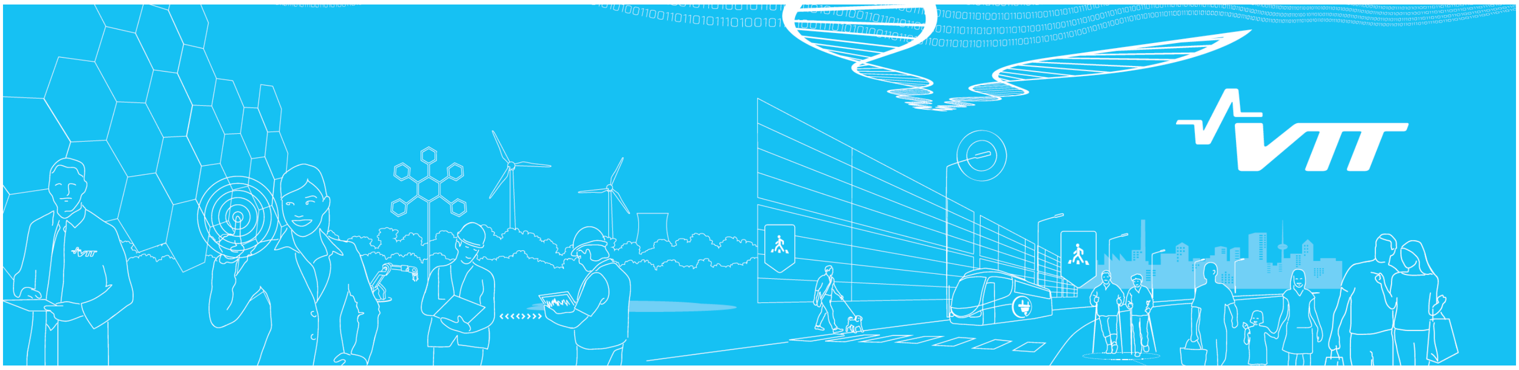

RESEARCH REPORT

VTT-R-04268-16

Potential deployment of CCS in Finland under low carbon scenarios

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Summary

Carbon capture and storage is generally considered an essential technology option that will be needed for achieving deep emission reductions already by 2050. However, the development of CCS technology still faces many challenges. Most of the CO_2 capture processes are currently very energy intensive and further development is needed to bring the costs down. In addition, the CO_2 captured needs to be transported to a suitable storage site for secure and permanent storage, which remains perhaps the most controversial part of the technology.

The individual technology and concept studies of the Carbon Capture and Storage Program (CCSP) have produced numerous up-to-date technology characterizations. The main objective of present study was to utilize the improved technology assessments for a long-term energy system analysis, making a broader analysis of the potential and significance of CCS. The analysis was made in an integrated context, using a large energy system model for consistently taking into account interactions between various decision-makers at different levels of the energy system. The work was carried out by exploring a few scenarios based on different storylines for achieving a low-carbon economy in Europe by 2050.

The results indicate that CCS based on fossil fuel does not have any notable potential in Finland. On the other hand, due to large biomass resources and utilization potential in the energy sector, bioenergy with carbon capture and storage (BECCS) does appear to have a considerable potential of reducing CO_2 emissions by about 15 Mt per year, of which power and heat generation accounts for 5–8 Mt, pulp and paper sector for 4–7 Mt, and biofuel refineries for about 3 Mt. The availability of CCS would reduce the total annual direct costs by up to 800 M€ in Finland, and up to €60 billion in Europe as a whole. CCS would also be valuable for maintaining flexibility when integrating large amounts of variable renewable electricity generation in the power system.

Confidentiality	Public

Espoo, 10.10.2016

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Preface

This work was carried out in the Carbon Capture and Storage Program (CCSP) research program coordinated by CLIC Innovation Ltd. with funding from Tekes – the Finnish Funding Agency for Innovation – and VTT Technical Research Centre of Finland (Deliverable number D147). The working group providing input and comments to the work consisted of Risto Sormunen (Fortum Oyj), Timo Arponen (Helen Oy), Mari Tuomaala (Gasum Oy), Timo Hyppänen (Lappeenranta University of Technology), Antti Arasto (VTT), Tiina Koljonen (VTT), Eemeli Tsupari (VTT), Janne Kärki (VTT) and Sebastian Teir (VTT).

Espoo, 10.10.2016

Antti Lehtilä Tiina Koljonen

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1. Introduction

Carbon capture and storage (CCS) is generally considered an essential technology option that will be needed for achieving deep emission reductions already by 2050. For many reasons, phasing out the use of fossil fuels would be extremely difficult and expensive in just a few decades, as fossil fuels still account for about 80% of the global primary energy supply. In the longer term, however, the advancement of various energy storage and carbon cycling systems will no doubt make even a 100% renewable energy system economically feasible.

According to the IEA technology roadmap (IEA 2013), the contribution of CCS in the global emission reductions would be close to 20% in 2050. In particular, the IEA report considers CCS deployment in industry basically necessary for achieving the 2°C target.

Moreover, it can be estimated that reaching the very tight target of at most 2°C global warming by the end of the century will require also negative emissions in some sectors to counter-balance the high costs of reducing the greenhouse gas (GHG) emissions in some sectors. The most difficult sector appears to be agriculture, where especially the non-CO_2 greenhouse gases, methane and nitrous oxide, are difficult to reduce. The second most difficult main sector is industry, and in particular, process-related emissions from basic metals, basic chemicals and minerals manufacturing, for which new low-emission processes are technically or economically difficult to implement. Consequently, larger reductions than the average overall target would be needed in other sectors. It is thus obvious that without achieving even higher cuts or negative emissions by some solutions, such as Bioenergy with Carbon Capture and Storage (BECCS) applications (IEA 2011a), reaching the very strict overall targets may become costly for the economy.

Although using fossil fuels combined with CCS may not be considered sustainable, in the medium term it can help solving the technological challenges with introducing large amounts of variable electricity generation. There are studies demonstrating that with fossil fuel power plants equipped with CCS, a system with a large amount of renewable energy would be sufficiently flexible for providing a reliable power supply. Combined the system with e.g. hydrogen production and storage, or polygeneration systems that could produce electricity during peak demand and liquid hydrocarbons during non-peak demand would further increase flexibility. CCS can thus be viewed valuable also as a means of supporting the integration of large amounts of renewable generation in the system, not competing with it. In the future electricity system the ability to balance between the generators will be valuable.

This report analyses the competitiveness of CCS technology options in the Finnish and European energy systems under low carbon pathways until 2050, and the impacts of the having the CCS option available for reaching the emission reduction objectives. The analysis is based on using a large multi-region energy system model, TIMES-VTT, for analysing several different scenarios, or storylines for the low carbon pathways of the whole economy until 2050.

The report is divided into eight chapters, the first four giving the introduction and describing the objectives, method used, and description of the alternative scenarios. The next two chapters present the key results for the energy system and GHG emission development. The last two chapters give a broader discussion on the results and present the main conclusions. Unless otherwise noted, all costs in this report are given in 2010 value euros.

2. Objectives

Carbon capture may offer significant potential for deployment in Finland. Being a large consumer of power and heat, Finland has unique opportunities in integrating CCS with combined heat and power (CHP) plants. As Finland is also a large consumer of biomass, adding CCS to bioenergy solutions (bio-CCS, or BECCS) would enable removal of CO_2 from the atmosphere. CCS can be employed for reducing CO_2 emissions from both thermal power plants and carbon intensive industry, such as oil refining and steel manufacturing. Identifying CCS solutions for heavy industry may therefore be considered important for looking ahead to reducing CO_2 emissions from the Finnish industry in the long-term.

The main objective of the Carbon Capture and Storage Program (CCSP, 2011–2016) has been to develop CCS-related technologies and concepts, leading to essential pilots and demonstrations by the end of the programme. A further objective has been to create a strong scientific basis for the development of CCS technology, concepts and frameworks, and to establish active, international CCS co-operation.

The programme has produced numerous up-to-date technology studies that can be used for techno-economic assessments concerning CCS technologies. The main objective of the present task is to utilize these improved technology characterizations for a long-term energy system analysis, for obtaining a broader view of the potential significance of CSS in Finland until 2050. Such an analysis should best be made in an integrated context, taking into account the interactions between supply and demand and the various decision-makers in different levels of the energy market. In order to take such interactions consistently into account, a large energy system model was used as the tool for the scenario assessments.

For the long term perspective, the objective of reaching a low carbon economy in Europe was chosen as the primary background assumption. However, due to the impossibility of making any firm predictions of the future developments up to 2050, the analysis of the transition to a low-carbon society was carried out by exploring alternative scenarios, based on a few low-carbon storylines. The aim was to construct scenarios that are sufficiently different in order to be able to reach a more broad-based assessment of the future from different viewpoints.

The computational analysis involved the modelling of the selected long-term scenarios with a multi-region energy system model, aiming at producing assessments concerning the impacts of the transition towards a low-carbon society on the energy production system as well as end-use in transport, buildings, and industrial sectors. Among the most important boundary conditions for the energy system development were the overall and sectoral targets for greenhouse gas emissions, and the limits on the use of various bioenergy resources, while satisfying the demand for useful energy services in all sectors.

On the concrete level, the main objectives of the integrated assessment were the following:

- The potential role and significance of different CCS technologies in the energy systems of Finland and Europe, when moving into a low carbon economy by 2050;
- The impacts of the availability of the CCS technology option on the Finnish energy system under the different low carbon storylines;
- The impacts of the availability of the CCS technology option on the economic burden of achieving the low carbon economy in Finland and Europe.

3. Methodology

In the energy systems analysis of the CCSP scenarios we employed the TIMES-VTT energy system model was the core tool. The model is a global multi-region model originally developed from the global ETSAP TIAM model (Loulou 2008, Loulou & Labriet 2008). It is based on the IEA TIMES modeling framework (Loulou et al. 2005), and is characterized as a technology-rich, bottom-up type partial equilibrium model. It consists of 17 regions, which are listed in Table 1. The model includes four regions for the Nordic countries (Denmark, Finland, Norway, Sweden), Western Europe, Eastern Europe, CIS (Former Soviet Union excluding the Baltic countries), Africa, the Middle East, India, China, Japan & South Korea, Other Developing Asia, Canada, the USA, Latin America and Australia & New Zealand. For the Nordic regions, the district heat production and demand is divided into four sub-regional areas for better modeling of the heat networks in these countries (Koljonen et al. 2013, Lehtilä et al. 2014).

The representation of energy supply chains starts from the extraction of energy resources, continues through a number of conversion and distribution steps, ultimately leading to end-use to provide a wide variety of energy services in five sectors (industry, residential, transportation, commercial and agriculture). The equilibrium solution is obtained by maximizing the present value of the total consumer and producer surplus over all model regions and periods, assuming perfect competition, employing inter-temporal optimization.

As a partial equilibrium model, the model maintains equilibrium between supply and demand of all commodities, and determines their prices. In each region, the demands of final useful services and commodities are assumed exogenous in the Baseline scenario, while in policy scenarios they are elastic to their own prices, according to price elasticities derived from the literature. In the policy scenarios, the demands of all commodities are thus affected by their prices, and vice versa. Trade in various commodities between regions is also included.

