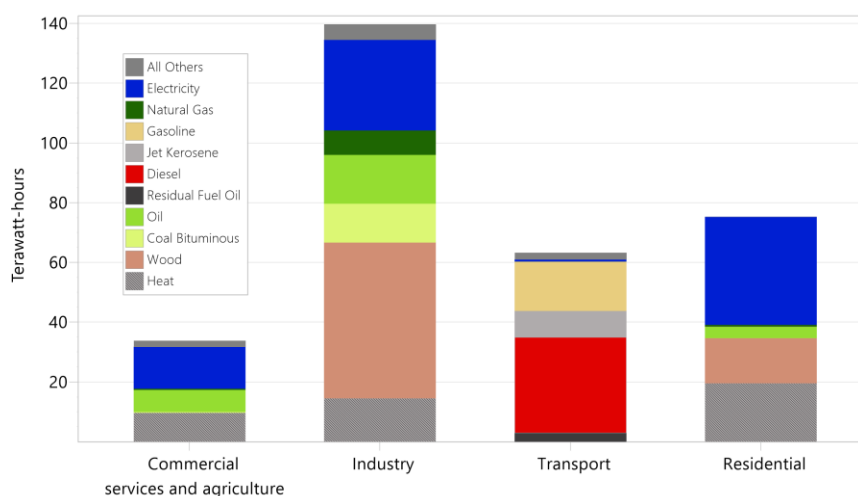


Figure 9: Energy demand represented by all fuels utilized directly in the end-use – Finland 2016.

The transport sector has a high GWP impact with around 15 MtCO₂. The industry is also a significant emitter while commercial and residential are substantially smaller. The industry sector's emissions are mostly from coal and oil, which is used in steel production and oil refining, and the chemical industry making plastics from fossil oil. From the pictures below and above we can see that the CO₂ equivalent emissions per GWh are exceptionally high for transport due to the fact that most of the energy is produced by burning different kinds of fossil oil with poor engine efficiency.

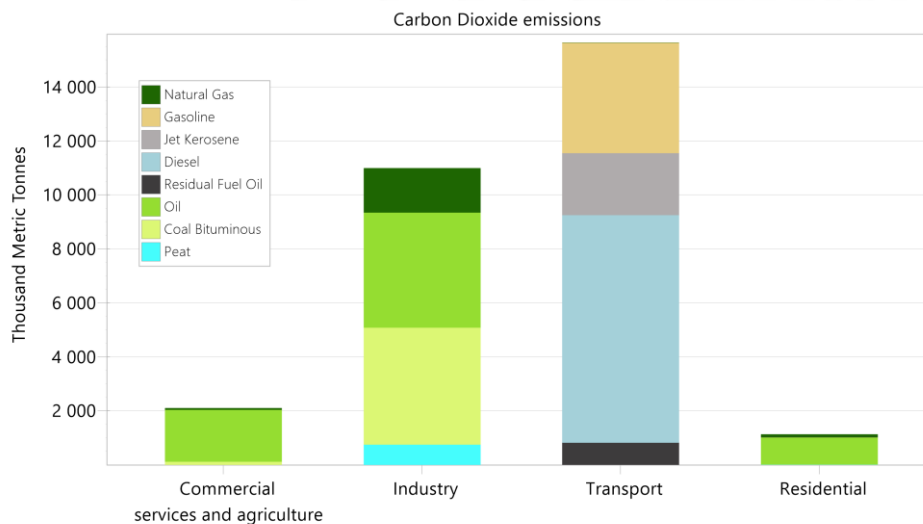


Figure 10: Carbon dioxide emissions represented by all fuels utilized directly in the end-use – Finland 2016.

5.2.3 Residential demand and GHG emissions

As Finland is a Northern country, the greatest part of residential energy demand is for heating of spaces. The heating is mostly sourced from electricity, district heat or wood while some older buildings are still using oil as a heat source.

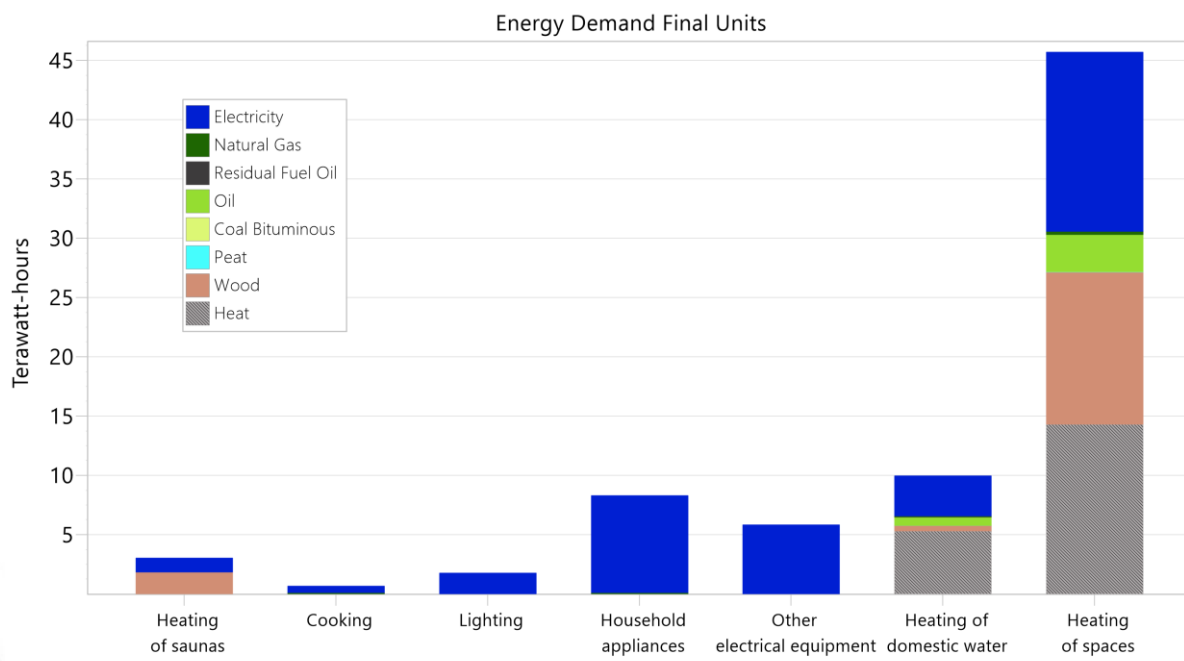


Figure 11: Domestic energy demand represented by all fuels utilized directly in households – Finland 2016.

The second-largest energy consumer in the residential sector is the heating of domestic water, which uses the same energy sources as space heating and is approximately 20% of the demand for space heating. Heating of saunas uses electricity and wood, depending on the type of the stove. The rest of the residential energy demand is nowadays electrical. The direct use of oil holds the highest share of GHGs emissions. Furthermore, the low emissions of Finnish electricity production can be easily seen when comparing the pictures above and below, since the significance of electricity is considerably smaller in the picture below than above. The single biggest action in the residential sector to decrease its emissions would be to replace the oil heating with electricity and heat pumps.

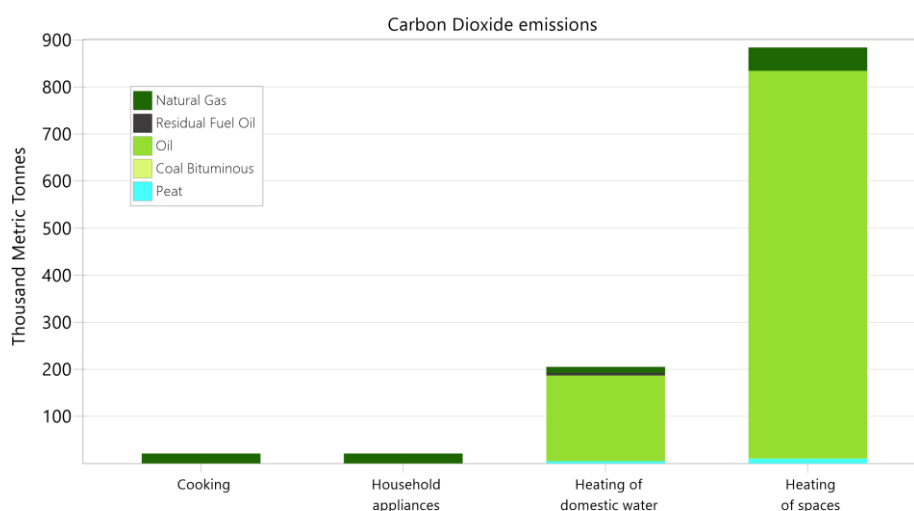


Figure 12: Finland 2016 residential emissions.

