The effect of carbon caps and renewable share targets on the European energy system using capacity expansion modeling

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Abstract

The usefulness of renewable energy share targets in fighting climate change has been under debate. They are an indirect way of reducing carbon emissions, and can thus cause unwanted side-effects on the energy mix and price.

Energy system models are a wide range of tools that can be used to analyze and predict the behaviour of real-world energy systems under various conditions. In this thesis, we build a power system optimization model, which is a type of energy system model that optimizes the cost of operation of the electricity sector in chosen scenarios. We use it to study the effects of carbon caps and renewable share targets on the cost, energy mix, storage and transmission patterns of the European power system. We study nine scenarios with differing restrictions on carbon emissions and renewable shares, which mimic targets set by the European Commission for 2030 and 2050.

The results show that the strategies to achieve a low-carbon system and a highly renewable system differ. An economical low-carbon system relies on nuclear power, while an economical highly renewable system relies on biomass. Neither of these energy sources can be utilized in the opposite systems, making them competing objectives. The cost of combining a strict carbon cap with a high renewable share therefore turns out to be more than the combined cost of having both of them active independently. From a purely economic point of view, renewable share targets are therefore not beneficial for reducing carbon emissions. Additionally, renewable share targets tend to hurt the dirtiest technologies less than cleaner ones, so the energy mix should be regulated separately if benefiting dirty technologies, such as coal, want to be avoided.

The model used in the thesis does not take into account possible environmental and sustainability-related benefits of renewable energy. Their inherent value and indirect financial consequences should therefore be assessed and studied separately.

Keywords Energy systems, capacity expansion modeling, carbon cap, renewable energy

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Tiivistelmä

Uusiutuvan energian osuuden tavoitteiden hyödyllisyys ilmastonmuutoksen vastaisessa taistelussa on epäselvää. Epäsuorana päästöjenvähennyskeinona ne voivat aiheuttaa haitallisia sivuvaikutuksia energialähteiden yhdistelmään sekä energiajärjestelmän hintaan.

Energiajärjestelmämallit ovat laaja kirjo työkaluja, joiden avulla energiajärjestelmien käyttäytymistä eri olosuhteissa voidaan analysoida ja ennustaa. Tässä työssä laadimme sähköjärjestelmän optimointimallin, eli energiajärjestelmämallin tyypin, joka minimoi sähköjärjestelmän kustannukset erilaisissa skenaarioissa. Tutkimme sen avulla hiilidioksidipäästörajoitusten ja uusiutuvan energian osuuden tavoitteiden vaikutusta Euroopan sähköjärjestelmän hintaan, energialähteiden koostumukseen, sekä energian varastointiin ja siirtoon. Hyödynnämme yhdeksää skenaariota, joissa päästörajoitukset ja uusiutuvan energian osuuden tavoitteet mukailevat asteittain Euroopan komission asettamia ilmastotavoitteita vuosille 2030 ja 2050.

Tulokset osoittavat, että vähäpäästöisen sähköjärjestelmän ja suurimmaksi osaksi uusiutuvan sähköjärjestelmän saavuttamiseen vaaditut strategiat eroavat toisistaan. Kustannustehokas vähäpäästöinen järjestelmä perustuu ydinvoimaan, kun taas kustannustehokas uusiutuva järjestelmä ei pärjää ilman biomassaa. Kumpaakaan energiamuotoa ei kuitenkaan voi käyttää vastakkaisessa järjestelmässä, mikä tekee niistä kilpailevat päämäärät. Päästörajoituksen ja korkean uusiutuvan energian osuuden tavoitteen yhdistelmä on siksi kalliimpi kuin osiensa summa. Puhtaan ekonomisesti ajateltuna uusiutuvan energian osuuden tavoitteet eivät siis ole hyödyksi hiilidioksidipäästöjen vähentämisessä. Niillä on lisäksi taipumus haitata puhtaampia energiamuotoja enemmän kuin likaisia, joten eri energialähteiden määrään pitää kiinnittää huomiota erillisin rajoituksin, jos likaisten teknologioiden, kuten hiilivoiman, hyödyttämistä halutaan välttää.

Työssä käytetty malli ei huomioi uusiutuvan energian mahdollisia ympäristöön tai kestävyyteen liittyviä hyötyjä. Niiden arvoa ja epäsuoria rahallisia vaikutuksia tulee siis arvioida ja tutkia erikseen.

Avainsanat Energiajärjestelmät, kapasiteetinlaajennusmallinnus, päästörajoitteet, uusiutuva energia

Contents

1 Introduction

To fight climate change, the European Commission has set a climate target plan for 2030, and aims for the European Union to be climate neutral by 2050. The 2030 plan includes cutting greenhouse gases by at least 55% compared to 1990 levels and having at least a 32% share for renewable energy. Becoming climate neutral means achieving net-zero greenhouse gas emissions. (European Commission, 2020)

There has been debate over the usefulness of renewable share targets in addition to emission reduction goals, since the renewable share targets affect greenhouse gas emissions only indirectly, and might make cutting emissions more expensive by requiring the use of costly renewable technologies. (Abrell and Weigt, 2008; Frondel et al., 2010). It has also been argued that while the addition of a renewable share target might decrease total emissions, it also decreases the cost of CO2 for the remaining non-renewable energy sources. This benefits the "dirtiest" fossil fuel technologies the most and thus lessens the decrease of energy production from the most emission-intensive technologies, leading to negative impacts on the energy mix (Böhringer and Rosendahl, 2010). On the other hand, del Río (2017) argues that under more careful multidisciplinary economic analysis, the additional renewable targets are beneficial, and that with coordination the negative effect of renewable constraints on CO2 prices can be mitigated.