The time horizon of the model is flexible, and can be extended to 2100 or even beyond. For the CCSP scenarios, we used a horizon extending to 2065, divided into successive periods of 5–10 years duration, each representing an average year of the period. To reflect seasonal

Table 1. Regions of the global TIMES-VTT model.

Code	Region description
AFR	Africa
AUS	Australia and New Zealand
CAN	Canada
CHI	China (includes Hong Kong, excludes Chinese Taipei)
CIS	Former Soviet Union excluding the Baltic States
EEU	Eastern Europe (excluding CIS)
IND	India
JPN	Japan and South Korea
LAM	Latin America, including Mexico
MEA	Middle-East (includes Turkey)
ODA	Other Developing Asia (includes Chinese Taipei and Pacific islands)
USA	United States
WEU	Western Europe (EU-12 excl. Denmark, Iceland, Malta, Norway, Switzerland)
DNK	Denmark
FIN	Finland
NOR	Norway
SWE	Sweden

and diurnal variations in supply and demand, each year is divided into five seasons with three daily time segments corresponding to day, night and peak hours.

The overall structure of the model in each region is illustrated in Figure 1. Primary bioenergy supply is modelled by using supply-cost curves with 2–7 cost steps for each bioenergy type. For example, in the Nordic countries the potential of forest residues is modelled with a supply curve of 8 steps in each country, divided into logging residues, stumps and smallwood from thinnings, and the potential itself is proportional to the total roundwood production. For bioenergy conversion, the model includes a wide selection of technology alternatives.

The model additionally includes all the GHG emissions and sources covered by the Kyoto protocol (CO_2, methane, nitrous oxide and F-gases), and a large number of different emissions abatement options, including fuel switching options, new energy conversion and end-use technologies. Carbon capture options have been included within the fuel conversion, power and heat generation, iron and steel, non-metallic minerals, basic chemicals and pulp and paper sectors. Carbon storage options include disposal into geological formations, such as depleted oil and gas fields and saline aquifers, mineralization of carbon dioxide and sequestration by afforestation.

Furthermore, the TIMES model incorporates also an integrated climate module, with a three-reservoir carbon cycle for CO_2 concentrations and single-box decay models for the atmospheric CH_4 and N_2O concentrations, and the corresponding functions for radiative forcing. Additional forcing induced by other natural and anthropogenic causes is taken into account by means of exogenous projections. Finally, the changes in mean temperature are simulated for two layers, surface, and deep ocean (Loulou et al. 2010). The climate module is very useful for the analysis of various climate policies, and extends the model into an integrated assessment model.

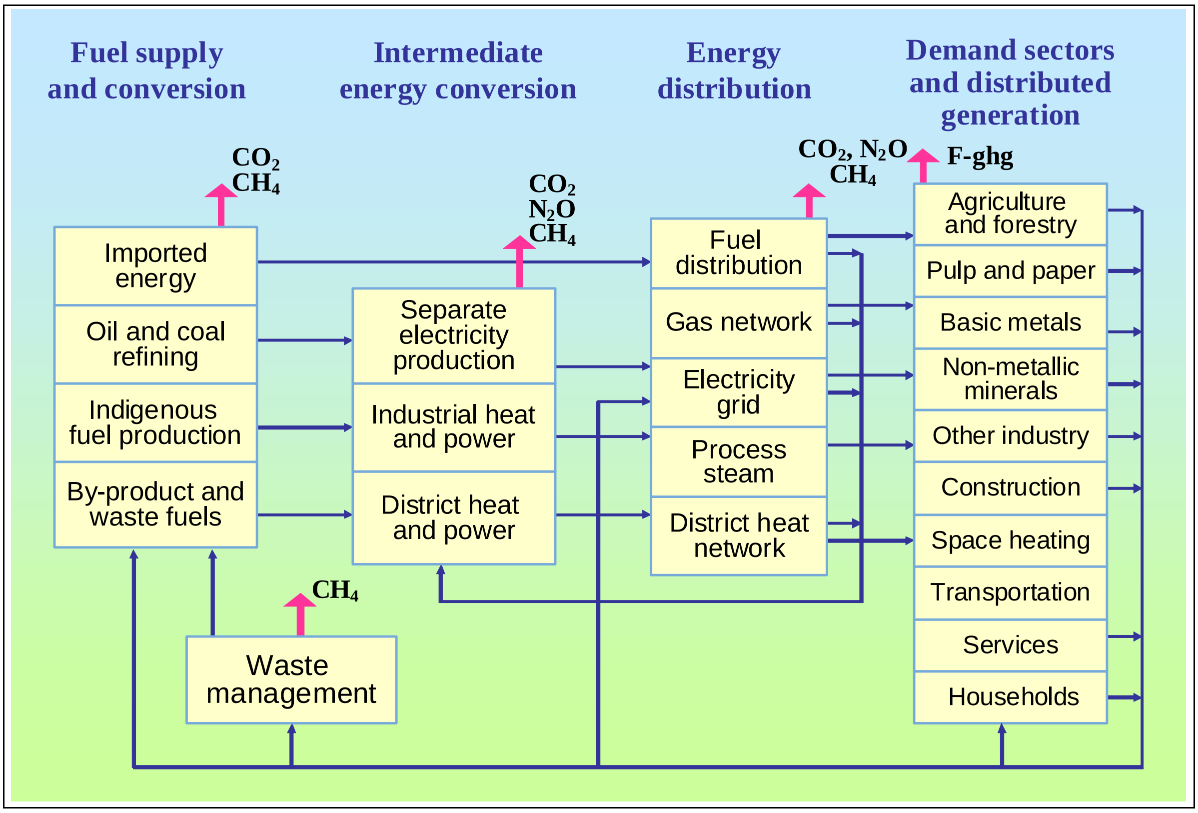

Figure 1. Simplified model structure of TIMES-VTT in each region.

4. Scenarios

4.1 Scenario overview

The long-term scenarios analysed for the CCSP project were based on the scenarios constructed in the Low Carbon Finland 2050 -platform -project, which was completed in 2014 (Koljonen et al. 2014) The four primary storylines constructed within the project were Growth, Stagnation, Save and Change, but additionally a Baseline and a Base–80% scenario were also modelled. The Baseline scenario was a reference scenario reflecting existing policies, including the EU 2030 energy and climate policy package, and the Base–80% scenario had the same assumptions, but also included the global target of limiting global warming to at most 2°C as well as the EU target of 80% GHG emission reduction by 2050 compared to the 1990 level. The main characteristics of the low carbon scenarios are presented in Table 2.

From these six scenarios, the Baseline, Base–80%, Growth and Change scenarios were selected to be re-modelled for the CCSP project, with thorough updates to all technology data closely related to carbon capture and storage. Compared to the earlier scenarios, the updates also include the most recent information related to burden sharing of the EU climate and energy policies. On the other hand, information on the new national 2016 energy and climate strategy was not yet available. Regarding the main factors affecting the overall energy demand, the Growth and Change scenarios have a much lower projection for the production of the pulp and paper industries, and considerably faster development in the energy efficiency in both buildings and industrial processes. For more information on the

Table 2. Main characteristics of the low-carbon scenarios.

Scenario	General characteristics	Policies
Baseline	Structure of economy and industry evolve slowly, moderate technology development. In Finland heavy industries remain important, current urban and regional form.	Current policies, EU 2030 policy
Base-80%	Structure of economy and industry evolve slowly, moderate technology development. In Finland heavy industries remain important, current urban and regional form.	Global 2°C climate policy, EU –80% policy
Growth	"Smart society": Global climate policies, good economic growth, internationalizing, open society, rapid development of technology. In Finland large structural changes in industry, increasing density of urban and regional form.	Global 2°C climate policy, EU –80% policy
Stagnation	"Climate crisis": Rise of global mean temperature of over 4°C ⇒ global economic crisis, closing society, and slow development of technology. In Finland stagnated industrial structure, current urban and regional form.	No global climate policy (~4°C) EU –80% policy
Save	"Modern oil crisis": Delayed global agreement on 2 degree climate target ⇒ forward-leaning climate policy of the EU, conservative development of technology, emphasis on energy efficiency and material efficiency. In Finland slow changes in industrial structure, current urban and regional form.	Global 2°C climate policy, EU –80% policy
Change	"Smart consumer": Radical innovations emphasized, developments in economic structure ⇒ role of services emphasized, intertwining work and leisure time, internationalizing, open society. In Finland slight dispersal in urban and regional form, large structural changes in industry.	Global 2°C climate policy, EU –80% policy, no new nuclear power, no CCS for fossil fuels

Table 3. Main differences in technology assumptions between the low carbon scenarios selected for the CCSP scenario study.

Technology	Base-80%	Growth	Change
Commercial CCS availability	Full	Full	Only BECCS and industrial processes
Chemical looping CCS power plants	Not available	Not available	Available
CCU & power-to-gas technologies	Hydrogen-boosted biofuel conversion	Hydrogen-boosted biofuel conversion	CCU with DAC, Hydrogen-boosted biofuel conversion
Advanced bi-directional fuel cells	Not available	Not available	Available
Electricity storage technologies	Conventional	Moderate development	Rapid development
Solar and wind power technology	Moderate development	Optimistic development	Optimistic development
New nuclear power	Hanhikivi-1	Hanhikivi-1	none
Low temperature district heat systems	No	Yes	Yes
Oxygen blast furnace technology with CCS	No	Available	No
Direct hydrogen reduced steel	No	No	Yes

scenario assumptions, the reader is referred to the reports from the Low Carbon project (Lehtilä et al. 2014, Koljonen et al 2014).

With respect to the core technology assumptions, Table 3 summarizes the main differences between the three selected low carbon scenarios. As an important sensitive analysis, all these scenarios were calculated also assuming that CCS is not commercially available.

4.2 Technology data for CCS options

The technology database of the model includes the following technologies related to CCS:

- CCS in fuel conversion: Production of hydrogen, synthetic hydrocarbons, biofuels from biomass (biodiesel, biogasoline, bio-jet, methane);
- CCS in condensing power generation: PC coal-fired plants, oxyfuel CFB coal plants, oxyfuel CFB multi-fuel plants, natural gas NGCC plants with post-combustion CCS, NGCC plants with pre-combustion CCS;
- CCS in combined power and district heat generation: large oxyfuel CFB coal plants, large oxyfuel CFB multi-fuel plants, large CLC multi-fuel plants, large natural gas NGCC plants with post-combustion CCS and with pre-combustion CCS;
- CCS in district heat plants: large CFB heat plants with CCS;
- CCS in industrial combined power heat generation: natural gas NGCC plants with post-combustion CCS, recovery boiler power plant in pulping with post combustion CCS;
- CCS in industrial processes: BOF steel-mill with CCS retrofit, oxygen blast furnace with CCS, cement kilns with CCS.