5.2.4 The transport sector and GHG emissions

In the transportation sector, road transport demands the most energy, over 45 TWh. The demand is met mainly with diesel and gasoline fuels but also with natural gas, ethanol and renewable diesel. Aviation is the second-largest and uses jet kerosene. Maritime uses residual fuel oil, diesel and small portions of other fuels. Rail traffic uses electricity and diesel.

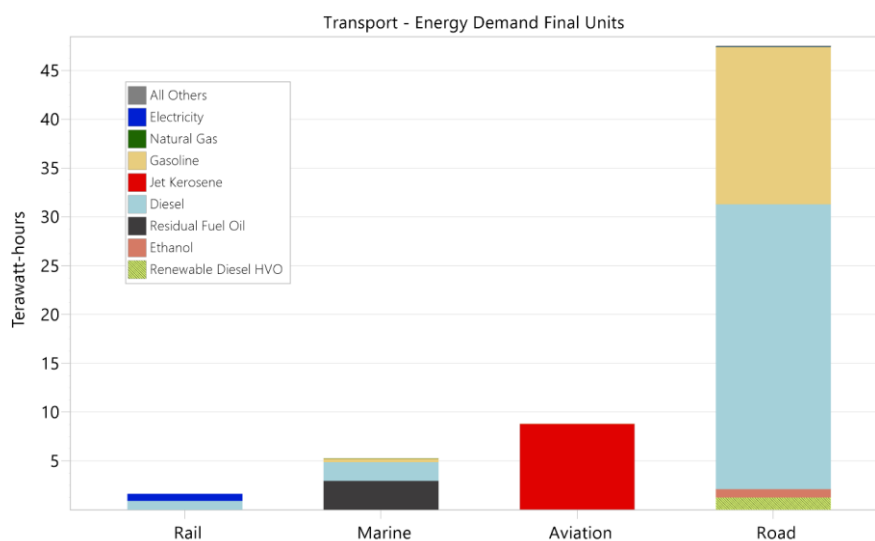


Figure 13: Transport sector energy demand - Finland 2016.

The global warming potential bars look almost identical to energy demand due to all sectors using mostly similar fuels. The road transport sector emitting almost 12 MtCO₂.

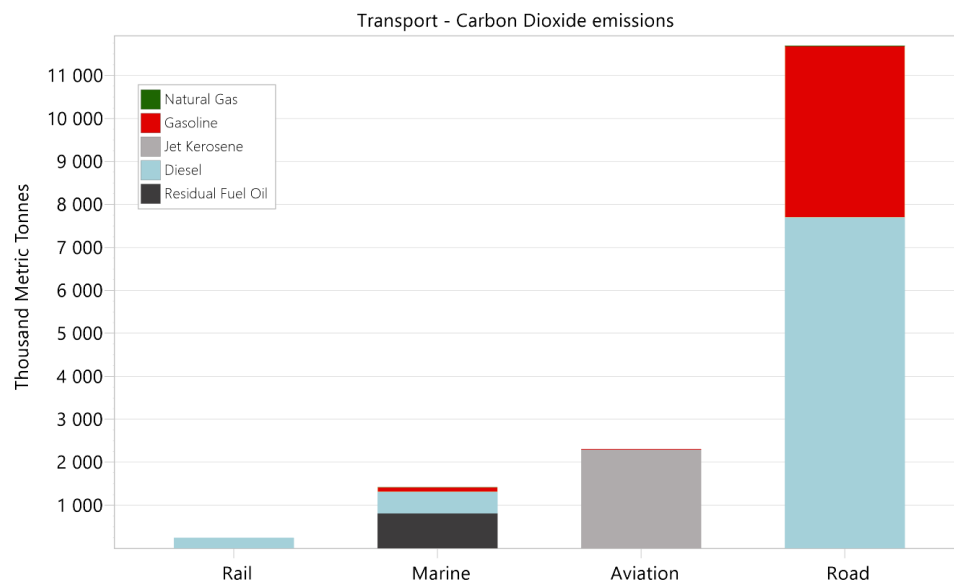


Figure 14: Finland 2016 Transport sector GHG emissions.

5.2.5 Industry energy demand and GHG emissions

The most energy demanding industry sector in Finland is the wood industry around 80 TWh dwarfing all other industry areas greatly. The metal refining and chemical industry also demand a lot of energy, between 20-30 TWh each.

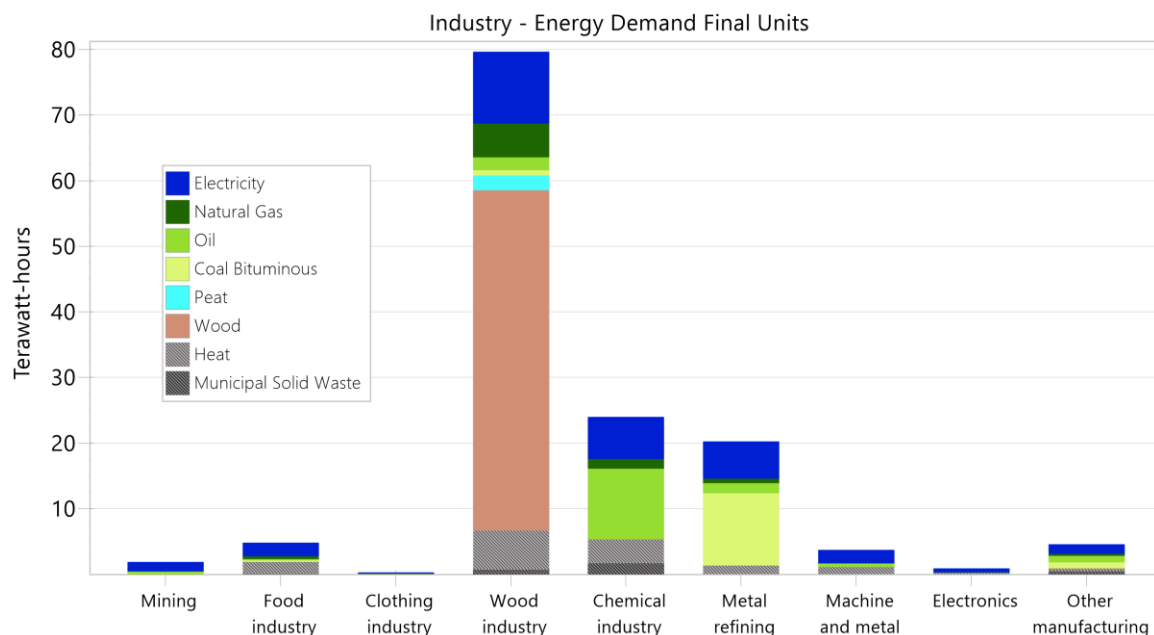


Figure 15: Finland 2016 industry energy demand.

Wood industry uses mainly wood as an energy source, which can be noted in the emissions when biomass related CO₂ emissions are calculated as zero. The GWP of the wood industry is calculated

smaller than metal refining or chemical industry even though it requires more energy when assuming that the biomass CO₂ does not affect the climate. The metal refining industry is the biggest in GHG emission due to energy production from coal. The chemical industry, on the other hand, uses a lot of oil which leads to it being a larger emitter than the wood industry when biomass CO₂ is not counted.

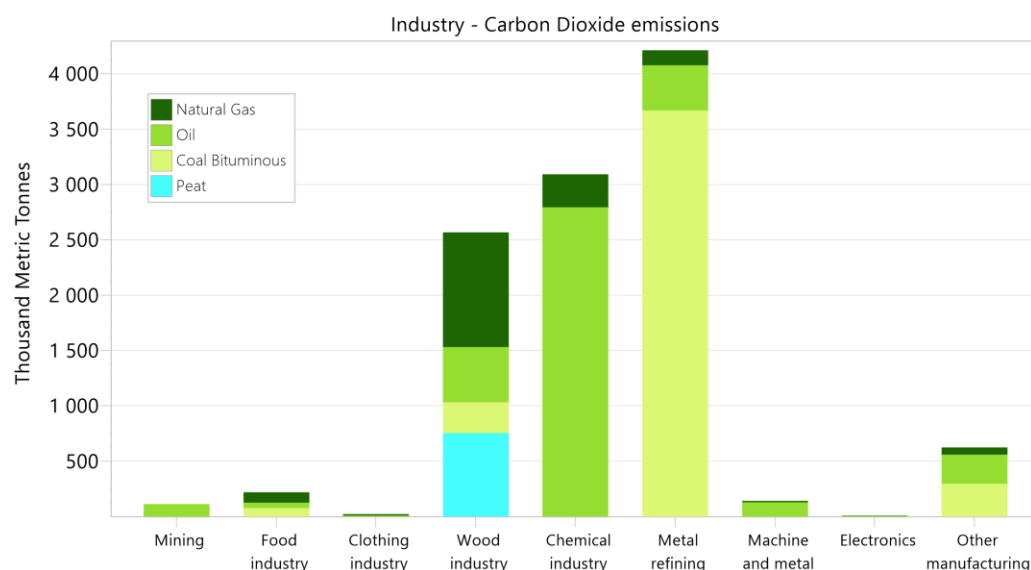


Figure 16: Finland 2016 industry GHG emissions.