Energy system models are a tool that can be used to analyze and predict the development of real-world energy systems. Early energy system models were simple linear programming models that were largely focused on energy security and cost, but climate change has since shifted the focus of the models to finding best ways to reduce greenhouse gas emissions. Since the early models, the inclusion of varying energy demand, energy storage, energy trading and renewable energy technologies that, unlike traditional fossil fuel technologies, have highly varying availability in time and space, have lead to the need of more complex energy system models. (Pfenninger et al., 2014)

Pfenninger et al. (2014) divide modern energy system models into four different paradigms. Energy system optimization models cover the whole energy system and use optimization methods to create possible future scenarios. They include detailed technical bottom-up models, economic top-down models and their hybrids. Energy system simulation models also cover the whole energy system, but use simulation methods in predicting how the system is likely to evolve, instead of providing a snapshot into the future. Power systems and electricity market models concentrate on modeling only the electricity sector, and can thus model it in more detail. Power system models focus on balancing power supply and demand in high detail, while electricity market models focus on the design and operation of the electricity market. Qualitative and mixed-method scenarios provide a contrast to the previous quantitative methods in that, instead of detailed mathematical models, they use qualitative methods to produce possible narrative scenarios.

In this thesis, we model the effects of a CO2 constraint and a renewable share target, combined and separately, on the European energy system using a power system optimization model and 9 different scenarios ranging from the 2030 climate targets to a fully renewable climate neutral system. Notably, the constraints are expanded to apply to the whole European continent instead of only the European Union. We then study how the constraints affect the total system cost, energy mixtures and transmission patterns.

2 Methods

2.1 Optimization model

The optimization model used is a continuous linear capacity expansion model that is developed by the Gamma-Opt research group in the Department of Mathematics and Systems Analysis in Aalto University (Gamma-Opt, 2021), and is expanded based on the REX model by Kan et al. (2020) and the Supergrid model by Mattsson et al. (2020) for this thesis. It includes the three main sectors of a power system: electricity generation, transmission and storage. The indices and sets, parameters and decision variables used in the model are presented in tables 1, 2 and 3, respectively.

Table 1: Indices and sets

Indices and sets	Description
$g \in G$	Generation technologies (excluding hydro)
$G^r \subseteq G$	Renewable generation technologies (excluding hydro)
$n \in N$	Nodes
$l \in L$	Transmission lines, bidimensional vectors (i, j) where $i, j \in N$
$t \in T$	Time-steps
$s \in S$	Storage technologies

Table 2: Parameters

Parameters	Description
Cap	Baseline for carbon cap (amount of emissions in 1990)
$C_E \in [0,1]$	Minimum percentage of emission reduction
$\kappa \in [0,1]$	Minimum renewables share required
$\overline{C} \in [0,1]$	Shedding capacity, percentage of demand
C	Shedding cost [€/MWh]
r	Interest rate
$D_{n,t}$	Demand at node n in time step t
$Q_{g,n}$	Initial generation capacity of technology g in node n [MW]
$A_{g,n,t} \in [0,1]$	Availability of technology g in node n at time-step t
I_g^G	Annualized investment cost of generation for technology g [€/MW]
M_g^G	Annual maintenance cost of generation for technology g [€/MW]
C_g^G	Operational cost of technology g [€/ MW]
$e_g \in [0,1]$	Efficiency of technology g
E_g	Emissions of fuel used by technology g [ton CO2 /MWh]
$r_g^- \in [0,1]$	Relative ramp-down limit of technology g
$r_g^+ \in [0,1]$	Relative ramp-up limit of technology g
W_n^{max}	Reservoir water capacity in node n [MWh]
W_n^{min}	Minimum reservoir water level in node n [MWh]
$f_{n,t}^i$	Water inflow to reservoirs in node n at time-step t [MWh]
$f_{n,t}^{i'}$	Water inflow to run-of-river plants in node n at time-step t [MWh]
H_n	Reservoir generation capacity in node n [MW]
H_n'	Run-of-river generation capacity in node n [MW]
$f_n^{o,min}$	Minimum water flow to environment in node n [MWh]
I_l^F	Annualized investment cost of transmission for line l [€/MW]
M_l^F	Annual maintenance cost of transmission for line l [€/MW]
C_l^F	Transmission cost [€/MWh]
$e_l \in [0,1]$	Transmission efficiency
I_s^S	Annualized investment cost of storage for technology s [€/MW]
M_s^S	Annual maintenance cost of storage for technology s [€/MW]
C_s^S	Operational cost of storage technology s [€/MWh]
$\xi_s \in [0,1]$	Efficiency of storage technology s

Table 3: Variables

Variables	Description
$\overline{p}_{g,n} \geq 0$	Generation capacity invested in technology g in node n [MW]
$p_{g,n,t} \geq 0$	Dispatch from technology g in node n at time-step t [MWh]
$w_{n,t} \geq 0$	Water level in reservoirs in node n at time-step t [MWh]
$f^{o}_{n,t} \geq 0$	Outflow from reservoirs in node n at time-step t [MWh]
$f^{o'}_{n,t} \geq 0$	Outflow from reservoirs trough turbines in node n at time-step t [MWh]
$f^{o''}_{n,t} \geq 0$	Outflow from reservoirs bypassing turbines in node n at time-step t [MWh]
$h'_{n,t} \geq 0$	Run-of-river generation in node n at time-step t [MWh]
$h_{n,t} \geq 0$	Total hydro generation in node n at time-step t [MWh]
$\sigma_{n,t} \geq 0$	Loss of load at node n in time-step t [MWh]
$\overline{f}_{l} \geq 0$	Transmission capacity of line l [MW]
$f^{+}_{l,t} \geq 0$	Transmission along the line direction in line l at time-step t [MWh]
$f^{-}_{l,t} \geq 0$	Transmission against the line direction in line l at time-step t [MWh]
$\overline{b}_{s,n} \geq 0$	Capacity of storage s in node n [MWh]
$b_{s,n,t} \geq 0$	Storage level of storage s in node n [MWh]
$b^{+}_{s,n,t} \geq 0$	Charging of storage s in node n at time-step t [MWh]
$b^{-}_{s,n,t} \geq 0$	Discharging of storage s in node n at time-step t [MWh]

Generation, transmission and storage capacities start at zero, meaning that the model can invest in capacity without being constrained by existing real-world infrastructure. This is known as the "green field" assumption. The only exception is hydro power, for which the capacity is fixed at current real world capacity. Due to environmental regulations and already used up potential, we assume new major hydro power investments in Europe to be unlikely and concentrated on pumped hydro storage or refurbishing existing infrastructure, rather than new reservoir or run-of-river plants (Wagner et al., 2019).