The technology database has been rather thoroughly updated with respect to the technologies mentioned above. Concerning the various biomass fuel conversion technologies based on the FT process concepts, the main data sources have been Hannula & Kurkela (2013), Hannula (2016) and Kakkonen & Syri (2014). These include also the data for the hydrogen-boosted biofuel production. The data for the hydrogen conversion processes have been mainly updated on the basis of IEA (2015).

Concerning the power and heat generation technologies, the updated data for condensing power plants are based on ZEP (2011), ETRI (2014) as well as Arasto et al. (2014b). Compared to the data used earlier e.g. in the CCS-Suomi project (Teir, Arasto et al. 2011), the updated estimates on investment costs are, in general, higher. However, for large oxy-fuel CHP plants this is compensated by the higher overall efficiencies in the updated data, reaching over 100% in the biomass-fueled oxyfuel cogeneration plants (Arasto et al. 2014b). Data for NGCC CHP plants with post-combustion CCS are based on ZEP (2011), and with pre-combustion CCS on Pirhonen (2011) and Suomalainen et al. (2013). The data for the chemical looping technologies are based on Tsupari et al. (2014).

For district heating plants, only a single technology with CCS has been modelled. This is the option of equipping a large CFB heat plant of the size 400 MW(h) with CCS, assumed available for Helsinki in 2030 as an alternative to a similar size plant without CCS. In both cases the plant would use biomass as its main fuel. The technology data for the CCS option has been obtained from Helen (Helen 2013, and personal communication).

In addition to the energy transformation sector, in the industrial sectors CCS can potentially become a very important option, because for many industrial processes deep cuts in emission are otherwise very difficult to reach, and would in many cases require completely different production processes. In the model, the main CCS options are within the iron and steel, non-metallic minerals, and pulp and paper manufacturing. In the iron and steel sector, the oxygen blast furnace appears to be one of the most promising options, for which the data have been updated according to Arasto et al. (2014a), Arasto (2015) and Tsupari et al. (2015). For the process emission from cement manufacturing, the CCS data is based on IEA and IEAGHG estimates (IEA 2011b, IEAGHG 2013). For the pulp-and paper sector, capture of CO_2 from the flue gas of recovery boilers is considered, and the technology data is from an IEAGHG report (IEAGHG 2016).

The **carbon storage** options include enhanced oil recovery, enhanced coalbed methane recovery, depleted oil and gas fields, saline aquifers, and mineralization of CO_2. The costs of these options are mainly based on the TIAM model database developed within the ETSAP programme (Loulou & Labriet 2008), and range from close to zero costs for enhanced oil recovery to 25 €/tonne for mineralization. However, for the option with the largest potentials, saline aquifers, the cost estimates of the TIAM database have been significantly increased in the VTT model database, reaching about 12 €/tonne in Europe. This cost level is at the high end of the cost range of most published estimates (see e.g. Teir, Pikkarainen et al. 2011). In accordance with the Nordic CCS study (Teir et al. 2010), no storage potential was assumed in Finland or Sweden in the scenarios, and any carbon captured in Finland would therefore have to be transported to storage sites in Norway or Western or Central Europe.

Carbon transportation costs from Finland to storage sites in the North Sea area were estimated in the CCS Suomi -project (Teir, Arasto et al. 2011), which arrived at costs ranging from about 10 €/tonne from the coast to the storage sites, and 3–20 € from inland sites to the coast. For the current CCSP scenarios, the transportation costs were assumed to be at the lowest 23 €/tonne (coastal sites) but for the CO_2 captured at inland sites the total transportation costs were assumed up to 32 €/tonne. In particular, the BECCS applications are usually assumed to be located at inland sites having larger transportation costs.

4.3 Biofuel refinery technologies

Climate policies have a large impact on the economic potential of biofuel refineries, in particular with respect to producing biofuels for transportation. According to the IEA 2011 roadmap, biofuels could provide 27% of global transportation fuel consumption by 2050 mainly by replacing diesel, kerosene and jet fuel (IEA 2011).

In the CCSP scenarios, bio-refineries were therefore among the key bioenergy technologies to be considered, even with respect to CCS deployment. The TIMES-VTT model includes over 20 technologies for liquid and gaseous biofuels production in each region, for which the technical and economic data has been collected from literature (e.g. Hannula & Kurkela 2013, Hannula 2016, Kakkonen & Syri 2014). The base estimates for the investment costs and feedstock efficiency in 2030 are shown in Table 4 for key biorefinery technologies. By-product flows and ancillary energy inputs were also taken into account for the processes. The base estimates have been used for both the Growth and Change scenarios. In the Base-80% scenario somewhat higher investment costs were assumed. CCS may be particularly attractive in the FT-based processes, because they produce an almost pure CO_2-stream that can be captured with low additional costs.

In order to take into account also the sustainability of wood biomass (Pingoud et al 2012), forest chips were assumed to have a CO_2 emission factor of 25 t/TJ when produced from logging residues, 40 t/TJ from smallwood, and 70 t/TJ when produced from stumps. These emissions only affect the decision variables in the model, but are not shown in the balances.

Table 4. Biorefinery technologies considered in the CCSP scenarios.

Technology	**Feedstock(s)**	**Available**	**Investment cost (2030) €/kW(out)**	**Tech-nical life**	**Fuel output / feedstock (2030)**
Biodiesel, integrated	wood	2020	2627	25	95 %
Biodiesel, integrated	black liquor	2030	2770	25	95 %
Biodiesel, non-integrated	wood, 2nd gen. crops	2020	2145	25	57 %
Biodiesel, non-integrated, CCS	wood, 2nd gen. crops	2030	2482	25	51 %
Biodiesel, non-integrated, CCS	black liquor	2030	3200	25	92 %
Biogasoline, non-integrated	wood, 2nd gen. crops	2030	2459	25	57 %
Biogasoline, non-integrated, CCS	wood, 2nd gen. crops	2030	2803	25	50 %
Biogasoline, hydrogen-boosted, non-integrated	wood, 2nd gen. crops	2030	1600	25	134%
Bio-methanol, hydrogen-boosted, non-integrated	wood, 2nd gen. crops	2030	1400	25	155%
SNG, non-integrated	wood	2020	1682	25	72 %
SNG, non-integrated, CCS	wood	2030	1983	25	72 %
SNG, hydrogen-boosted, non-integrated	wood	2030	900	25	205%
Heavy bio-oil, integrated	wood	2010	660	25	78 %
Ethanol	1st gen. crops	2010	1060	25	56 %
Ethanol, ligno-cellul.	residues, 2nd gen crops	2020	1990	25	42 %

5. Results from Base scenario variants

5.1 Development of energy supply

In Finland, the total primary energy consumption was about 1500 PJ in 2010, of which 52% consisted of fossil fuels and peat. The use of renewable energy has already for a long time been at a high level, close to 30% of primary energy, and the role of nuclear energy is also considerable in Finland, about 18% of primary energy. The projected future development of primary energy consumption is shown in Figure 2 for the CCSP scenarios.

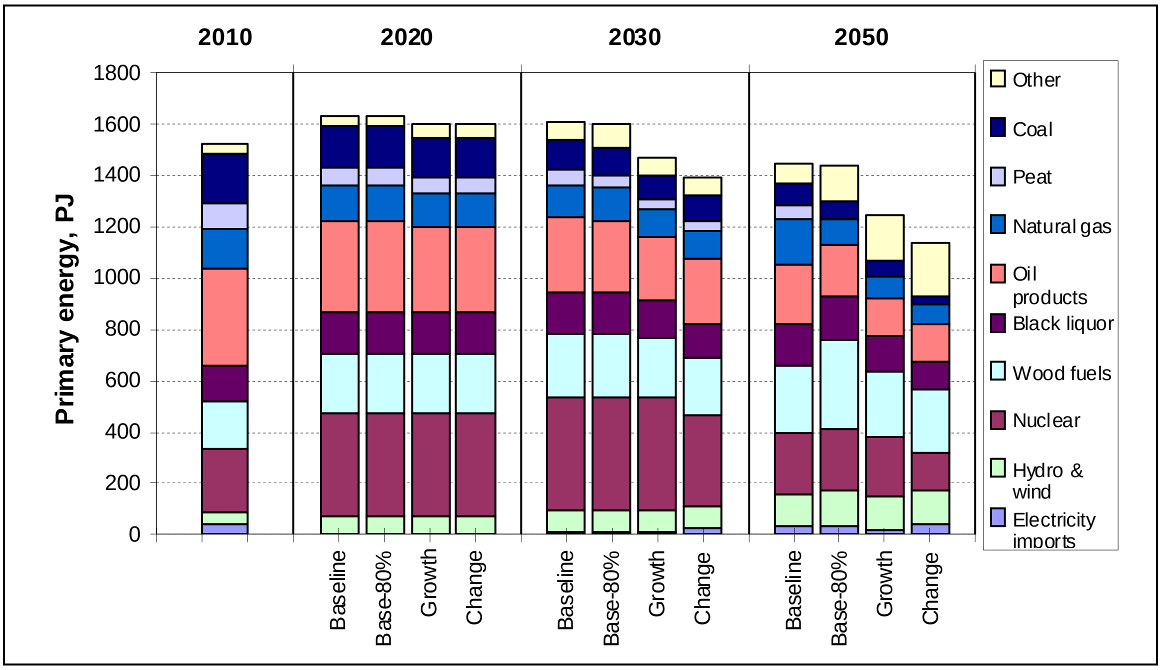

Figure 2: Development of primary energy supply in Finland ("Other" includes solar).

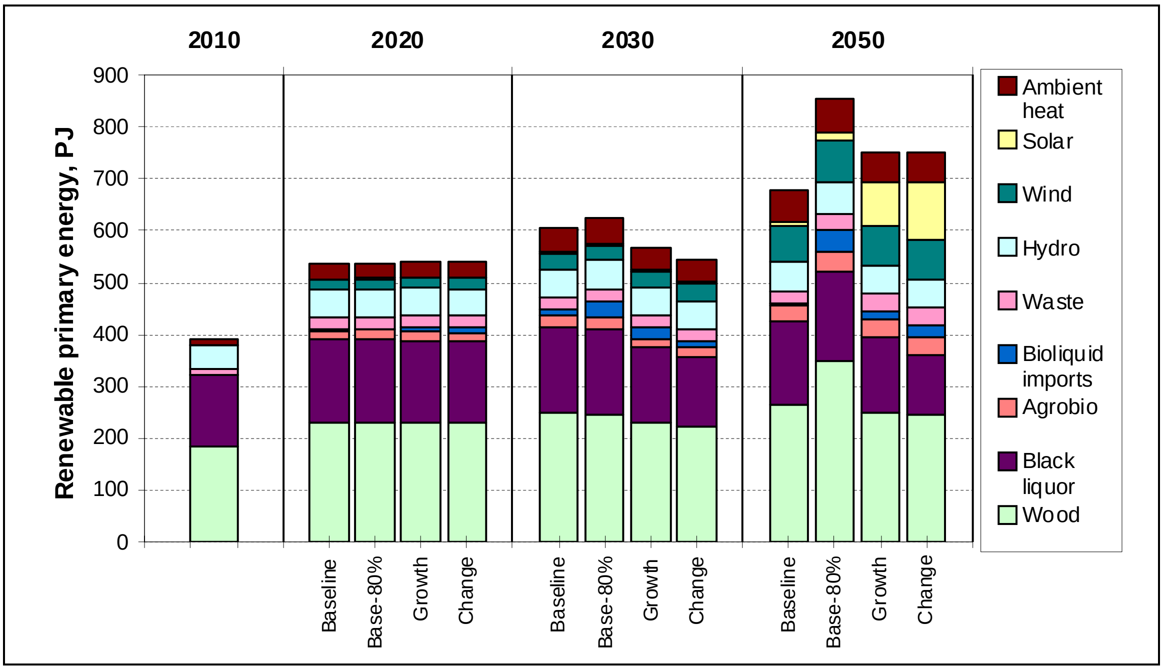

Figure 3: Development of renewable primary energy supply in Finland.