5.2.6 Commercial energy demand and GHG emissions

The commercial sector uses mainly electricity, heat and oil as energy sources with a little biomass, coal and natural gas being used.

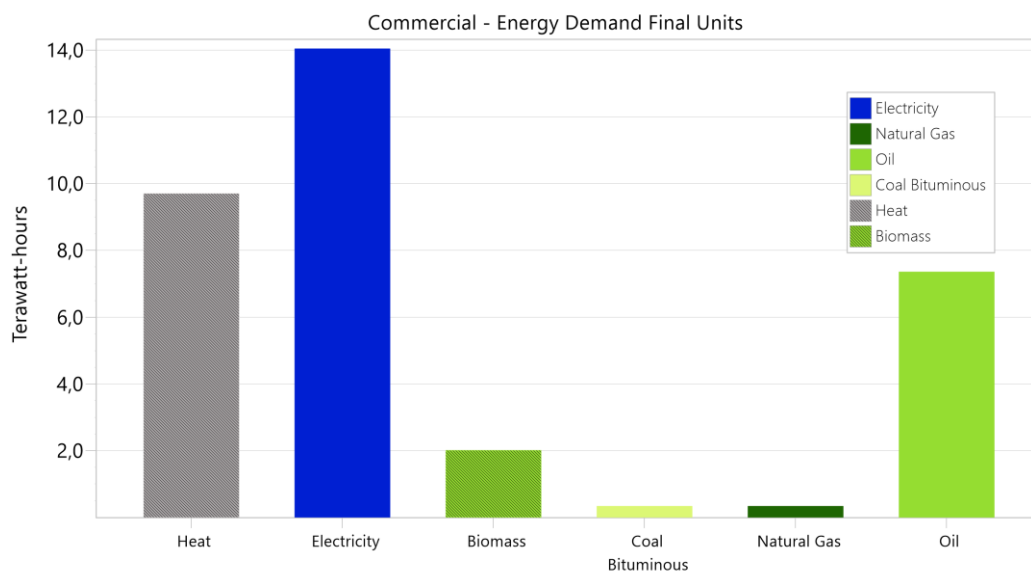


Figure 17: Finland 2016 commercial energy demand.

Oil is the only significant energy source in the commercial sector in terms of global warming potential dwarfing all other energy sources.

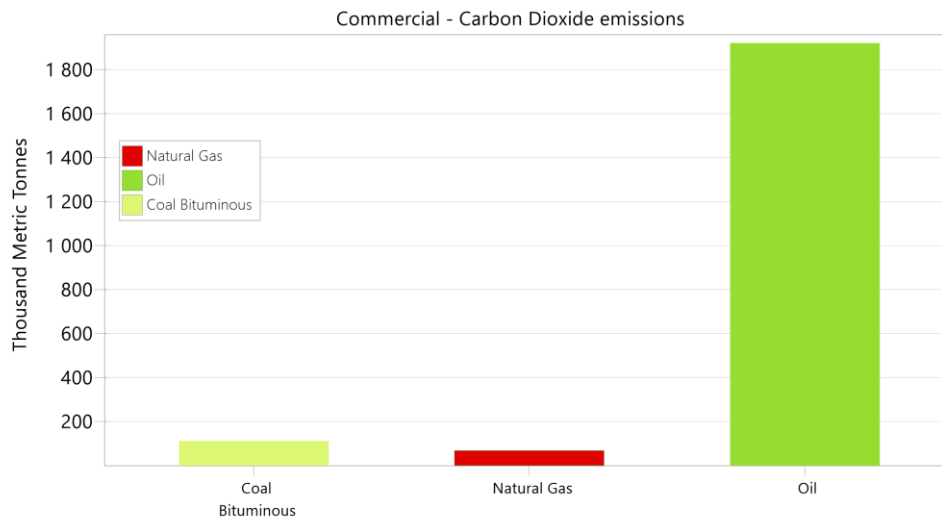


Figure 18: Finland 2016 commercial GHG emissions by source.

5.2.7 From the present state to the target

In the energy demand side, the industry is playing the biggest role followed by residential, transport and commercial sectors. In industry, most demand goes to the Wood industry as well as the Chemical industry and Metal refining. In transport, roads are responsible for the vast majority of demand, followed by aviation, marine and rail. The electricity in Finland is produced from nuclear, CHP, condensing, hydro and wind power. Biggest Greenhouse gas producers are Industry, Electricity and Heat production and Oil refining. (Baseline LEAP model). Our target is to reach carbon neutrality in Finland by 2035. This means meeting the growing demand and electrification. In transportation, there is estimated to be around 500 000 electric vehicles (Pitkän aikavälin kokonaispäästökehitys 2019) (Koljonen, et al. 2019), which alone require 1,66 TWh of electric energy.

5.2.8 Carbon neutral Finland 2035

The government of Finland has set the target to reach carbon neutrality by 2035, which is determined so that the GHG emissions are on the same level as the carbon sinks are on the negative side so that the net effect to the climate is zero. The target is also to reach carbon negativity soon after that. (Valtioneuvosto (Finnish Government) 2019). The measured GHG emissions and the estimation of sinks in Finland are shown in figure X (Statistics Finland 2019). In this figure, the energy sector is marked as blue color, and it includes all energy use of fuels, including transport, industry, residential and commercial. LULUCF sector includes Land Use, Land Use Change and Forestry, and that is still a carbon sink in Finland, even though the sinks will reduce due to the growing use of wood as a feedstock in energy processes. For example, last year in 2018 the decrease in carbon sinks was 30% in comparison with the previous year. The rest of the sectors are as following: light green is from waste handling, orange is from direct industry process emissions and use of products, red is from agriculture, and lilac is indirect CO₂-emissions. These sectors' emissions are hard to remove, so the overall target requires that the energy sector here has reduced the emissions near-zero level, depending on the level of the sinks, and especially if the sinks are continuing to decrease.

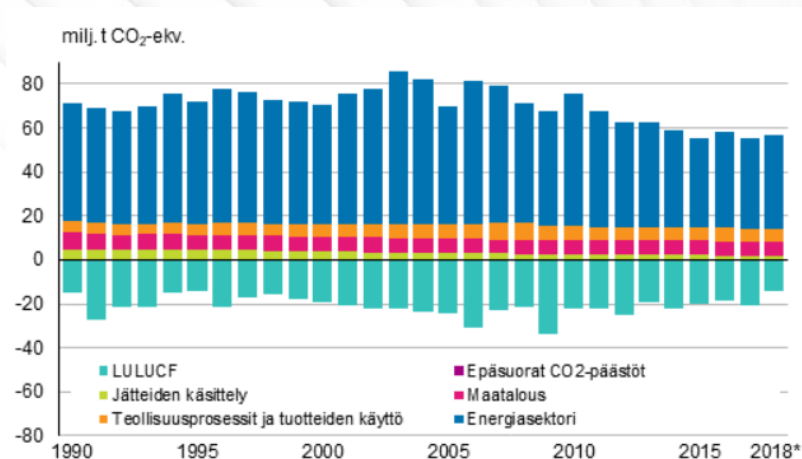


Figure 19. GHG emissions and sinks in Finland in different sectors (Statistics Finland, 2019).

Considering the difficulties in emission reductions in some sectors, to reach the target of carbon-neutral Finland, all the GHG emissions from the energy use of fuels should go to near-zero levels. That includes the transportation and industry use of fuels that are also difficult to decarbonize faster than a certain rate. Therefore, the leading role in achieving the target will fall to the energy sector, where big impacts can be achieved by a few big actions. One of the intermediate steps to reach the target is the law banning the energy use of coal by May 2029 (Ministry of Economic Affairs and Employment 2019). The other is halving the use of peat by 2030 (Valtioneuvosto (Finnish Government) 2019). In addition to this, many more steps are needed.