Investments happen instantaneously, meaning that the model does not take into account the path to reach the optimal power system from the starting state. Because of this and the zero starting capacities, the optimal system produced by the model is to be considered as an ideal scenario to aim towards in the long run, rather than an actual immediately executable plan.

The model is optimized for a one year period with an hourly time resolution. We divide Europe into 11 aggregated regions or nodes, with a slight focus on the Nordic countries (i.e., the Nordics are not aggregated, but are their own nodes). The nodes are Finland (FIN), Norway (NOR), Sweden (SWE), Denmark (DEN), France (FRA), Germany (GER), United Kingdom (UK), Mediterranean (MED), Baltics (BAL), Spain (SPA) and Central Europe (CEN). Figure 1 shows the node definitions and the possible transmission lines between the nodes.

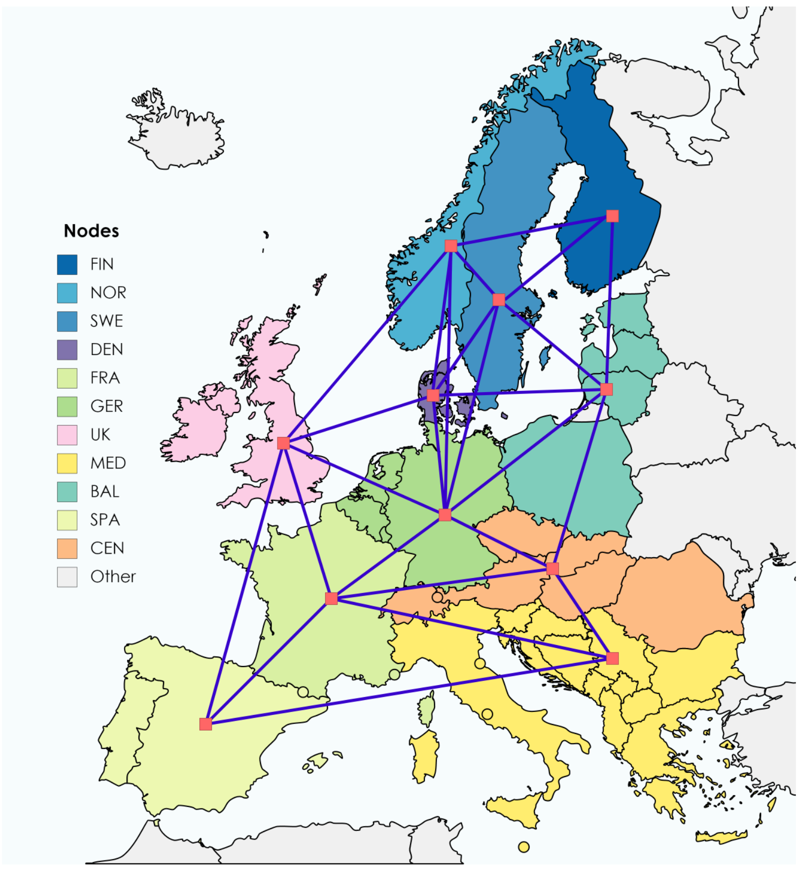

Figure 1: Nodes and possible transmission lines

2.1.1 Objective function

The goal is to find the least overall cost way to satisfy electricity demand while also satisfying emission and renewable share constraints. Therefore, the problem is a minimization problem, with the objective function being the total system cost (9). The cost consists of the investment and maintenance cost of generation capacity (2), the operational cost of generation dispatch (3), shedding (amount of demand unsatisfied) cost (4), the investment and maintenance cost of transmission capacity (5), the operational cost of transmission flow (6), the investment cost of storage capacity (7) and the operational cost of storage (8). Many emission reducing strategies include a cost for carbon emissions for example via a carbon tax, but the only means of emission reduction we consider is a carbon cap, so emissions do not have a direct monetary cost in this model.

Investment costs are annualized using the equivalent annual cost (EAC) formula:

$$EAC(c, n, r) = \frac{c}{a_{n,r}}, \; a_{n,r} = \frac{1-(1+r)^{-n}}{r}, \; a_{n,0} = n, \tag{1}$$

where c is the net present cost of the investment, n is the number of payments, or the lifetime of the technology invested in, and r is the interest rate. With this in mind, the individual cost functions are formulated as

$$f_1 = \sum_{g,n} (I_g^G + M_g^G)\overline{p}_{g,n}, \tag{2}$$

where I_g^G is the annualized investment cost per MW of generation technology g, calculated as $EAC(c_g, \tau_g, r)$, where c_g is the investment cost per MW of generation technology g, τ_g is the lifetime of generation technology g and r is the interest rate. M_g^G is the annual maintenance cost of generation for technology g and $\overline{p}_{g,n}$ is the generation capacity invested in technology g in node n. Since hydro capacity is predetermined, its costs are not included in the objective function.