In the Baseline scenarios, total primary energy increases slightly by 2020 from the 2010 level, but this increase is mostly attributable to the notable increase in nuclear power, which tends to increase the computational primary energy. In the Growth and Change scenarios the consumption falls below the 2010 level already in 2030. After 2030 total primary energy consumption is steadily decreasing, and falls below the 2010 level in all of the scenarios, most prominently in the Change scenario, to a level over 25% lower than in 2010.

Figure 3 gives a somewhat more detailed account of the development of renewable primary energy in Finland in the scenarios. As one can see, the level of bioenergy use is clearly highest in the Base-80% scenario, where the slower development of other renewables sets a high pressure on bioenergy demand. However, the utilization level is almost the same in the Baseline, Growth and Change scenarios, despite the assumed differences e.g. in the forest industry production and development of new technology. This indicates that a competitive and sustainable level of using bio-energy is not very sensitive to the scenario assumptions.

The development of the overall electricity supply is illustrated in Figure 4. The results clearly illustrate that when moving towards a low carbon economy, electricity generation should gradually become practically free of GHG emissions. However, in Finland this requirement also tends to cause some shrinking in the economic potential for CHP and district heating, despite the high overall energy efficiency of CHP generation. As reaching the emission targets would entail that basically all thermal generation should be based either on biofuels, carbon-free synthetic fuels, or CCS, maintaining a very high share of CHP generation may become both logistically difficult and uneconomical. This impact is shown by the district CHP generation remaining below the 2010 level in all low carbon scenarios until 2050. However, due to the assumed higher power-to-heat ratios in new plants, the results show some increase in industrial CHP generation, partly serving also community heating demands. In the longer term, the results indicate CCS becoming competitive also in CHP plants producing district heat for large urban areas, in particular combined with the oxyfuel or the CLC technology, as they both enable maintaining high total energy efficiency in CHP generation. This is realised in all of the low carbon scenarios, and most notably in the Base-80% and Change scenarios in the Helsinki metropolitan area where CHP competitiveness is improved by investing into a large multi-fuel plant with CCS, using biomass as its main fuel.

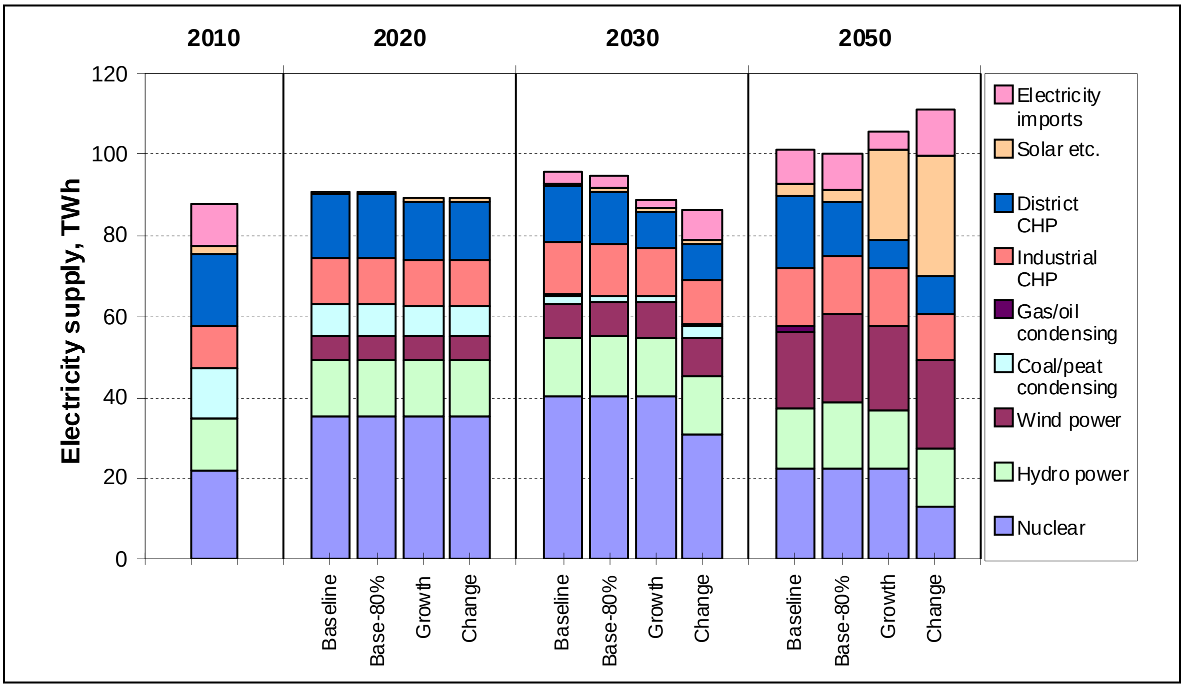

Figure 4: Development of electricity supply in Finland.

The phase-out of fossil fuels after 2030 can be seen more clearly in Figure 5, showing the generation by energy source. Furthermore, Figure 6 gives a more transparent summary on renewable electricity generation. With respect to the variable renewable generation options, the Change scenario exhibits the highest penetration of solar power, 29 TWh, which would be realistic only under the optimistic assumptions concerning energy storage technologies in this scenario, especially given that also wind power has almost an equally high market share. However, in 2030 solar power still accounts only for 0.6 TWh of the electricity supply even in the Change scenario, while wind power does reach about 10 TWh already in 2030 in this scenario. Although dark winters make solar power in Finland considerably less cost effective than in many other countries, the results suggest that it becomes competitive after 2030 on a large scale even without subsidies, and very prominently under steep learning curves.

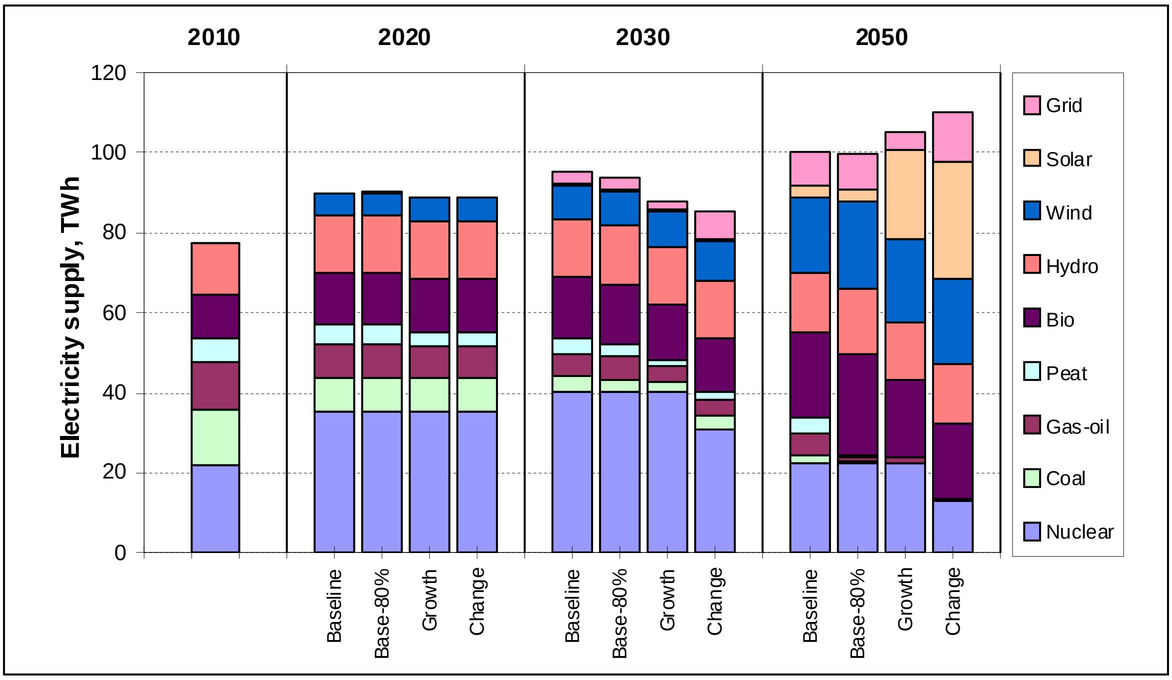

Figure 5: Electricity supply by energy source in Finland.

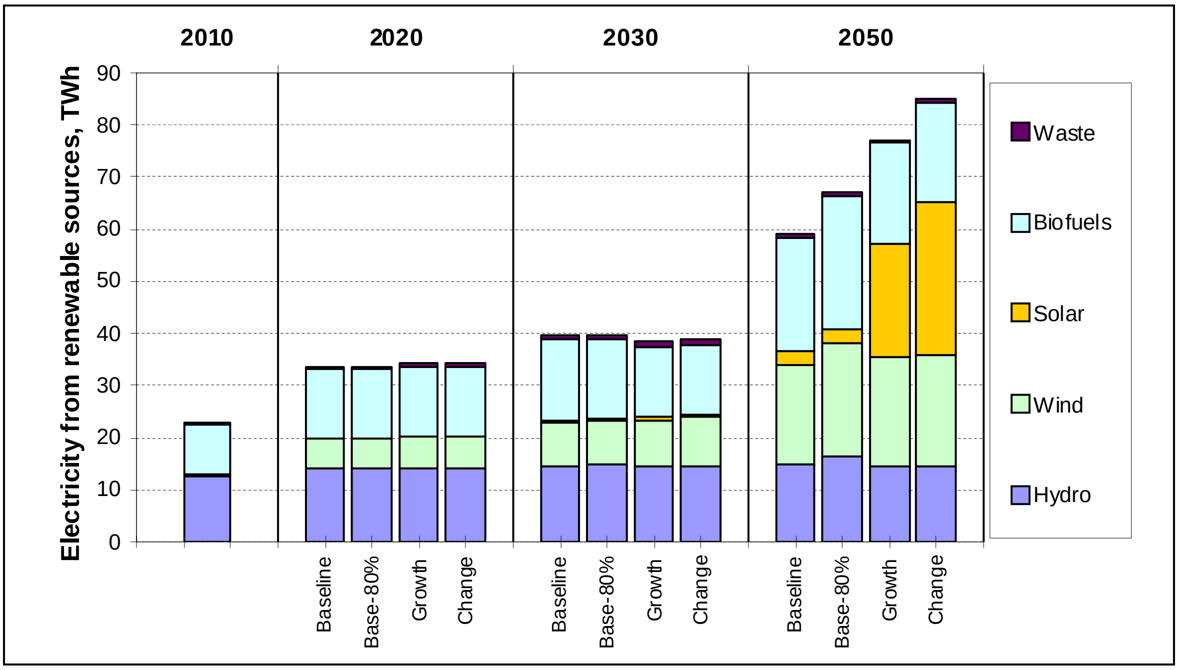

Figure 6: Development of renewable electricity generation in Finland.