5.3 Deployment of the system coupling.

Deployment of the sector coupling in the system and modeling was performed using Long-range Energy Alternatives Planning System (LEAP) software. (LEAP 2016). LEAP is an integrated, scenario-based modeling tool, which we used to track energy consumption in different sectors in Finland. Together with the energy transition, greenhouse gas (GHG) emissions from different sectors were included in the analysis. Data were gathered from the Statistics Finland's PxWeb databases. (Statistics Finland 2019). Additional data, especially for commercial sector energy usage was derived from the IEA energy policy review of Finland (IEA 2018). All data were integrated into the LEAP, and the baseline for the year 2016 produced. Subsequently, business-as-usual scenario, in which the energy demand grew as predicted by the long-term development of emissions study PITKO, a report written to the Prime minister's office of Finland by VTT (Koljonen, et al. 2019) and by European Commission (European Commission 2014). More specific sources were used for aviation development (Eurocontrol 2018), marine forecasting (DNV GL 2018) and residential energy usage (Mattinen, Heljo and Savolahti 2016).

All data sources are summarized in Appendix 4.

5.4 Analyzed scenarios

After the development of the baseline scenario, which represents the current state of the Finnish energy system, Business as Usual Scenario (BAU) was implemented. In the BAU scenario, the estimated overall growth of energy demand was included, corresponding growth of production and

changes on the demand and production side, the industry (declines and growths), transport (mainly growth), commercial (mainly decline) and decline in the residential consumption. However, no changes in the composition of the primary energy carriers were assumed.

Subsequent, scenario the Carbon Caps (CC), includes governmental targets by 2030; no coal for energy purposes, no oil for heating, half of the peat and 30% renewables in the fuel mix and 250 000 electrical vehicles. While implementing those changes the demand was satisfied by implementing various sector coupling techniques presented in table 1, providing more renewable and efficient energy.

The ultimate scenario - Carbon Neutral Finland (CN) is targeting to achieve the carbon neutrality in the system by 2035. The CN scenario includes all changes implemented in the CC scenario with addition of the following actions: totally 50% of renewable fuels in road transportation, totally 400000 EV's, no condensing power, meaning that also all existing nuclear plants are modified to utilize the heat, more heat pumps, 20% of sustainable aviation fuels (to meet the carbon-neutral growth – international aviation target ICAO) and 20% of wind electricity. Additionally, due to the new International Maritime Organization Sulphur caps from 2020, a strong reduction of heavy fuel oils (HFO) was included and the demand was satisfied by Liquefied Natural Gas (LNG), and Marine Diesel Oil (MDO).



Figure 20 Summary of scenarios.

6 Results

In this chapter outcomes from the modeling of three scenarios; Business as Usual (BAU), Carbon Caps (CC) and Carbon Neutral (CN) will be presented.

6.1 Comparison of scenarios

In the BAU scenario, there is the highest end-use of energy and the largest growth in the total emissions of CO₂. However, on the production side, BAU has the lowest growth, which is resulting from the poor electrification, weak growth of the district heating network and no big changes in the use of alternative fuels. Additionally, very limited changes in the energy efficiency of the entire system leading to the growth in the requirements for primary energy carriers. In the CC scenario, there is the lowest end-use of energy, but second-highest production of heat, electricity and fuels (among scenarios). Additionally, CC represents the highest demand for primary energy carriers. However, due to the implementation of governmental targets carbon dioxide emissions dropped significantly. Carbon Neutral Finland scenario represents a moderate end-use of energy. However, significant electrification and larger demand for district heating cause the largest production of energy compared to other scenarios. Nevertheless, due to the more efficient use of resources, (no more condensed power and utilization of the nuclear heat), the requirement for the primary energy carriers declined strongly. In the CN total emissions of carbon dioxide are decreasing most rapidly and they reach the lowest level compared to the other scenarios.

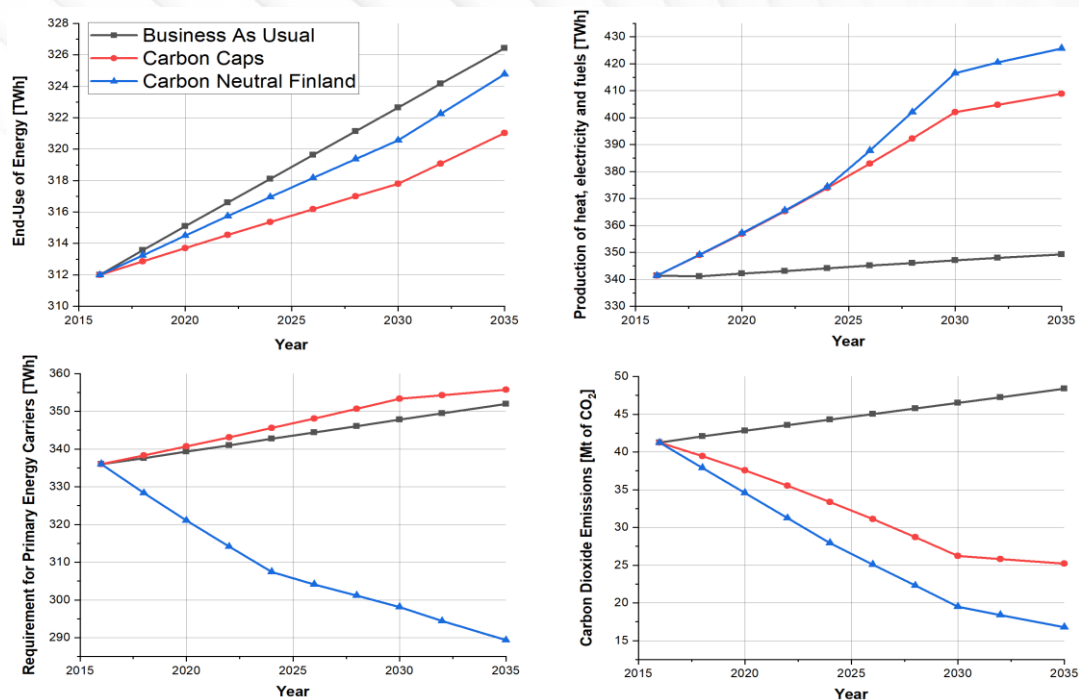


Figure 21 Comparison of scenarios.

6.2 Carbon Neutral Finland 2035

In the Carbon Neutral Finland scenario, the growth of the electricity and heat consumption could be observed. Additionally, there is a significant growth in the use of renewable liquid fuels in the transportation sector, such as renewable diesel (HVO), renewable gasoline, sustainable aviation fuels (SAF) and ethanol. Furthermore, due to the growing number of electrical vehicles on the roads, the demand for electricity in the transport sector increases. The end-use of fossil fuels is declining strongly in the CN scenario, especially; coal, oil, peat, gasoline and diesel.

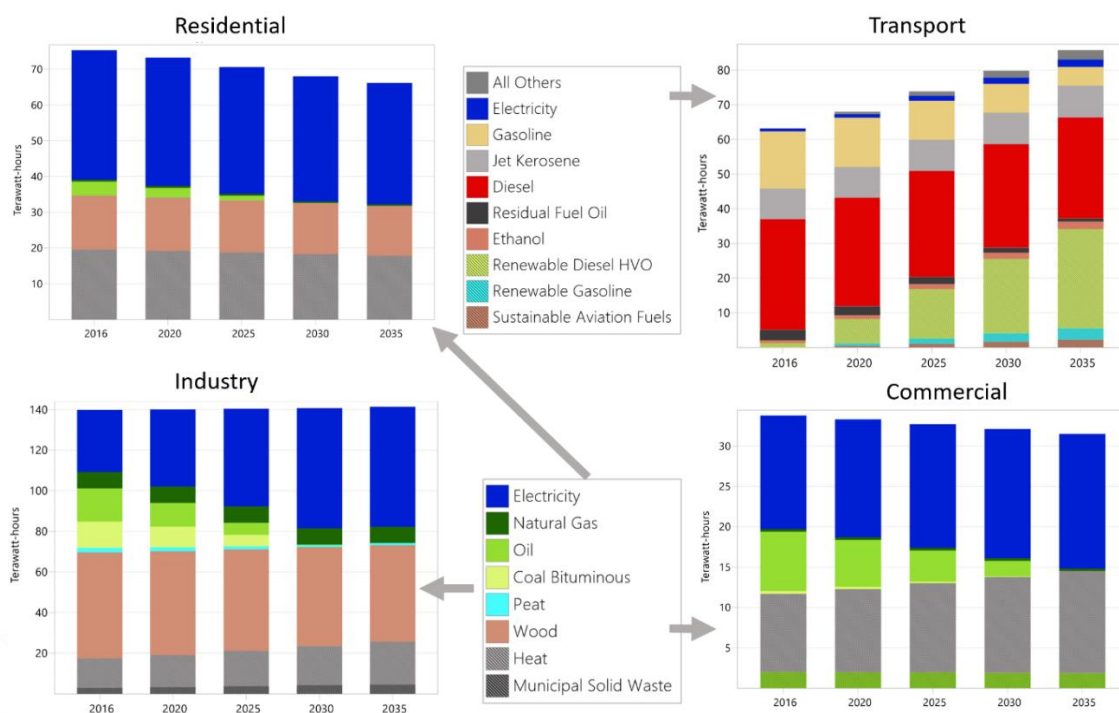


Figure 22 Energy demand in the Carbon Neutral Finland scenario - the transition from 2016 to 2035.