$$f_2 = \sum_{g,n,t} C_g^G p_{g,n,t}, \tag{3}$$

where C_g^G is the total operational cost per MWh of technology g, calculated as $c_g^f/e_g + c_g^v$, where c_g^f is fuel cost, e_g is efficiency and c_g^v is the variable operational and maintenance cost of technology g, and $p_{g,n,t}$ is the generation dispatch from technology g at node n at time step t.

$$f_3 = \sum_{n,t} C\sigma_{n,t}, \tag{4}$$

where C is shedding cost and $\sigma_{n,t}$ is loss of load at node n in time step t.

$$f_4 = \sum_{l} (I_l^F + M_l^F)\overline{f}_l, \tag{5}$$

where I_l^F is the annualized investment cost for transmission for line l, calculated as $EAC(c^F d_l + c^c, \tau_l, r)$, where c^F is the investment cost per MW of transmission line capacity for one kilometer, d_l is the length of transmission line l, c^c is the investment cost of converters for both ends of the line per MW, τ_l is the lifetime of transmission investments and r is the interest rate. M_l^F is the annual maintenance cost for transmission per line l and $\overline{f}_l$ is the transmission capacity for line l.

$$f_5 = \sum_{l,t} C_l^F (f_{l,t}^+ + f_{l,t}^-), \tag{6}$$

where C_l^F is the transmission cost per MWh, and $f_{l,t}^+ + f_{l,t}^-$ is the total transmission flow for line l in time step t.

$$f_6 = \sum_{s,n} (I_s^S + M_s^S)\overline{b}_{s,n}, \tag{7}$$

where I_s^S is the annualized investment cost of storage technology s, calculated as $EAC(c_s^S, \tau_s, r)$, where c_s^S is the investment cost per MWh of storage technology s, τ_s is the lifetime of storage technology s, and r is the interest rate. M_s^S is the annual maintenance cost of storage for technology s, and $\overline{b}_{s,n}$ is the capacity of storage s at node n.

$$f_7 = \sum_{s,n,t} C_s^S (b_{s,n,t}^+ + b_{s,n,t}^-), \tag{8}$$

where C_s^S is the operational cost of storage technology s, and $b_{s,n,t}^+$ and $b_{s,n,t}^-$ are the charging and discharging of storage s at node n in time step t.

The objective function is thus

$$\underset{\overline{p}_{g,n}, p_{g,n,t}, \sigma_{n,t}, \overline{f}_l, f_{l,t}^+, f_{l,t}^-, \overline{b}_{s,n}, b_{s,n,t}, b_{s,n,t}^+, b_{s,n,t}^-}{\text{minimize}} (f_1 + f_2 + f_3 + f_4 + f_5 + f_6 + f_7). \tag{9}$$

2.1.2 Power generation

The possible energy production technologies chosen for this model are onshore wind, offshore wind, solar, biomass, nuclear, coal, closed-cycle gas, open-cycle gas and hydro power, which includes reservoir and run of river generation, but not pumped hydro storage. Hydro power is modeled separately from the other technologies, because we need to take into account extra factors, such as reservoir levels and water outflow to the environment.

For the other technologies, generation dispatch $p_{g,n,t}$ is constrained by the availability of technology $A_{g,n,t} \in [0, 1]$, starting capacity $Q_{g,n}$ and invested capacity $\overline{p}_{g,n}$:

$$p_{g,n,t} \leq A_{g,n,t}(Q_{g,n} + \overline{p}_{g,n}), \ \forall g, n, t. \tag{10}$$

We do not take into account fuel availability or transportation, so availability for the non-renewable technologies and biomass is always 100%. Availability for wind and solar is determined by wind speeds and sunlight, and we describe how we obtain this data, as well as all the other availability and capacity data, in section 2.2.

Total generation capacity for each technology is constrained by the maximum capacity $\overline{Q}_{g,n}$:

$$Q_{g,n} + \overline{p}_{g,n} \leq \overline{Q}_{g,n}, \ \forall g, n. \tag{11}$$

For most technologies the maximum capacity is unlimited, but for wind and solar it is determined by available suitable land and sea area. This prevents area-wise small nodes with high wind or solar availability, such as Denmark, from investing in more capacity than could actually fit inside the respective countries territories. In addition, we allow nuclear energy only in nodes that have existing nuclear power plants, so we limit nuclear capacity to zero in Denmark and the Baltics (World Nuclear Association, 2020).

Ramping rates limit the speed at which generation dispatch from each technology can be increased or decreased:

$$p_{g,n,t} - p_{g,n,t-1} \leq r_g^+(Q_{g,n} + \overline{p}_{g,n}), \ \forall g, n, t > 1 \tag{12}$$

$$p_{g,n,t} - p_{g,n,t-1} \geq -r_g^-(Q_{g,n} + \overline{p}_{g,n}), \ \forall g, n, t > 1, \tag{13}$$

where r_g^+ and r_g^- are the ramp-up and ramp-down limits, respectively.

Hydro reservoir and run of river power are modeled as follows. Reservoirs store water, and the water level $w_{n,t}$ must always be between the reservoir capacity W_n^{max} and minimum water level W_n^{min}:

$$W_n^{min} \leq w_{n,t} \leq W_n^{max}, \ \forall n, t. \tag{14}$$

The water level is determined by the water level in the previous time step, inflow to the reservoir $f_{n,t}^i$ and outflow from the reservoir $f_{n,t}^o$. To prevent the model from benefiting from starting the modeling period with full reservoirs and ending with empty ones, we also require that the water level in the first time-step is equal to the level in the last time-step.