5.2 Development GHG emissions and deployment of CCS

The development of the Finnish greenhouse gas emissions is depicted in Figure 7. According to the results, the national target of an 80% reduction in GHG emissions by 2050 is fully achieved in all of the low carbon scenarios, where that target was set only for the total European emissions. Results from the Base cases thus indicate that, if CCS is available, deep emission reductions are in Finland somewhat less costly than in Europe as a whole, primarily due to the large potential of utilizing BECCS for reaching negative emissions. The GHG reductions in the Base-80% scenario (84%) are actually rather close to the national target, but the Growth and Change scenarios achieve substantially deeper reductions.

Of the main sectors causing GHG emissions, agriculture turns turn out to be the one where achieving substantial reductions is most difficult. The majority of the emissions in this sector are methane and N_2O emissions not directly related to energy use. The second most difficult main sector is industry, and in particular, process-related emissions from basic metals, basic chemicals and minerals manufacturing, for which new low-emission processes are technically or economically difficult to implement. Consequently, even larger reductions than the overall target would be needed in other sectors. In all the scenarios, total CO_2 emissions from the energy sector and industry fall in the Base cases to zero or below in 2050 (note that Figure 7 does not show the negative amount of those emissions).

As mentioned earlier, due to there being no suitable geological CO_2 storage capacity within the territory of Finland, the CO_2 transportation costs for CCS in Finland have been estimated by assuming the storage site being located either in the North Sea or the Barents Sea (Teir & al. 2010). Despite the higher transportation costs involved, the results indicate that CCS could still have a notable role in Finland, insofar as large-scale storage technology will be commercialized in Europe. However, as long as bio-fuel based CCS (BECCS) will be credited, CCS based on fossil fuel does not have seem to have notable potential in Finland. As there is much more large condensing power elsewhere in Europe, where the transportation costs are much lower, the model prefers to invest into fossil fuel based CCS there.

On the other hand, with BECCS alone, annual emission reductions of up to 15 Mt CO_2 could be reached by 2050 in the low carbon scenarios as illustrated in Figure 8. Of this total

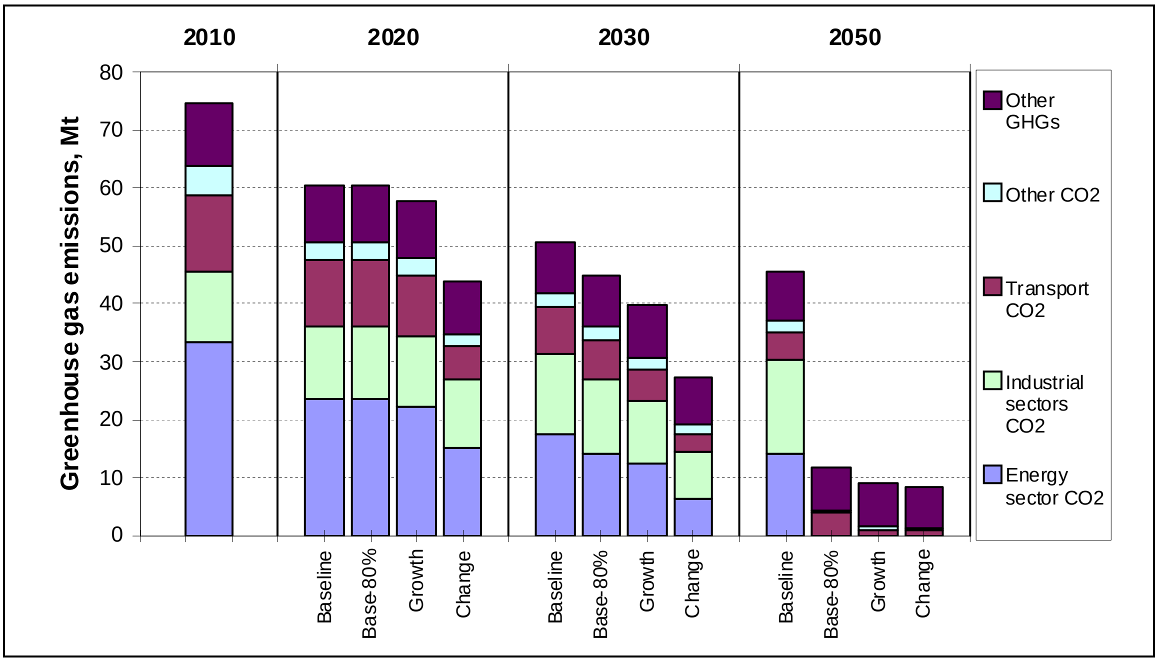

Figure 7: Development of greenhouse gas emissions in Finland.

amount, main activity producer power and heat generation accounted for 5–8 Mt in the scenarios, pulp and paper sector for 4–7 Mt, and biofuel refineries for about 3 Mt. Each of these sectors would thus have a significant level of deployment in BECCS. For the metropolitan region, the new Vuosaari C 410 MW heat plant would be equipped with CCS in the Growth scenario, but that CCS investment would not be made in the two other scenarios.

In Europe as a whole, CCS would contribute to emission reductions of up to 930 Mt in 2050, of which fossil fuel based power and heat generation up to 300 Mt, and BECCS applications in total up to 400 Mt. It is notable that also in Europe as a whole, BECCS in second generation biofuel refineries would have a very significant contribution to the emission reductions. Albeit the potential may be overestimated, this result appears to be important.

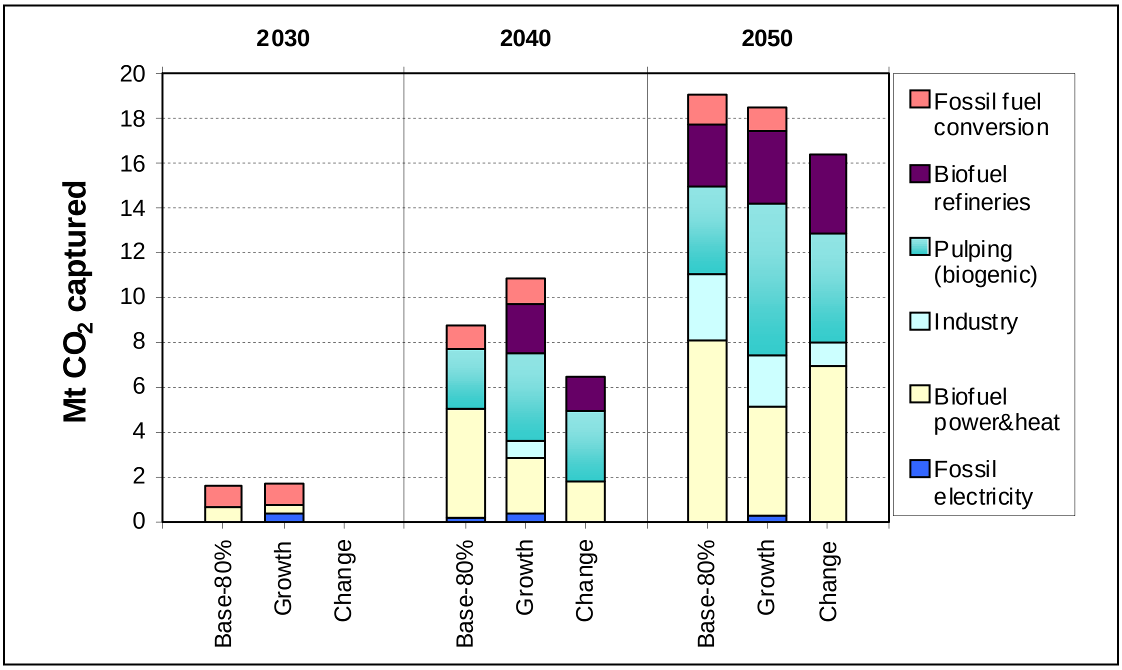

Figure 8: Deployment of CCS in Finland in the Base case scenario variants.

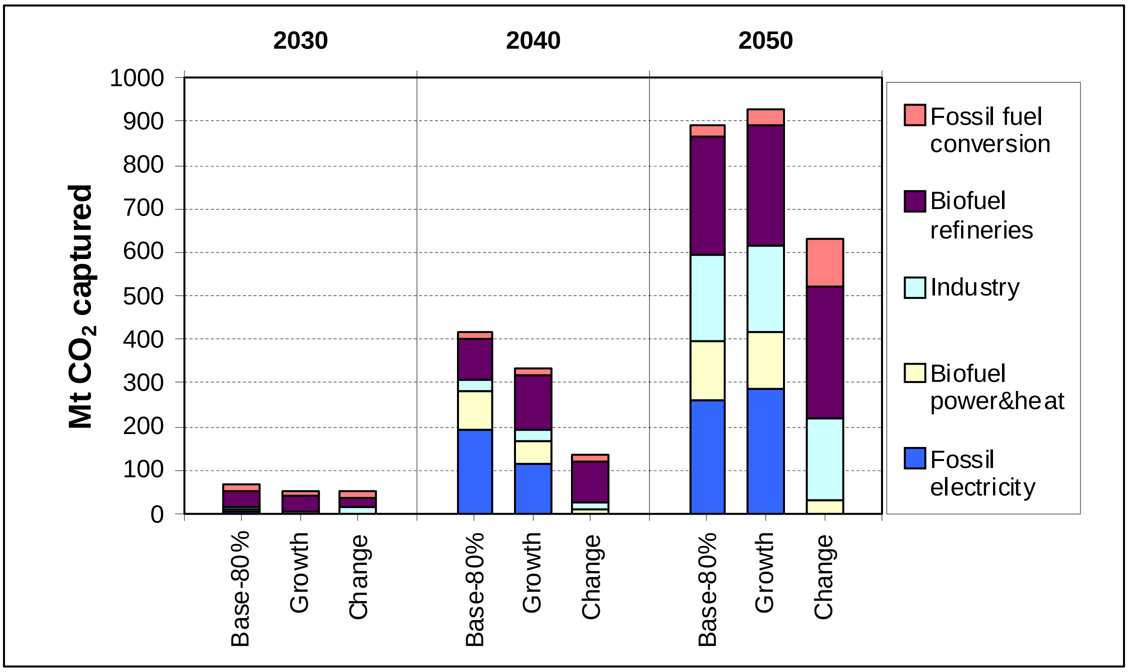

Figure 9: Deployment of CCS in Europe in the Base case scenario variants.