Emissions of carbon dioxide in all branches of the end-use are declining. The biggest slopes could be observed in the residential, industrial and commercial branches, due to the implementation of governmental targets on coal, oil, and peat and partially because of the higher electrification in growth in the district heating network. When it comes to transport, the total amount of carbon dioxide is declining as well. There could be observed a large share of diesel in 2035, jet kerosene and gasoline in emissions. Additionally, the growing contribution of natural gas and declining residual fuel oil are the effect of the International Maritime Organization (IMO) regulations for the low sulfur content 0.5% fuels. Those regulations drive the transition from HFO to the natural gas in the marine sector.

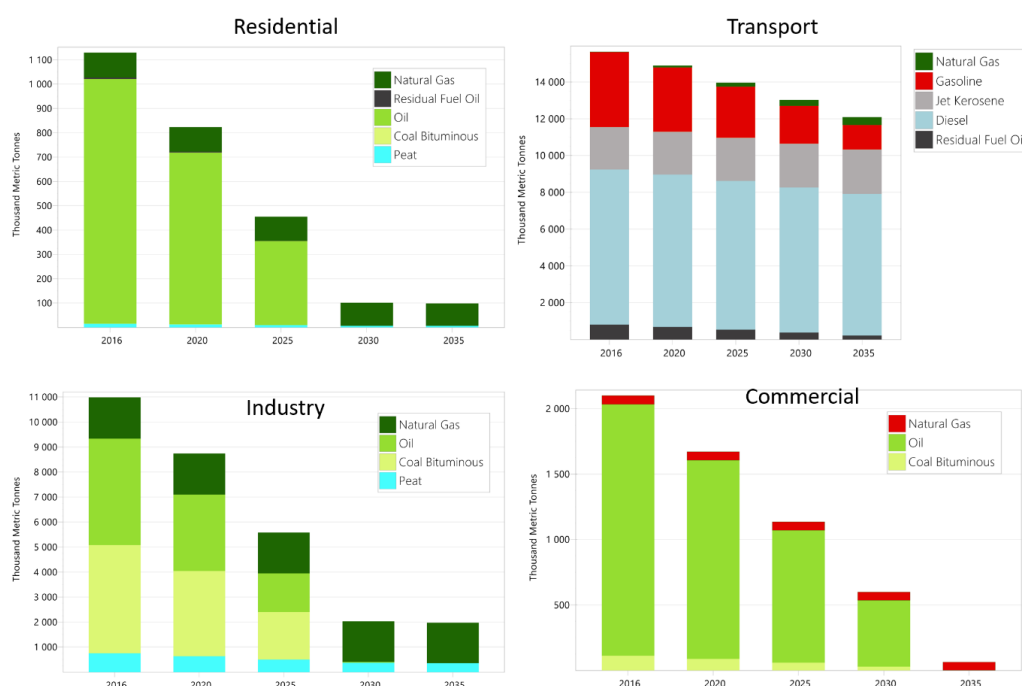


Figure 23 Emissions (demand side) in the Carbon Neutral Finland scenario - the transition from 2016 to 2035.

With the growing energy conversion efficiency on the production and end-use side, there is an overall decline in the requirements for the primary energy carriers. However, there could be observed a significant transition in the share of various energy carriers, with the high trend towards sustainability and low emission feedstock.

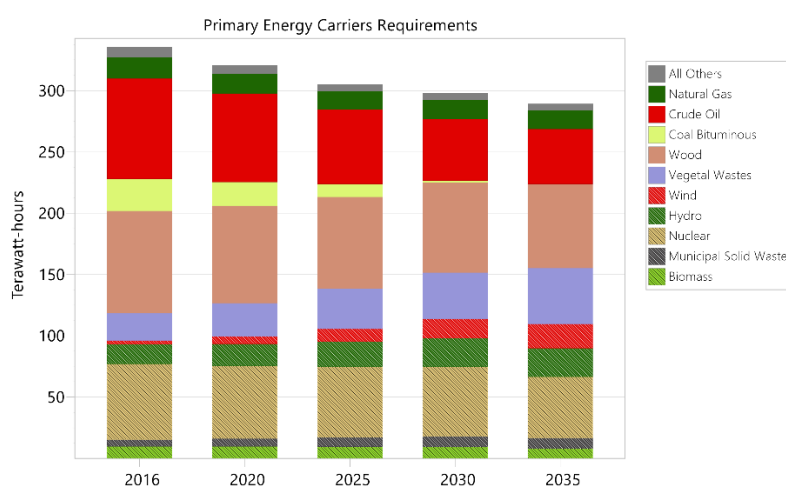


Figure 24 Transition of the total demand for the primary energy carries in Finland from 2016 to 2035.

After implementing all changes in the carbon-neutral scenario, the highest contribution to carbon dioxide emissions is coming from the transport sector.

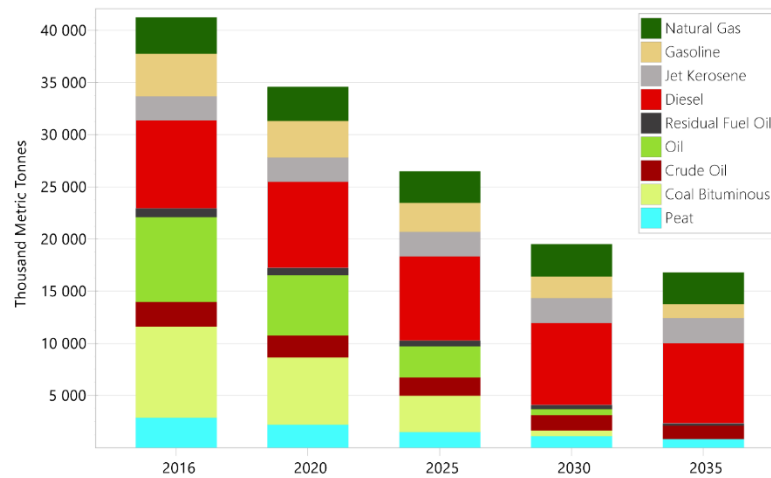


Figure 25 Transition of the emissions by the primary energy carries in Finland from 2016 to 2035.

7 Conclusions

The present work identified sector-coupling opportunities and pathways that allow utilizing excess electricity, heat and waste streams of various materials to satisfy the needs of other sectors. After the literature review of successfully applied sector coupling cases in the world, there have been found examples that excess electricity from various sectors, was used for the production of gaseous and liquid fuels (P2X), generation of heat (P2H) or stored in various ways. Waste heat from different industries could be used to produce biogas and alcohols (H2X), whereas low heat sources could be further explored by the heat pumps. Additionally, a surplus of heat could be sorted in a short, medium and long term depending on the technology. Various sustainable materials and waste streams can be refined to renewable liquid fuels (X2X) or used directly to produce heat and power (X2P). However, it has been noticed that some technologies could be deployed with greater success, due to the various technological and system-specific issues. For example, some power to x applications may require a large and continuous electricity supply, which could be challenging in many locations. However, in Finland, there is the potential to increase the capacity of wind power, and combine it with electrolysis to produce hydrogen, that can be utilized in many sectors. Because of the large heat demand in Finland, sector coupling via providing the excess heat has great potential. These waste sources could be from either industrial processes or condensing nuclear power plants since presently the heat is not utilized at all, which is an extremely large waste of energy in Finland. In addition, heat could be generated using heat pumps, or electric heat boilers. The utilization of CAES seemed to be an attractive option for energy storage in Finland. This was due to the infeasibility of pumped hydro storage in Finland, and the availability of old mines, which could potentially be used for CAES. Furthermore, the rock caverns might also be suitable for sensible water heat storage if they are near habited areas equipped with district heat networks. For local use near wind generation, lithium-ion batteries seemed to be the best option for balancing the grid-related problems caused by wind generation. Another opportunity for energy storage would be V2G technology, as the amount of EVs is predicted to grow substantially by 2035. In addition, the literacy review part of the task also revealed increasing interest in the artificial pumped hydro possibility for decommissioned mines in Lapland,