$$w_{n,t} = w_{n,t-1} + f_{n,t-1}^i - f_{n,t-1}^o, \ \forall n, t > 1 \tag{15}$$

$$w_{n,1} = w_{n,end}, \ \forall n. \tag{16}$$

The outflow can either be directed through turbines to generate power, or bypass the turbines. Total outflow from a reservoir is set to be equal to the sum of outflow through turbines $f_{n,t}^{o'}$ and outflow bypassing the turbines $f_{n,t}^{o''}$ in equation (17). Equation (18) constrains outflow through the turbines, i.e., reservoir generation, by reservoir generation capacity H_n. The amount of total outflow can be adjusted to fill or empty the reservoir, but it must always satisfy a minimum environmental flow requirement $f_n^{o,min}$, as stated in equation (19).

$$f_{n,t}^o = f_{n,t}^{o'} + f_{n,t}^{o''}, \ \forall n, t \tag{17}$$

$$f_{n,t}^{o'} \leq H_n \ \forall n, t \tag{18}$$

$$f_{n,t}^o \geq f_n^{o,min} \ \forall n, t. \tag{19}$$

Run of river generation $h'_{n,t}$ is constrained by the available inflow to run of river plants $f^{i'}_{n,t}$ and run of river generation capacity H'_n:

$$h'_{n,t} \leq f^{i'}_{n,t} \ \forall n, t \tag{20}$$

$$h'_{n,t} \leq H'_n \ \forall n, t. \tag{21}$$

Finally, total hydro generation $h_{n,t}$ is the sum of reservoir generation and run of river generation:

$$h_{n,t} = f^{o'}_{n,t} + h'_{n,t} \ \forall n, t \tag{22}$$

$$\tag{23}$$

2.1.3 Demand response

Real world energy systems utilize different demand response methods, such as time dependent energy pricing and incentive-based load reducing contracts, in order to lower peak energy demand and during emergencies (Palensky and Dietrich, 2011). We include a simple load shedding mechanism, where some demand can be left unsatisfied for a cost. Loss of load $\sigma_{n,t}$ must however not exceed a limit percentage $\overline{C}$ of demand $D_{n,t}$:

$$\sigma_{n,t} \leq \overline{C} D_{n,t}, \ \forall n, t. \tag{24}$$

2.1.4 Transmission

The nodes can transmit electricity between each other through predetermined lines that are illustrated in figure 1. The transmission lines are links between two nodes, and each line is represented by one node-node pair, e.g., $l = (\text{FIN}, \text{SWE})$. The same node-node pair represents a transmission line going both ways, so there is no separate (SWE, FIN) line, for example. To make it possible to always assign transmission losses to the receiving end of transmission in equation (34), transmission through a line is divided into transmission along the line direction, $f^+_{l,t}$, and transmission against the line direction, $f^-_{l,t}$, which are both non-negative, instead of representing the transmission direction with the sign of a common transmission variable. Transmission capacity $\overline{f}_l$ must be invested in for each line, and the total transmission through a line must not exceed its capacity:

$$f^+_{l,t} + f^-_{l,t} \leq \overline{f}_l, \ \forall l, t. \tag{25}$$

Modeling the different transmission directions separately without additional disjunctive constraints (i.e., ones that allow only one of them to be greater than zero at a time) does not disallow transmission from happening to both directions through the same line during the same time-step. However, this kind of circular transmission is always sub-optimal due to transmission losses and costs, so it should never happen. We do not consider transmission from outside Europe or inside the nodes.

2.1.5 Storage

Energy can be stored for later use. We consider only one storage technology, battery storage, but again the model formulation allows multiple technologies s with different efficiencies ξ_s. The amount of energy stored, or storage level, $b_{s,n,t}$ cannot exceed storage capacity $\bar{b}_{s,n,t}$:

$$b_{s,n,t} \leq \bar{b}_{s,n,t}, \ \forall s, n, t. \tag{26}$$

We do not consider charging or discharging speeds, so charge $b^+_{s,n,t}$ and discharge $b^-_{s,n,t}$ are only constrained by energy left in storage and remaining capacity:

$$b^-_{s,n,t} \leq b_{s,n,t}, \ \forall s, n, t \tag{27}$$

$$\xi_s b^+_{s,n,t} \leq \bar{b}_{s,n,t} - b_{s,n,t}, \ \forall s, n, t. \tag{28}$$

Storage level is determined by the level, charging and discharging in the previous time-step. For continuity, the level in the first time-step must be equal to the level in the last time-step.

$$b_{s,n,t} = b_{s,n,t-1} + \xi_s b^+_{s,n,t-1} - b^-_{s,n,t-1}, \ \forall s, n, t > 1 \tag{29}$$

$$b_{s,n,1} = b_{s,n,end}, \ \forall s, n. \tag{30}$$

2.1.6 Carbon cap and renewable share target

The emissions from a generation technology are determined by the amount of electricity generated p_g, its efficiency e_g, and the emissions per MWh of fuel, E_g. Total emissions from the system are constrained by the amount of emissions in 1990 in tonnes, Cap, and an emission reduction percentage C_E:

$$\sum_{g,n,t} \frac{E_g p_{g,n,t}}{e_g} \leq (1 - C_E)Cap \tag{31}$$

The amount of electricity generated with renewable technologies must exceed the target percentage κ of total generation:

$$\sum_{g \in G^r, n, t} p_{g,n,t} + \sum_{n,t} h_{n,t} \geq \kappa \Big(\sum_{g \in G, n, t} p_{g,n,t} + \sum_{n,t} h_{n,t} \Big), \tag{32}$$

where G is the set of all generation technologies excluding hydro, and

$$G^r = \{ g \in G \mid g \text{ is a renewable technology} \} \tag{33}$$

2.1.7 Satisfying demand

Finally, electricity demand $D_{n,t}$ must always be satisfied by generation dispatch $p_{g,n,t}$ ($h_{n,t}$ for hydro), shedding $\sigma_{n,t}$, transmission $f^+_{l,t}$ and $f^-_{l,t}$, and storage charging $b^+_{s,n,t}$ and discharging $b^-_{s,n,t}$:

$$\sum_g p_{g,n,t} + h_{n,t} + \sigma_{n,t} + \sum_{l \in L^-_n} (e_l f^+_{l,t} - f^-_{l,t}) - \sum_{l \in L^+_n} (f^+_{l,t} - e_l f^-_{l,t}) + \sum_s (\xi_s b^-_{s,n,t} - b^+_{s,n,t}) = D_{n,t}, \ \forall n, t, \tag{34}$$

where ξ_s is the efficiency of storage technology s, e_l is transmission efficiency, and the transmission lines to and from node n are formulated as

$$L_n^- = \{l \in L \mid i \in N, (i,n) = l\} \tag{35}$$
$$L_n^+ = \{l \in L \mid j \in N, (n,j) = l\}, \tag{36}$$

respectively, where L is the set of all transmission lines.

2.2 Data

Hourly wind and solar availability data, water inflow data, and demand data for each node is generated using the GlobalEnergyGIS Julia package by Mattsson et al. (2020). It also provides the maximum possible capacities for wind and solar based on suitable land and sea area, and the possible transmission lines and their lengths. Hydro power capacities are from the ENTSO-E Transparency Platform (ENTSO-E, 2021).

Technology parameters are presented in table 4. The generation technology parameters include predictions for year 2040 by Schröder et al. (2013), values used by Mattsson et al. (2020) in their Supergrid model, and emission values by Van Harmelen and Koch (2002). Additionally, a high cost of 1000 €/MWh is used for load shedding to discourage it. Transmission parameters are by Schlachtberger et al. (2017) and IEA ETSAP (2014). Storage parameters are by Cole et al. (2021). All investment costs are annualized using a 5% interest rate.

Table 4: Technology parameters

Technology	Investment cost [€/kW]	Fixed O&M cost [€/kW/year]	Variable O&M cost [€/MWh]	Fuel cost [€/MWh]	Efficiency	Emissions [tonCO2 /MWh]	Lifetime [years]	Ramp-up limit	Ramp-down limit
Onshore wind	1127	35	0	0	1	0	25	1	1
Offshore wind	2290	80	0	0	1	0	25	1	1
Solar	480	26	0	0	1	0	25	1	1
Biomass	2076	100	0	7	0.478	0.39	30	1	1
Nuclear	5000	150	3	3	0.34	0	60	0.05	0.05
Coal	1300	25	6	8	0.466	0.34	40	0.15	0.15
Gas CC	800	20	4	22	0.615	0.2	30	0.3	0.3
Gas OC	400	15	3	22	0.395	0.2	30	1	1
Transmission	400 €/MWkm	2%	0	-	0.95	-	40	1	1
Converter pair	150000 €/MW	-	-	-	-	-	-	-	-
Storage	150 €/kWh	15	0.1	-	0.85	-	15	-	-

2.3 Implementing and solving the model

The model is implemented in Julia version 1.4.2 (Bezanson et al., 2017) using JuMP (Dunning et al., 2017). The model has 38800594 rows and 2750764 columns. It is solved using the Gurobi Optimizer version 9.0.2 (Gurobi Optimization, 2021) on a Windows 10 desktop computer with a i7-6700k processor running at 4.3 GHz, and 32 Gigabytes of 4100 Mhz DDR4 RAM, resulting in a solving time of approximately 22 hours for a single scenario using the default parameters for the solver (other than for the time limit).

3 Results

3.1 System cost

The system costs in each scenario are presented in figure 2. Increasing the renewable share requirement and the CO2 reduction both increase the costs. Considering the EU-2030 scenario (55% carbon reduction, 32% renewables) as the base scenario, the 80%-80% scenario is 11% more expensive, and the 95%-100% scenario is 50% more expensive. The 95%-32% scenario and the 55%-100% scenario have nearly the same costs, so with the cost of a fully renewable system with low carbon reduction, the system could be made carbon neutral. This suggests that focusing on increasing the renewable share might indeed make it more expensive to lower emissions.

The cost of generation capacity investments rise with the constraints, while the cost of generation dispatch goes down. This is due to the switch away form coal and gas, which have low investment costs to renewable technologies and nuclear, which have higher investment costs but lower operating costs, and also due to increased overall generation capacity that is needed when the system is highly renewable. The amount of transmission capacity and storage capacity and operation also increase, leading to them accounting for a higher share of the total cost. However, storage accounts for a significant share only in the 100% renewable scenarios, and in the 95% carbon reduction, 80% renewable scenario.