6. Results from No-CCS scenario variants

6.1 Development of energy supply

For the most crucial sensitivity analysis, the No-CSS cases were modelled for all of the three low carbon scenarios. Only a few selected results are presented below for these cases.

The development of renewable primary energy in Finland is shown in Figure 10 for the Non-CCS cases. One can see that the total level renewable energy utilization is in the Base-80% and Growth scenarios somewhat higher in the No-CCS cases compared to the Base cases, but remains on the same level in the Change scenario. However, the use of wood bioenergy decreases in all scenarios, while the use of wind and solar energy as well as in the utilization of ambient heat in heat pump applications are most notably increasing. The availability of BECCS is thus seen to enhance the competiveness of bioenergy use, while excluding it further improves the competitive position of other renewables. Concerning solar energy, the Change scenario boasts with the most remarkable increases, such that in 2050 solar energy would even exceed the use of wood for energy (excluding black liquor). Apart from solar power, thermal solar energy use is also utilized about 10 PJ in the Change scenario.

The development of the total electricity supply by energy source is illustrated in Figure 11 and the renewable electricity generation in Figure 12. Excluding CCS from the available options effectively makes the emission reductions tighter, and thereby electrification becomes yet more pronounced in the results, which is in agreement with many other studies. This can be clearly seen in the total electricity consumption, which is in all three low carbon scenarios notably higher than in the Base cases. The additional supply is mainly provided by solar and wind power, but to some extent also the net imports of electricity are increasing. With respect to the required electricity supply capacity, even higher investments into new capacity would thus be required than those indicated by Figure 16 below in Chapter 7.

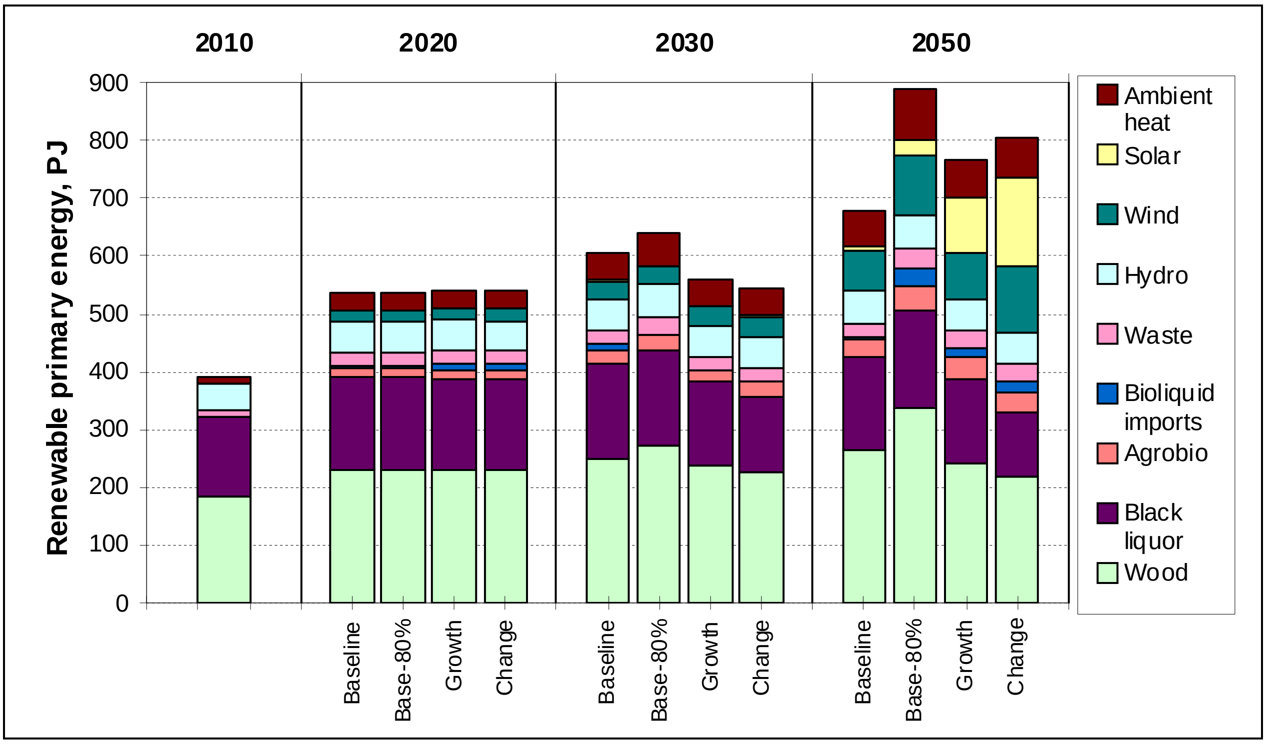

Figure 10: Development of renewable primary energy supply in Finland – No-CCS case.

As one can expect, the position of CHP generation becomes more difficult when the CCS option is excluded. In 2050, district CHP accounts for only 7.1 TWh in the Growth scenario and 5.7 TWh in the Change scenario. Without low temperature district heating networks, which were assumed to penetrate in the Growth and Change scenarios, the role of CHP would have become even smaller. Although in view of the high efficiency of CHP generation that may seem counter-intuitive, in the end the economic potential is mostly driven by the limited sustainable biofuel resources, which, together with high distribution costs to large utilization centres, tends to increase the price of biofuels to a level no longer competitive for electricity generation, especially when the BECCS option is excluded. BECCS and CHP thus appear to have a clear synergy benefit in Finland. Nonetheless, bioenergy remains quite competitive in district heat generation, where the production levels are much less affected.

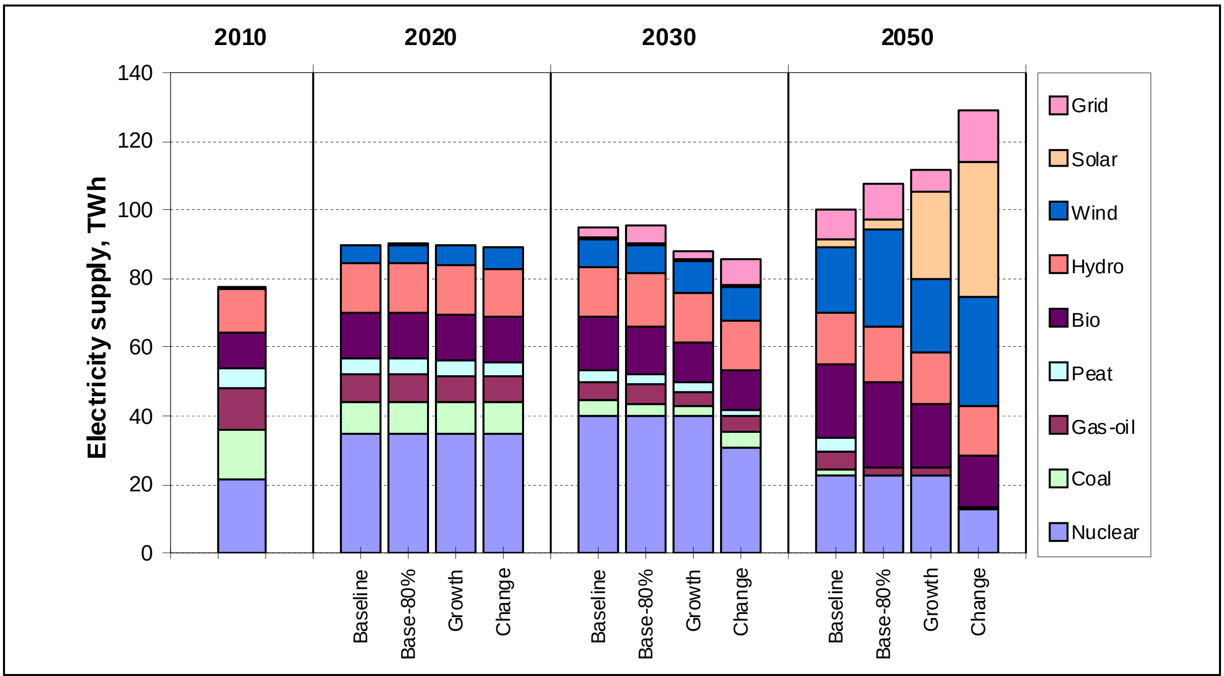

Figure 11: Development of electricity supply by energy source in Finland – No-CCS case.

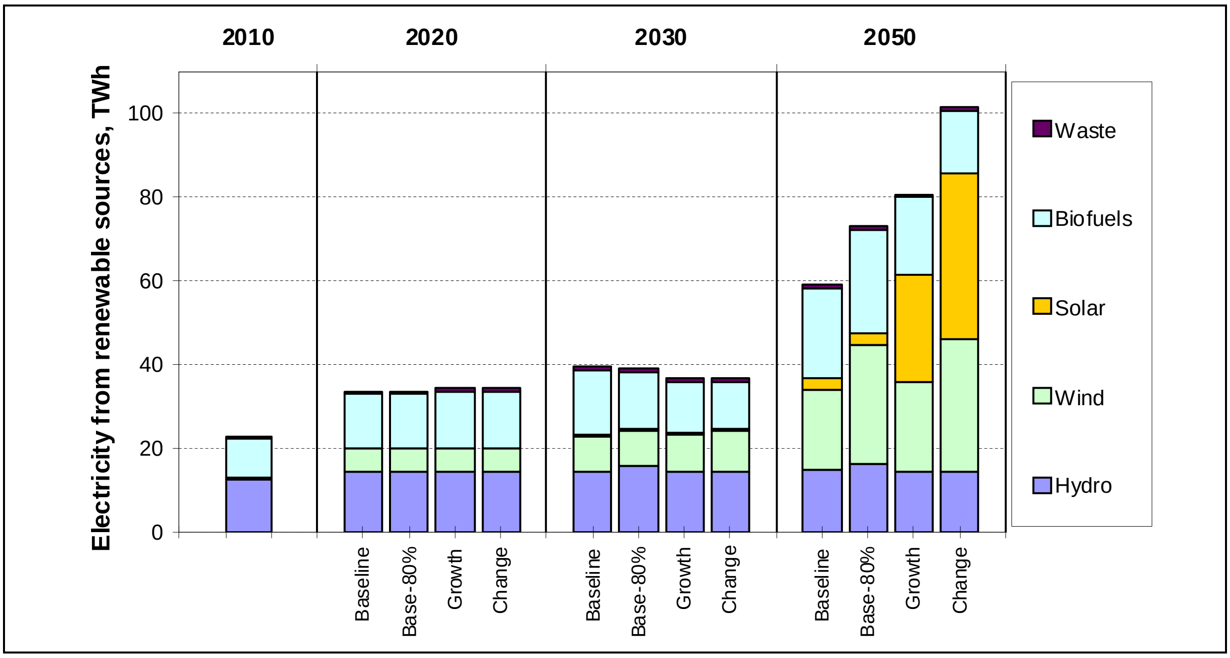

Figure 12: Development of renewable electricity generation in Finland – No-CCS case.