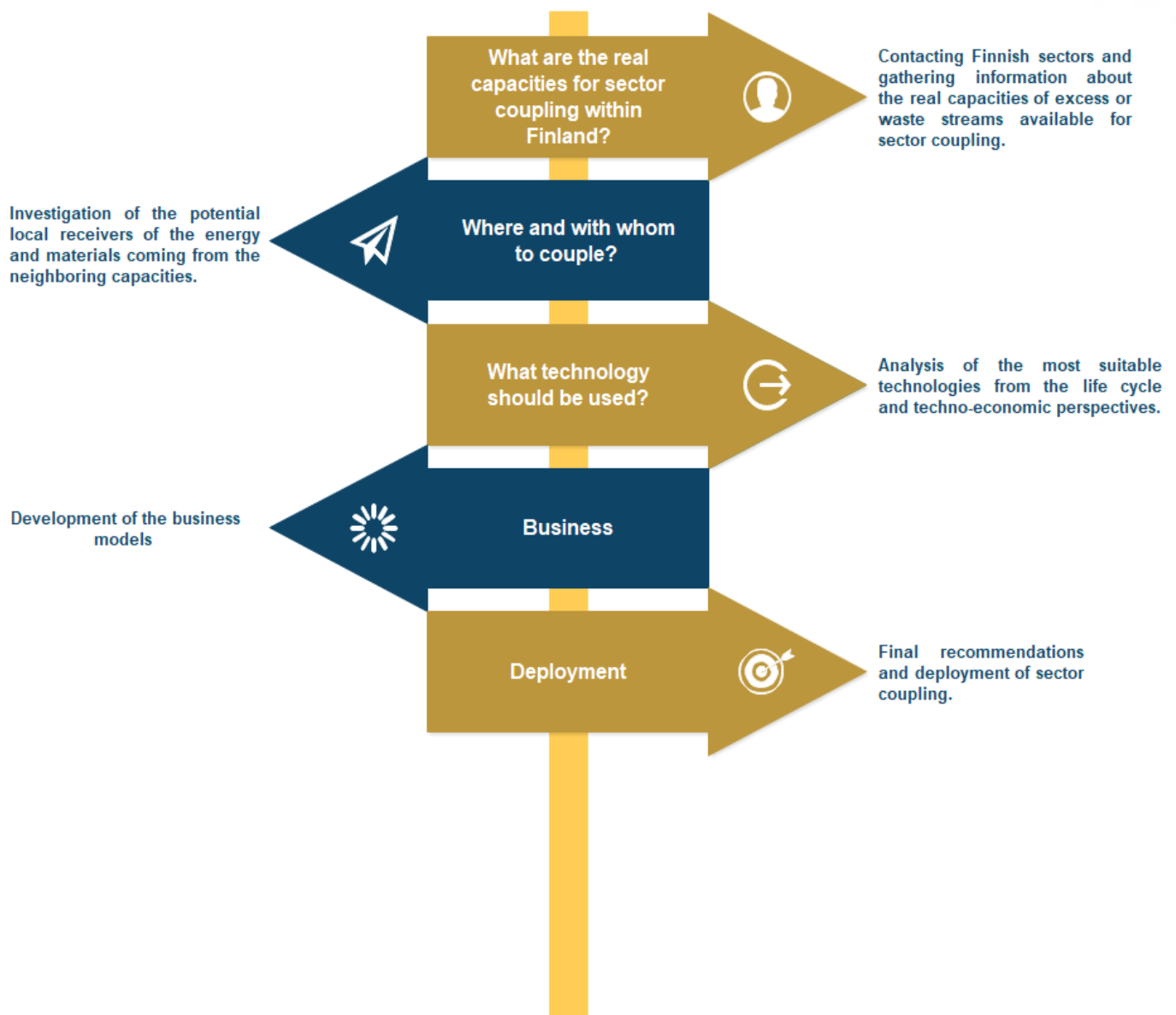
and liquid air energy storage technology especially in the UK. Both of these are in the demonstration stage. Opportunities for materials-related sector coupling in Finland were mainly in applications of lignin and bio-based waste products. Biofuels based on lignin would have a large potential to supply the majority of yearly gasoline consumption of Finland. Another significant sector coupling opportunity in Finland is in the steel industry, and there is already an SSAB HYBRIT project, that is aiming to utilize hydrogen in the steel production, thus cutting down the use of coal and reducing emissions. In transport, the need for drop-in fuels was recognized, mainly due to the high average age of Finnish cars, which will mean, that current IC-cars will be on the roads still in 2035. These fuels could be produced from lignin, other types of side streams and bio-wastes or alternatively from the hydrogen production mentioned in the electricity chapter. The main utilization of sector coupling would then according to these findings be the production of transportation fuels, since in that sector, mainly due to slow transformation of the road-transportation fleet, at least in the mid-term, requires liquid fuels to be used also in the coming decades. These could be produced using various means, where electrolysis done with excess renewable power would be among the most interesting options.

In the modeling stage three scenarios were projected; Business As Usual, Carbon Caps (governmental actions) and Carbon Neutral Finland by 2035 (new government's target). It has been observed that governmental targets by 2030 implemented in the Carbon Caps scenario reduce emissions in the direct use of resources in the residential, commercial and industry. A significant decrease in carbon dioxide emissions is observed on the production side of heat and electricity as well. However, 30% of renewables in the transportation fuels mix, is clearly not enough, as the contribution of the transport sector to the total carbon dioxide emissions in Finland remains the strongest. Therefore, in order to achieve carbon-neutral Finland, there should be substantial growth of renewable liquid fuels in the mix, accelerated electrification, and higher energy efficiency. Additionally, it is strongly recommended to begin utilization of the large waste streams such as heat from the nuclear stations. When speaking about the carbon neutrality, the targeted amount of the carbon dioxide emissions that could be offsite by the carbon sinks should be carefully investigated and determined. Based on various sources, the group decided that around 18 MtCO₂ emissions would be the amount in 2035 that could be neutralized by the sinks, and Carbon Neutral Finland (CN) scenario was targeting that amount of CO₂. CN scenario represents a moderate end-use of energy when compared with BAU and CC scenarios. However, it has the largest production of energy compared to other scenarios, and because of the more efficient use of resources, (no more condensed power and utilization of the nuclear heat), the lowest requirements for the primary energy carriers. Additionally, the nuclear heat satisfies all the district heat demand in Finland and leaves over 20% of heat generation still available to use for another purpose (wasted line in the coming out from the heat in the Sankey diagram – appendix 4). The final emissions in the CN scenario are 16.8 MtCO₂, which should stay below the sinks threshold for 2035, and allow reaching carbon neutrality. This target was achieved, by focusing mostly on the transportation sector (where the share of renewables reached around 50%) and increasing the energy efficiency of the existing plants. However, various other sector-coupling techniques presented in table 1, were implemented during the modeling stage and they helped to reach the CN state in 2035 more effectively.

Ultimately, sector coupling is an excellent way to utilize resources more efficiently; it helps to bring down greenhouse gas emissions significantly, increases the energy independence of the system (country) and enables new waste management opportunities. Besides those benefits, there are also economic profits for sectors that are coupled. Therefore, in order to achieve the new government's target of Carbon Neutral Finland by 2035, sector coupling should be an inseparable part of the plan. It will help to reduce the need for increasing the energy production capacity in the system, by satisfying the growing demand with more efficient existing energy production units.