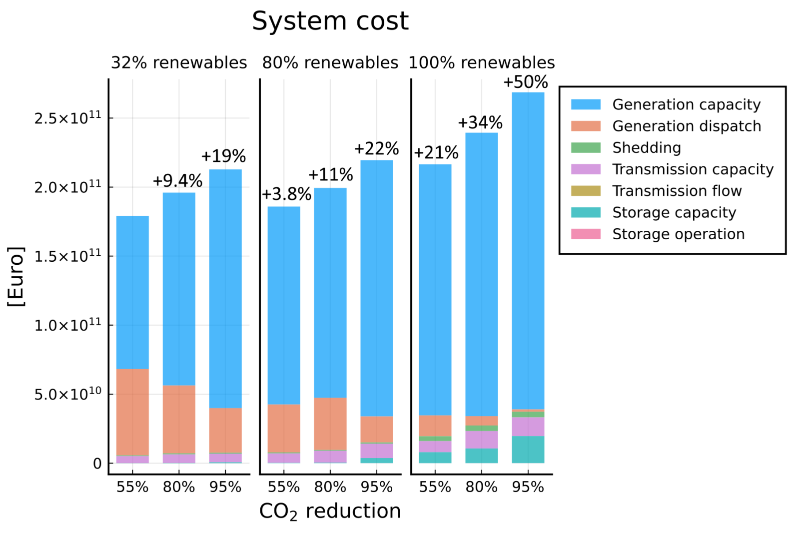

Figure 2: System cost and its composition in the different scenarios

The system costs correspond to average energy generation prices that are presented in figure 3. The slight discrepancy between the percentual increases in the system cost and energy prices are due to the fact that with stricter CO2 and renewable share constraints, a larger share of energy is lost to transmission and storage losses, and thus the total generated amount is also larger. The costs are similar to the ones obtained by Kan et al. (2020) and Mattsson et al. (2020). With 95% CO2 reduction, which corresponds to an emission constraint of 25g/kWh, we obtain energy prices that range from 40€/MWh to 59€/MWh depending on the required renewable share, while Mattsson et al. (2020) obtain an average price of 56€/MWh using a similar 25g/kWh emission constraint, and Kan et al. (2020) obtain a price of 48€/MWh using a stricter 10g/kWh emission constraint.

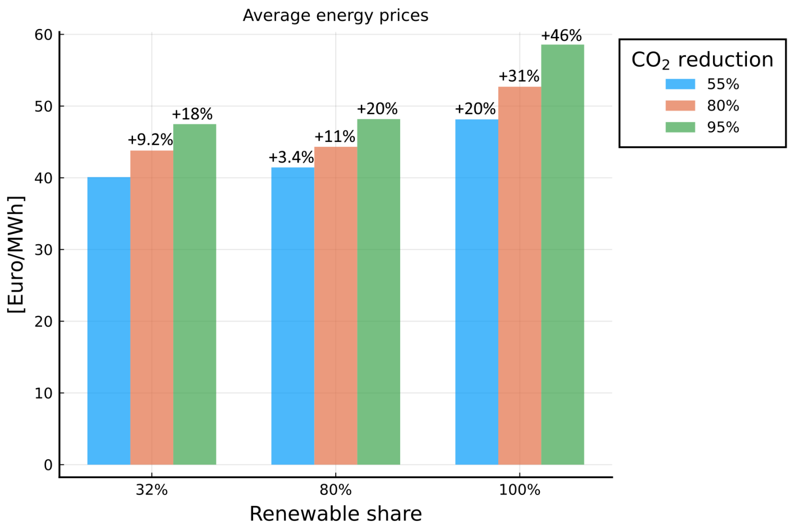

Figure 3: Average energy prices in the different scenarios

3.2 Energy mix

Generation capacities for each technology and node in each scenario are presented in figure 4. Wind capacity is highest in Norway, France, UK, and the Baltics, while solar is mostly concentrated in France, Germany, the Mediterranean, Spain and Central Europe. Coal, gas, nuclear and biomass is mostly used in the nodes that also use solar. Norway and Sweden rely only on wind and hydro power in all scenarios. Denmark also relies mostly on wind, but Finland on the other hand has a significant amount of solar, coal, gas, nuclear or biomass capacity, depending on the scenario.

Wind and solar have the most overall capacity in every scenario, and their capacities increase as the required renewable share gets higher. They also increase when the CO2-reduction grows from 55% to 80% with all renewable shares, and from 80% to 100% with a 100% renewable share. However, when CO2 emissions are cut by 95% but only a 32% or 80% renewable share is required, the amount of solar capacity decreases. This is because the strict carbon cap cuts out most of the coal and gas capacity, leaving more room for nuclear power. Compared to coal, and especially gas, nuclear power is expensive to invest in but cheaper to run, so it is utilized at nearly full capacity at all times, as opposed to being dispatched only during low solar availability hours. This leaves less need for solar capacity also during the day.

The amount of energy produced with each technology in each node, and the yearly demands, are presented in figure 5, and the hourly generation amounts are presented in figure 6. The difference between demand and total generation is balanced with transmission, which is analysed in section 3.4. Due to night time, the share of solar

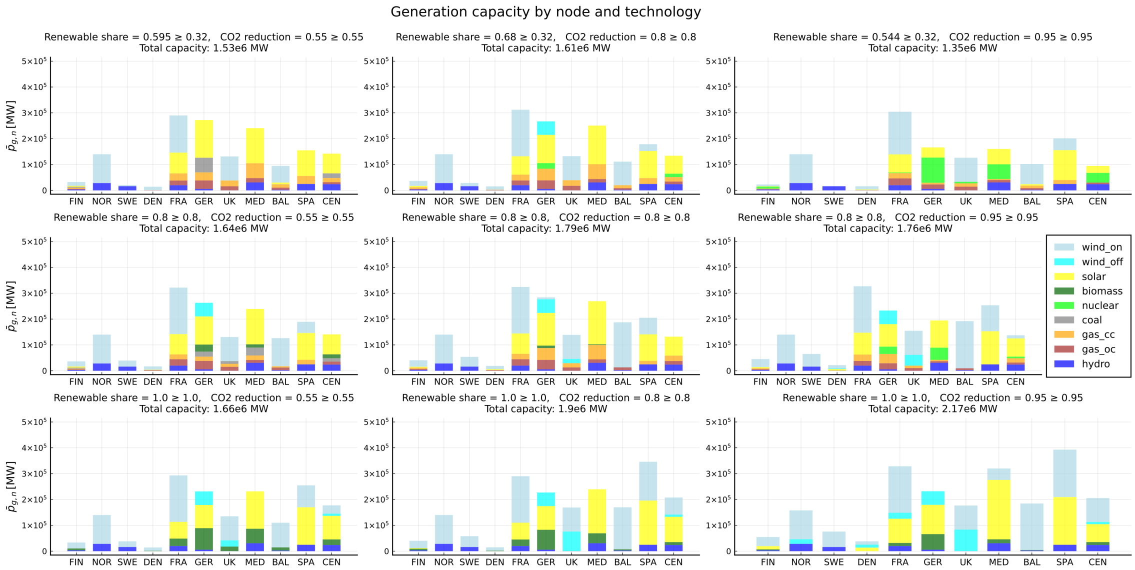

Figure 4: Generation capacities by node and technology in each scenario. CO2-reduction increases from left to right, and the renewable share increases from top to bottom.

power produced is much smaller than the share of solar capacity. On the other hand, coal, gas, biomass, and especially nuclear, have higher shares for production than for their respective capacities, because most of the capacity can be - and for coal and nuclear, is - utilized most of the time.