6.2 Development of emissions

Under the No-CCS cases, the development of the Finnish greenhouse gas emissions is less favourable than in the Base cases, as one can see by comparing the results shown in Figure 13 to those in Figure 7. The differences are in fact larger than what can be directly seen from these two figures, because in the Base cases, BECCS actually brought the energy sector emissions down to amounts below zero in all three scenarios. In the No-CCS cases, for Finland there were no options for achieving negative emissions available in the model. However, one should bear in mind that changes in emissions related to land use and forestry (LULUCF) were excluded from the EU-wide emission targets in the energy system model runs. These changes could still bring about negative emissions, if the forest stocks would be growing favourably, but they should best be assessed with forestry sector models.

According to the results, the national target of an 80% reduction in GHG emissions by 2050 is not fully achieved in any of the low carbon scenarios when the CCS option is excluded. The results thus indicate that deep emission reductions are in that case somewhat more costly in Finland than in Europe as a whole. Emissions from the energy sector and industry remain in these cases close to 10 Mt in 2050 in all scenarios. However, one should also note that the use of wood biomass for energy remains at a somewhat smaller level in the No-CCS cases compared to the Base cases. The difference is the largest in the Change scenarios, about 25 PJ in 2050, while in the Base-80% it is about 15 PJ and in the Growth scenario only about 5 PJ. Should these differences be reflected in the growth of forest stocks, the impact of CCS availability on the full emission balance would be somewhat smaller.

Summing up all effects, unavailability of CCS clearly appears to have an unfavourable impact on the total greenhouse gas emission balances in Finland. That might eventually be counter-balanced by achieving larger carbon sinks by forests, which, in turn, would be at least to some extent more realizable if advanced energy storage and carbon recycling technologies can be commercialized and deployed on a large scale by 2050, as it was assumed in the Change scenario. Only with these technologies a very large integration of other renewables in the energy system can be supported without compromising reliability of the system.

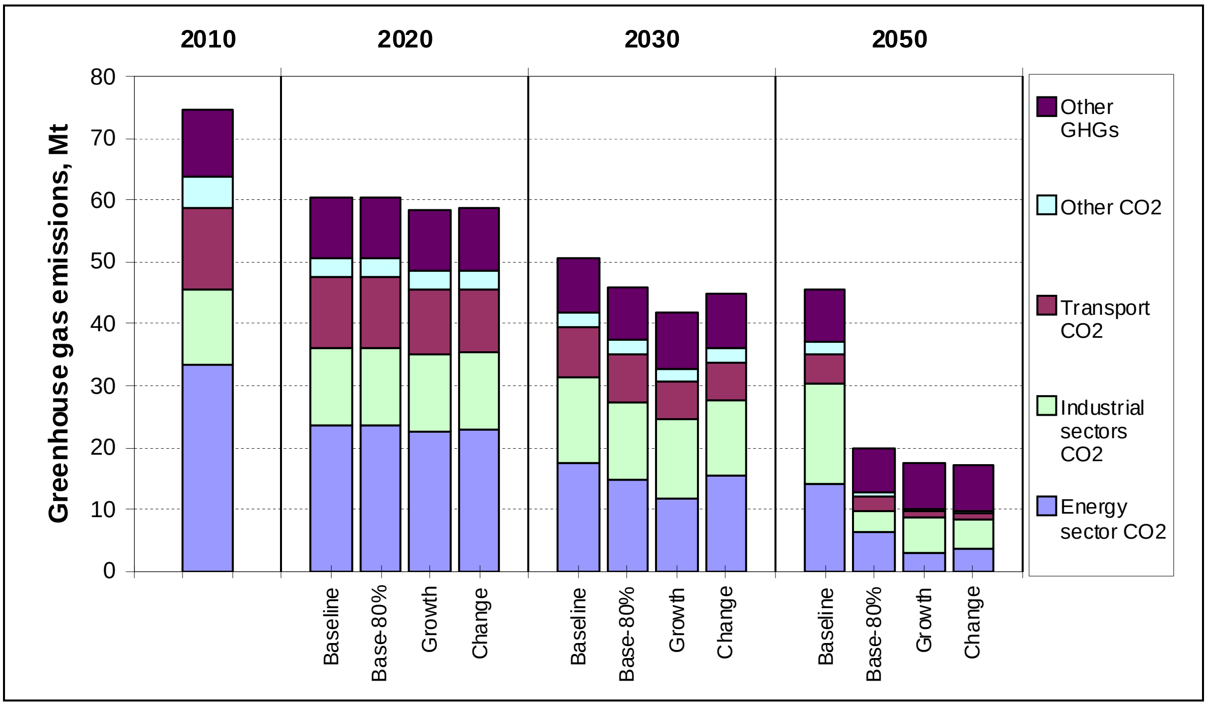

Figure 13: Development of greenhouse gas emissions in Finland – No-CCS case.

7. Discussion

The potential role of CCS for achieving the low carbon energy system by 2050 appears to be quite significant. This is clearly demonstrated by the amounts of carbon captured in the Base cases, both on the European level as a whole and in Finland. In Europe, the amount of emissions reduced by using CCS could reach almost 1 Gt by 2050, and even if CCS in fossil fuel based power generation would be prohibited (the Change scenario), using BECCS for capturing biogenic CO_2 emissions would be an important option in Europe, especially in second generation biofuel refineries employing the FT process concepts.

Reaching the tight emission reduction targets in the low carbon scenarios would become considerably more costly without CCS. The difference is most prominent in the marginal cost of emission reduction, which should also well correspond to the price of emission allowances in the ETS sector. The development of these prices is illustrated in Figure 14. According to the model results, in the Base cases where CCS is available, the price would increase to 30–40 €/tonne by 2030, to 60–70 €/tonne in 2040 and to 110–120 in 2050. Without CCS the price would get slightly higher already in 2030, reach the level of 80–90 €/tonne by 2040 and well over 200 €/tonne by 2050. Among the three low carbon storylines, the emission prices would remain the lowest in the Growth scenarios both with and without CCS, but in 2050 the difference in the emission price between the three scenarios is below 20 € in both variants.

With respect to the total direct costs of emission reduction, the differences are less prominent, but still significant. On the European level, the annual costs without CCS would be € 7–12 billion higher in 2040 and € 45–61 billion higher in 2050, as shown in Table 5. If we divide the cost difference in 2050 by the amount of emissions reduced from the Baseline level in 2050 (about 1.6 Gt CO_2), we can calculate the average costs of the required additional emission reduction being 28–38 € higher in 2050 without CCS.

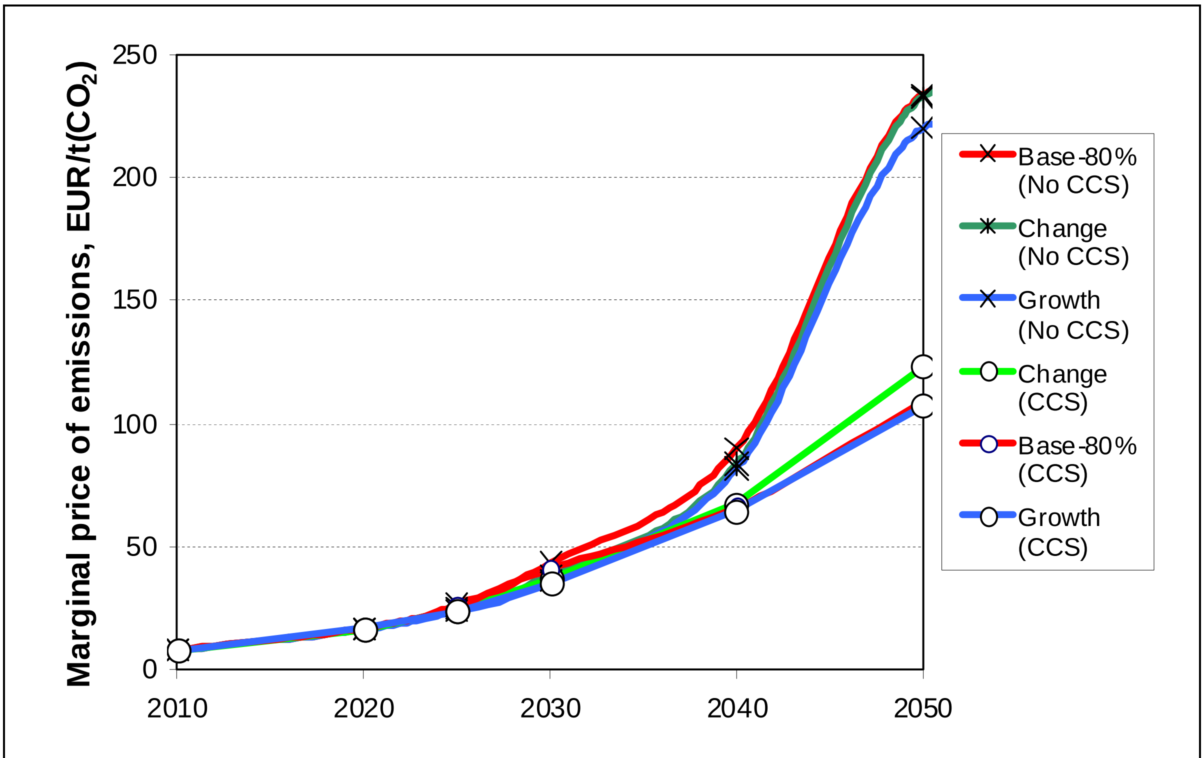

Figure 14. Evolution of the marginal price of emissions (allowance price) in the Base cases and No-CCS cases.

Table 5. Annual direct additional costs in the No-CCS cases compared to the Base cases.

Region / Scenario	**2030**	**2040**	**2050**
Whole Europe (M€)			
Base–80%	2200	12300	60700
Growth	1800	6900	44700
Change	1400	10200	44300
Finland (M€)			
Base–80%	200	330	820
Growth	70	80	250
Change	40	140	300

For Finland, the impact of CCS availability in the emission price level is, of course, the same as for Europe as a whole, as the 80% emission reduction target is assumed for the total European emissions and not as quotas for each member country. According to the results, the direct additional annual energy system costs would be 250–820 M€ higher in 2050 without CCS, the total annual policy costs being close to 3000 M€ for Base-80%. Compared to the projected GDP in 2050 the direct additional costs are thus relatively small, 0.1%–0.2%. However, as the results also indicate that the emission reductions achieved in Finland become smaller without CCS, one should take into account also the implied impact on the emission allowance balance. In the Base cases, all scenarios appear to have a surplus in the balance of trade in emission allowances in 2050, but in the No-CCS cases there appears to be a need purchase allowances in all scenarios. The impact of these differences in the emission allowance trade balance is shown in Figure 15, where one can see that the additional cost impact on the Finnish industries can be notable, when the balance in emission allowances is taken into account.