8 Recommendation for future studies

Those studies proved that sector coupling has large opportunities in Finland and showed the effect on energy demand and GHGs emissions in 2035 when deploying SC. The following areas of research are recommended as a continuation of this work:



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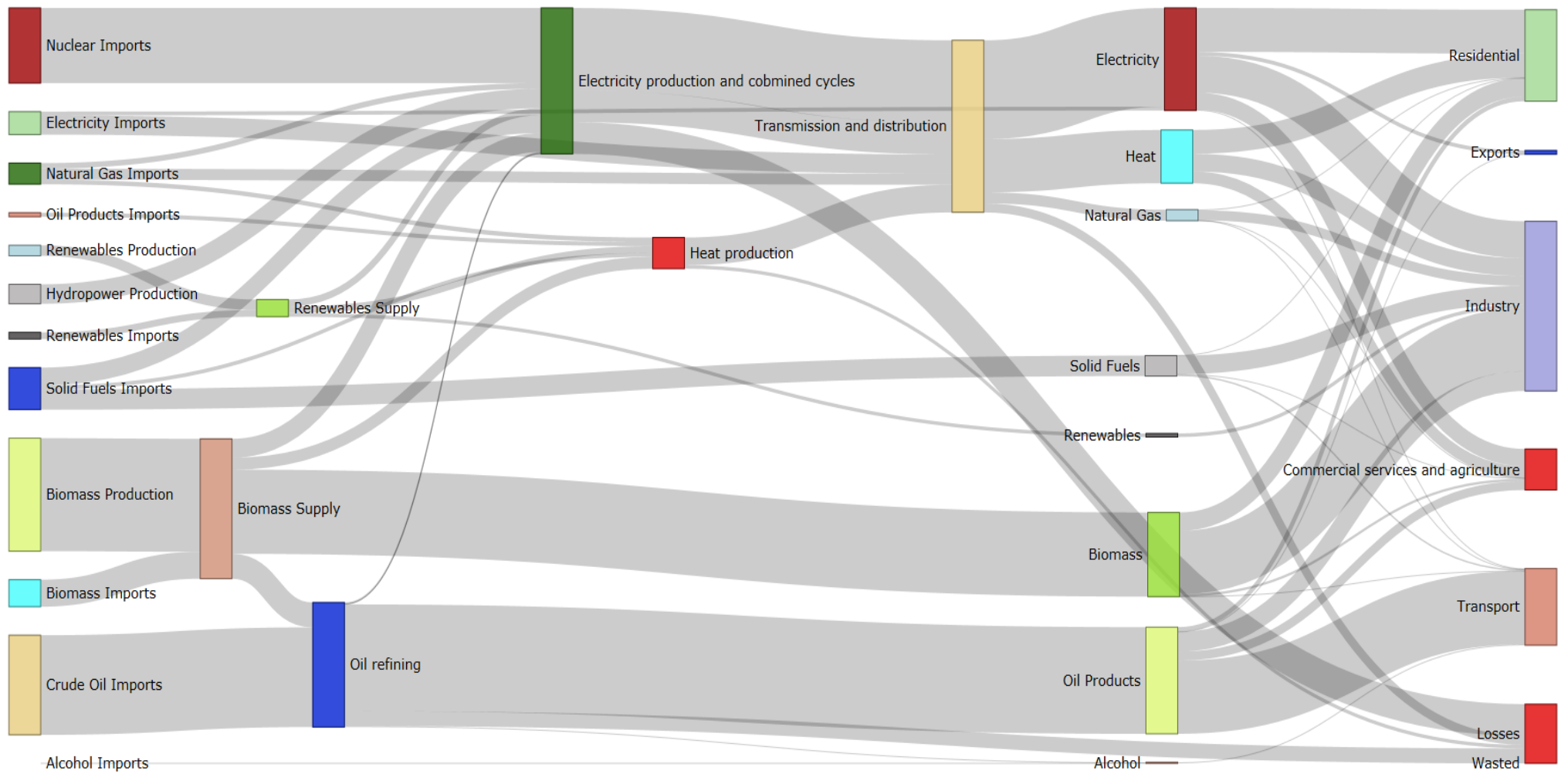
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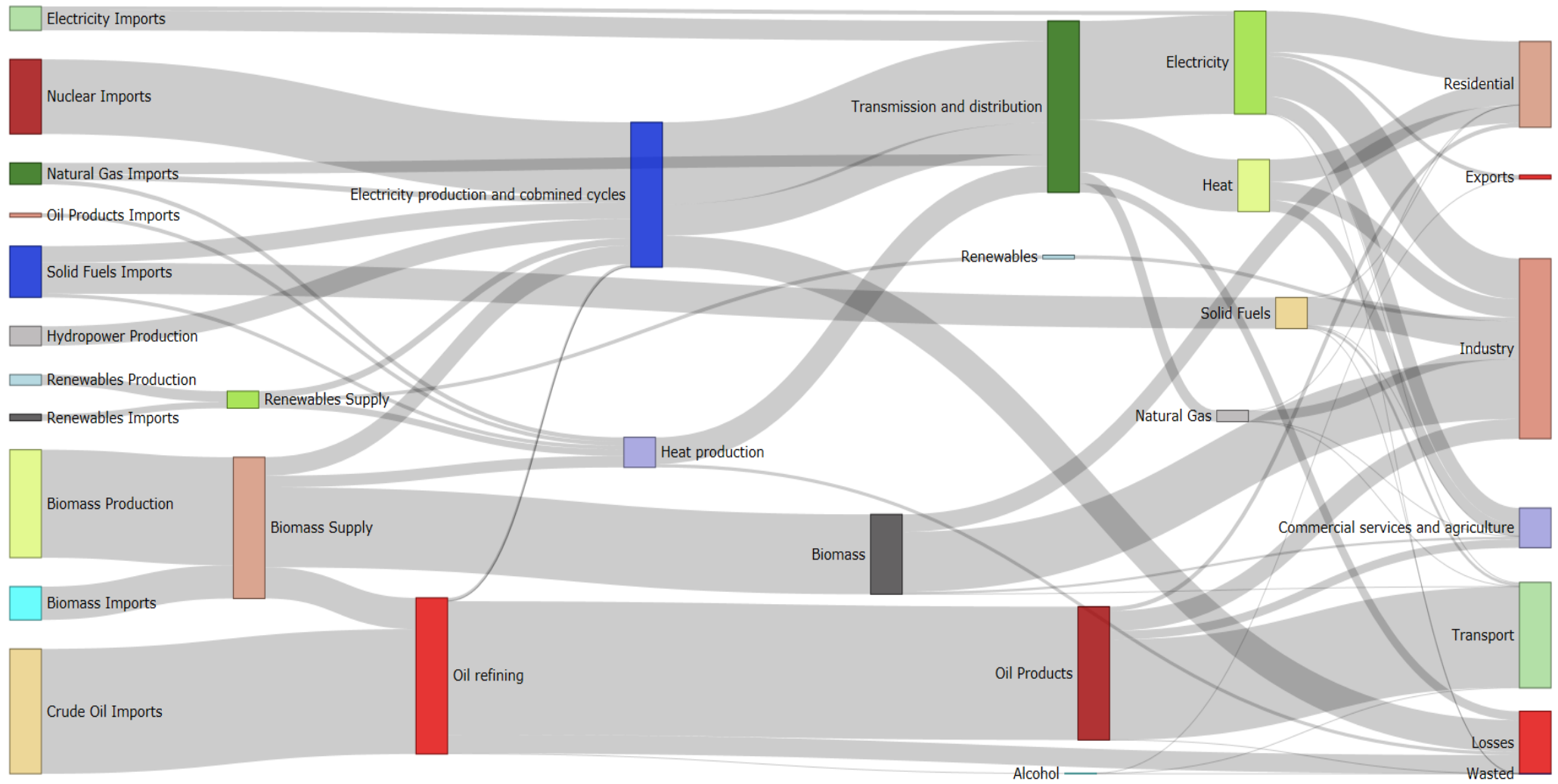
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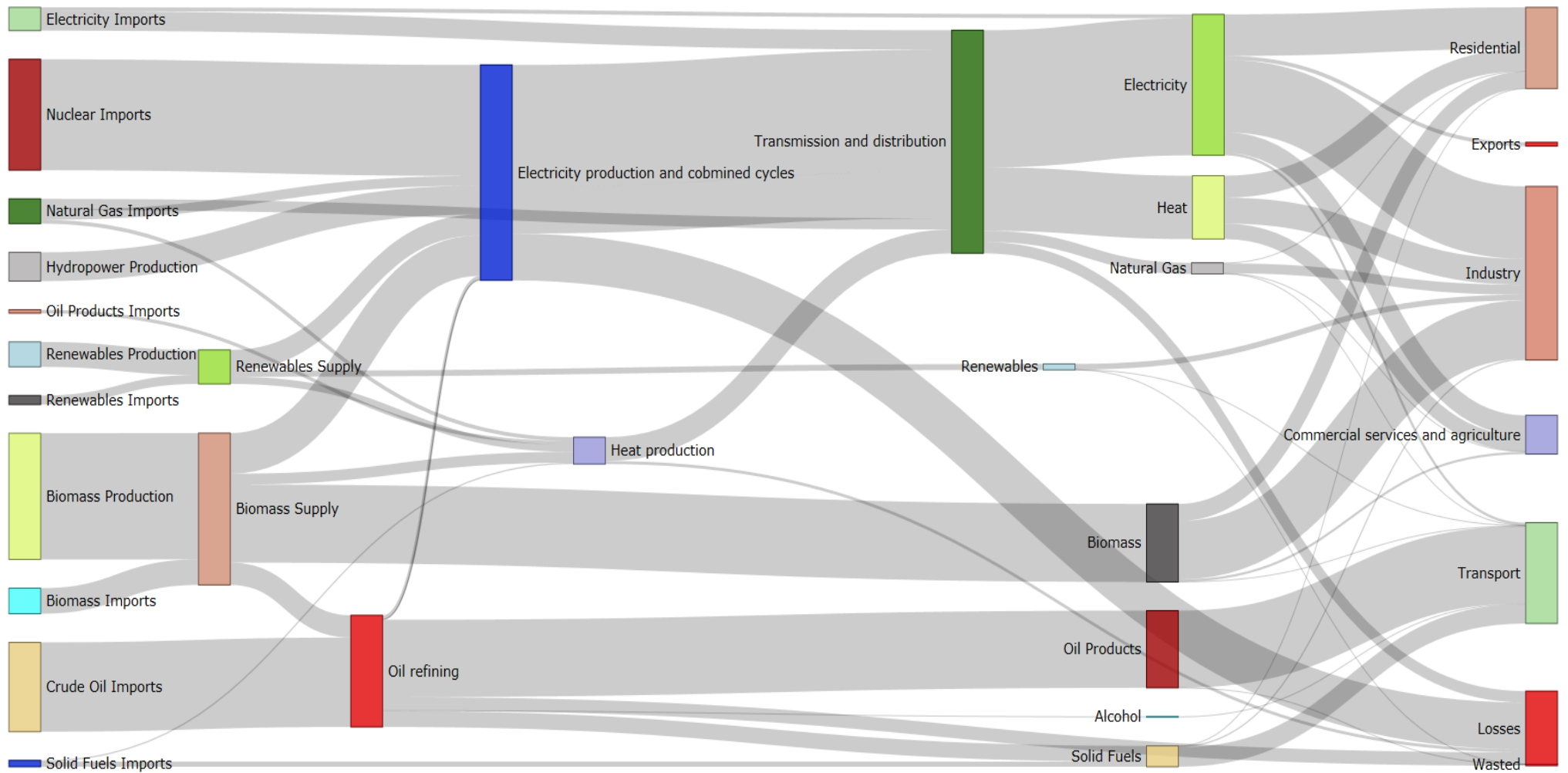
Appendix 1 – Finland energy and materials flow in the baseline year 2016