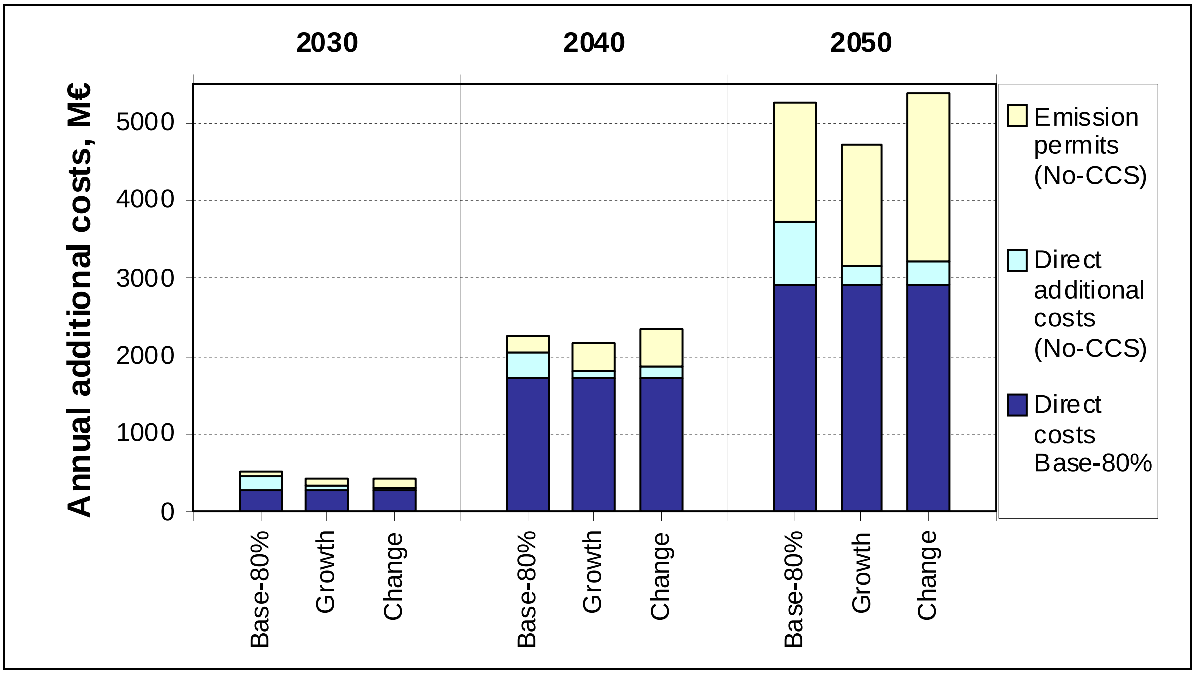

Figure 15. Total annual direct costs from the Base-80% policy, and the additional costs from the No-CCS cases compared to the Base cases. Emission permit costs are computational, derived by multiplying the emission price (shown in Figure 14) by the deviation in total emissions from the target level in each year.

Finally, looking at electricity supply, when the power system is mostly based on thermal plants, the unit commitment and dispatching of plants can be usually well optimized according to the need for electricity supply capacity. The total capacity needed in the system follows in such cases quite well the peak load, added with a sufficient reserve margins. In Finland the total maximum generating capacity was 16740 MW at the end of 2010. The peak load was 14965 in the 2010–2011 peak load period, and the annual demand was 87.7 TWh. However, the simultaneously available capacity of power plants during the peak was only 13100 MW, and the residual load primarily covered by imports can be estimated at about 1900 MW. The total capacity needed in 2010 can thus be roughly estimated at 18600 MW, as shown in Figure 16. While the average peak utilization time was thus 5860 hours for the peak load, the total utilization factor was only 4720 hours.

For the future energy system, the capacity credits at peak time and reserve capacity requirements have been modelled on the basis of technology characteristics and historical statistics. The resulting development of the total maximum generating capacity and the utilized import capacity during the peak are shown in Figure 16. As one can see, the expansion of variable electricity generation has a strong impact on the total amount of capacity required, and the impacts are become very pronounced in the longer term. According to the Base case model results, in 2050 the total capacity needed in the Finnish system would be 27–45 GW, depending on the scenario. As expected, the highest capacity requirements appear in the Change scenario, where the large solar power capacity has practically no contribution to the winter peak load. However, the mitigation factor in the Change scenario is the introduction of additional energy storage in the system, which can be effectively used for balancing the short-term variations in the demand. Nonetheless, in the No-CCS cases the capacity requirements would become even higher, again uttermost in the Change scenario. The results indicate that CCS would be quite valuable also for providing the additional flexibility and reliability needed in a system with high amounts of variable renewable generation.

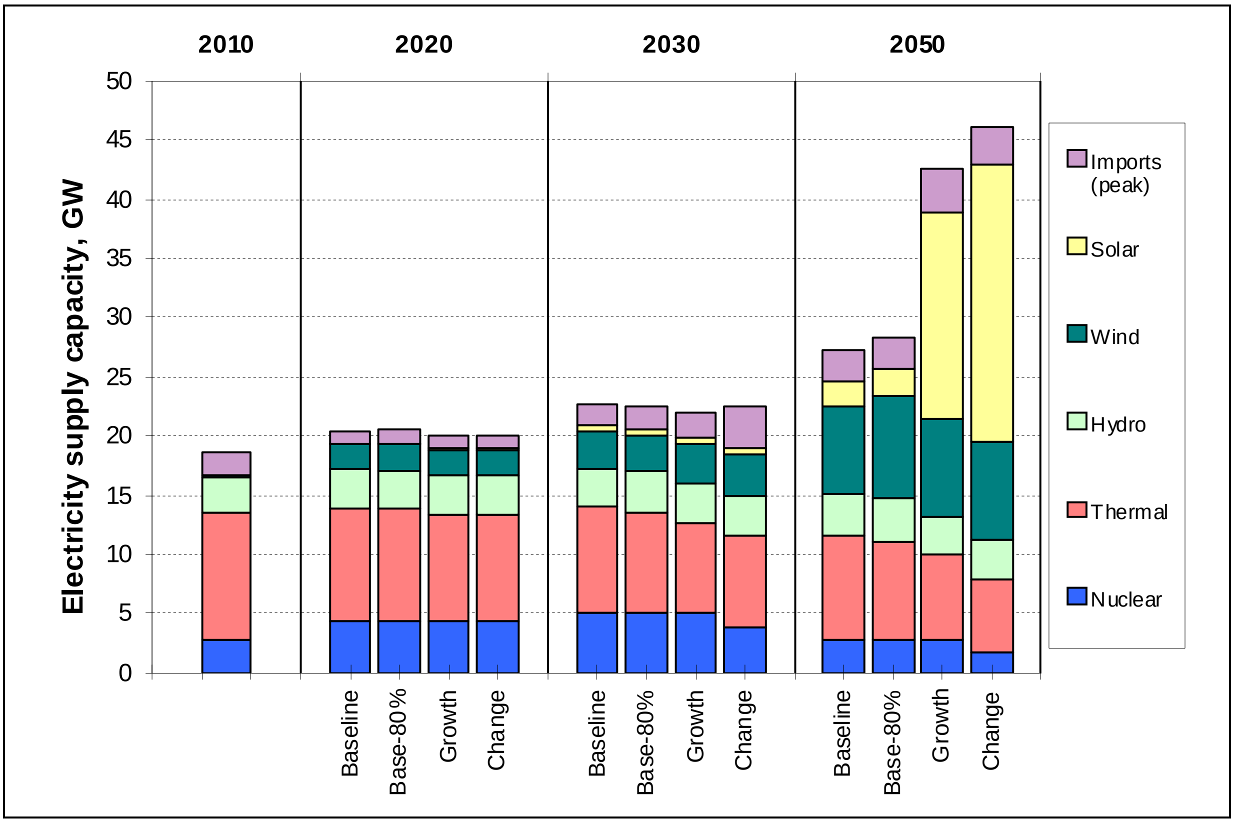

Figure 16. Development of electricity supply capacity in the Base case scenarios.

8. Conclusions

Carbon capture and storage is generally considered to be needed for achieving deep emission reductions already by 2050, in line with the stringent “below 2 °C” target of the Paris climate agreement. In particular, the IEA roadmap considers CCS deployment in industry basically necessary for achieving the 2°C target. In the electricity generation system CCS is foreseen to be a useful option not only for reducing emissions but also for maintaining a sufficient amount of dispatchable thermal power in the system and thereby contributing to the additional flexibility needed to support large amounts of variable renewable generation.
In general, CCS is not among the most economical emission reduction options, but becomes cost-effective when extremely deep emission cuts are needed: Having CCS in the technology portfolio reduces the unit costs for reaching over 50% cuts in emissions, such that the marginal cost of additional emission reduction is at the level of 50 €/tonne or above.

According to the TIMES-VTT model results, the deployment of CCS in Europe would amount to 600–900 Mt in 2050. The cumulative amount of CO_2 captured between 2030 and 2050 would be up to 10 Gt (in the Base-80% scenario), which is slightly less than the corresponding amount estimated by the IEA for OECD Europe (IEA 2013). Industrial deployment of CCS reaches over 200 Mt in 2050 in the VTT model results, which is in good agreement with the IEA estimates. However, the scale of applying BECCS in biofuel refineries is much more prominent in the TIMES-VTT results, where bio-refineries would account in 2050 for up to 300 Mt of the total CCS in Europe, if fossil fuel CCS is excluded.

Concerning the Finnish energy system, due to the higher CO_2 transportation costs, fuel taxes and negative impacts on CHP power-to-heat ratios, CCS based on fossil fuel does not have seem to have notable potential, unless bio-fuel based CCS (BECCS) would be left uncredited. On the other hand, if credited, BECCS does appear to have a considerable potential both in Finland and Sweden, where wood biomass resources are large and can be utilized in relatively large plants amenable for BECCS. It is also an opportunity for the Finnish technology providers having the know-how to develop the technology into a business.

The results indicate that for both Finland and Sweden, the prospects for applying BECCS appear far too important to overlook. With BECCS alone, Finland could by 2050 reach up to 15 Mt CO_2 emission reductions per year, enabling offsetting of emissions across sectors, e.g. in the carbon intensive industry. Reaching even negative overall GHG emissions would be possible, as well as a considerable surplus in the balance of emission allowances. Of this total amount, main activity producer power and heat generation accounted for 5–8 Mt in the scenarios, pulp and paper sector for 4–7 Mt, and biofuel refineries for about 3 Mt. Each of these sectors would thus have a significant level of deployment in BECCS.

In the Finnish power and heat system, large CHP plants with BECCS appear the most competitive technology option for applying CCS. This conclusion applies both to large community district heat systems, where both the oxy-fuel CFB technology and chemical looping can retain an excellent total energy efficiency even with CCS, and to large recovery boiler CHP plants in the pulp an paper industry. In the metropolitan region, the competitiveness of applying CCS in the 400 MW Vuosaari heat plant to be commissioned in 2030 appears controversial, as it was realized in only in one of the scenarios (Growth).

Even when assuming that with advanced energy storage systems solar and wind power will reach a very high share in the total electricity supply, BECCS enabled CHP plants still appear to be an attractive option in Finland and Sweden. These CCS plants help to maintain sufficient thermal generation in the system, thereby providing more flexibility in terms of dispatchable generation balancing the large amount of variable generation.

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