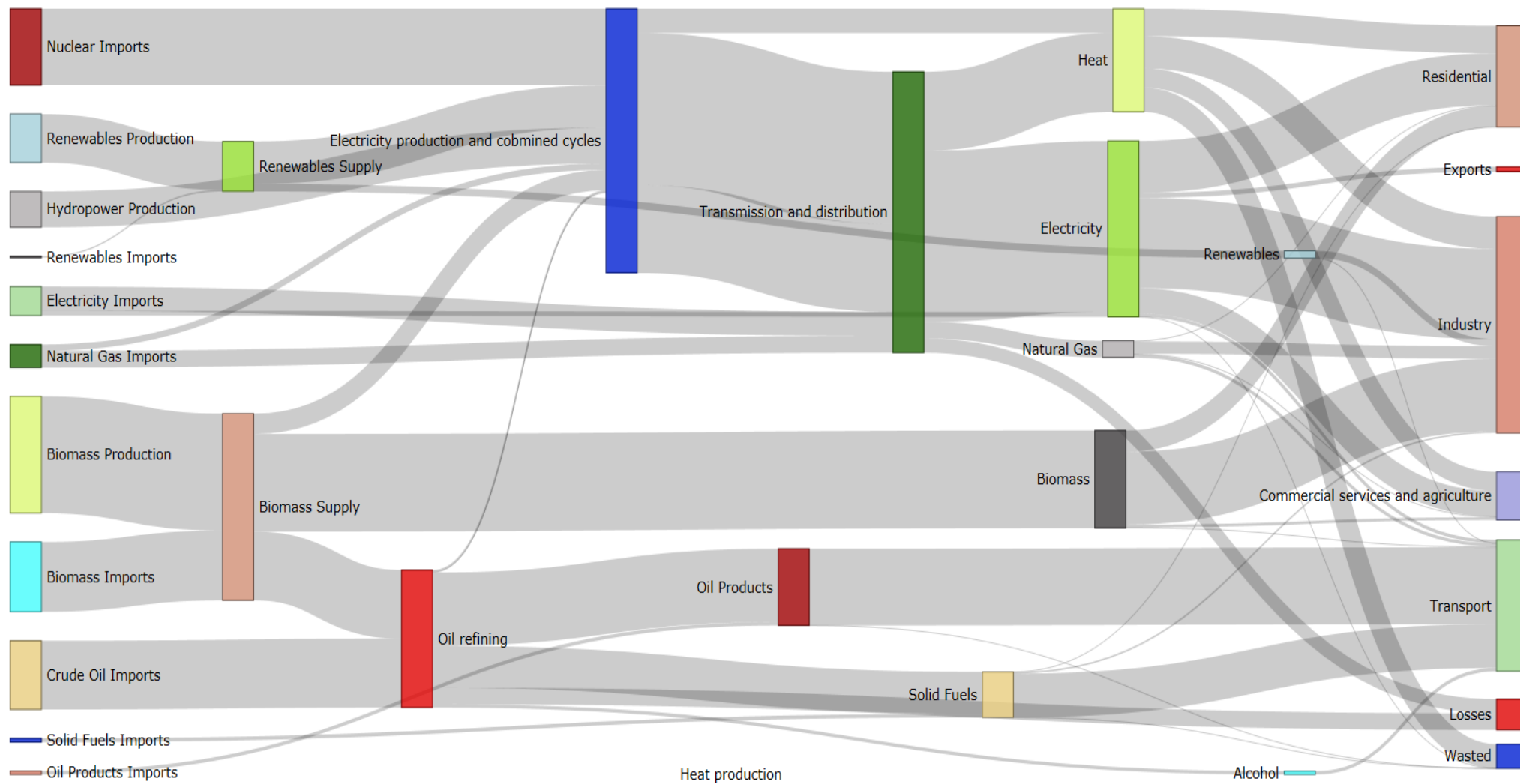
Appendix 2 - Finland energy and materials flow in the target year 2035 – Business as Usual scenario



Appendix 3 - Finland energy and materials flow in the target year 2035 - Carbon Caps scenario



Appendix 4 - Finland energy and materials flow in the target year 2035 - Carbon Neutral Finland 2035 scenario



Appendix 4 – Data sources table for the development of the Business as Usual scenario.

Model	What the source contained	Description	Reference
Baseline	Energy consumption data, population forecast, GDP	<p>Statistics Finland's PxWeb databases contained all data in table forms. Using this interface, we extracted data for making the baseline model.</p> <p>More specifically, from energy category following tables were used (references to Finnish tables, since they contain more data):</p> <p>11zs – Asumisen energiankulutus 011 – Liikenteen energiankulutus 012 – Kaukolämmön tuotanto ja kulutus 013 – Sähkön kulutus sektoreittain 11sr- Sähkön hankinta ja tuotanto 12b7 – Kaukolämmön tuotanto Suomessa 12b8 – Teollisuuslämmön tuotanto Suomessa 001 – Teollisuuden energiankäyttö toimialoittain</p> <p>Additionally, population forecast was used, both in baseline and the projections, as the source contains both past data and future projections</p> <p>128t – Väestö iän ja sukupuolen mukaan eri vuosien väestöennusteissa, koko maa</p> <p>GDP data was retrieved also from Statistics Finland, at https://www.tilastokeskus.fi/tup/suoluk/suoluk_kansantalous.html</p>	(Statistics Finland 2019)
Baseline	Energy usage in commercial sector	The IEA energy policy review of Finland was used to gain more detailed consumption data in the commercial sector, as this was not clearly defined as a sector in the Statistics Finland data	(IEA 2018)
BAU	Energy forecasting data for 2035, EV predictions	Most forecasting was taken from the PITKO-report. For BAU, we used the reference scenario (VEM)	(Koljonen, et al. 2019)
BAU	Additional energy forecasting data for 2035	Additional information, at a more general European level was taken from the European Commission 2050 reference scenario. The EU trends were assumed to also happen in Finland similarly	(European Commission 2014)
BAU	Forecasting of Aviation development	An annual growth percentage for Finnish aviation from an Eurocontrol report was used until 2035.	(Eurocontrol 2018)
BAU	Forecasting of Marine development	Marine growth was estimated to follow globally forecasted trend, which was presented in DNV GL report, which forecasted marine developments up to 2050.	(DNV GL 2018)
BAU	Forecasting of residential energy	In this report by the Finnish Environmental Institute, the energy demand in buildings is forecasted until 2050. Values for 2035 were interpolated from this publication.	(Mattinen, Heljo and Savolahti 2016)