Biomass and gas have a bit more variation in capacity utilization, but for different reasons - gas is relatively cheap to invest in and more expensive to run than the other fuel-using technologies, so it can be used to fill what demand is left after other technologies. Biomass, on the other hand, is expensive to invest in but cheap to run, so the system is inclined to run it at full capacity. However, in the 100% renewable scenarios, biomass is the only technology that can be dispatched at full capacity at any time, and a lot of capacity is needed for it in order to satisfy demand during low availability hours for the other renewables. Most of this capacity then can not be utilized most of the time due to the carbon cap.

In the 32% renewable scenarios the actual renewable share is higher than 32%, indicating that a low carbon system will naturally use lots of renewable energy, even without explicit constraints. Lowering the carbon cap does not guarantee a higher renewable share, however. The renewable share grows from 59.5% to 68.0% when CO2 reduction grows from 55% to 80%, but in the 95% CO2 reduction scenario nuclear takes over some dispatch from solar, lowering the renewable share again. Without a renewable share constraint, the energy mix of a low carbon system in composed of mainly nuclear and wind, some hydro and solar, and gas to balance the system.

When the renewable share required is increased, CO2 reduction remains at the minimum level, even in the 100% renewable, 55% carbon reduction scenario. By itself, increasing the renewable share is therefore not a sufficient means of achieving a low-emission system if emissive renewable technologies, such as biomass, are allowed. In accordance with the findings of Böhringer and Rosendahl (2010), when a stricter renewable share is enforced, the dispatch from technologies that have the smallest emissions decrease the fastest, while the dispatch from dirtier technologies decreases slower. For example, the share of combined cycle gas decreases from 26% in the 32% renewable 55% carbon reduction scenario to 8.5% in the 80% renewable 55% carbon reduction scenario, while the share of coal decreases only from 14% to 11%, and the share of biomass actually increases. Similarly, in the 80% and 95% carbon reduction scenarios, nuclear dispatch decreases faster than open cycle gas dispatch. This happens, because the same amount of CO2 can be emitted by a smaller share of total dispatch, meaning that, on average, each unit of emissive dispatch can be more emissive than before.

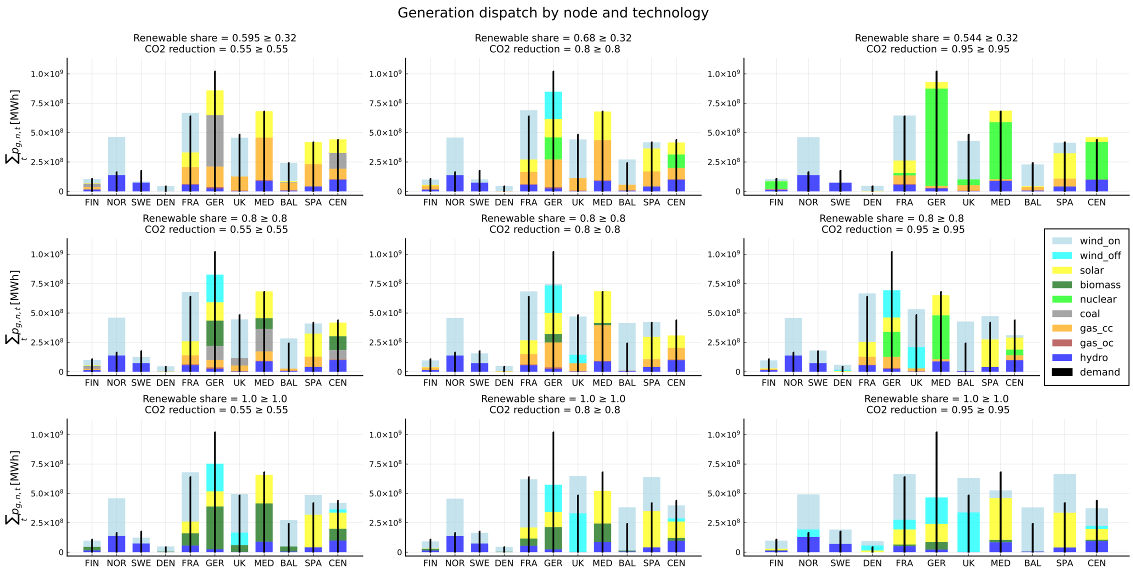

Figure 5: Generation dispatch and yearly demand

3.3 Storage

Storage capacities are presented in figure 7. In the 32% renewable share scenarios only the Mediterranean and Spain have some storage. Decreasing CO2 emissions increases the amount of storage needed, but overall not much storage is needed when the required renewable share is low, because night time generation can be handled by coal, gas and nuclear.

The same is true for the 80% renewable scenarios, except for the 95% CO2 reduction scenario, where also France, Germany and Central Europe have some storage, and the total amount needed is almost six times as large as in the 32% renewable counterpart. The nodes that use solar power all have storage.

In the fully renewable scenarios even more storage is needed, especially when CO2 emissions are also reduced by 95%, because biomass dispatch is more limited by the carbon cap than gas or nuclear. The other nodes, that use mainly wind, have some

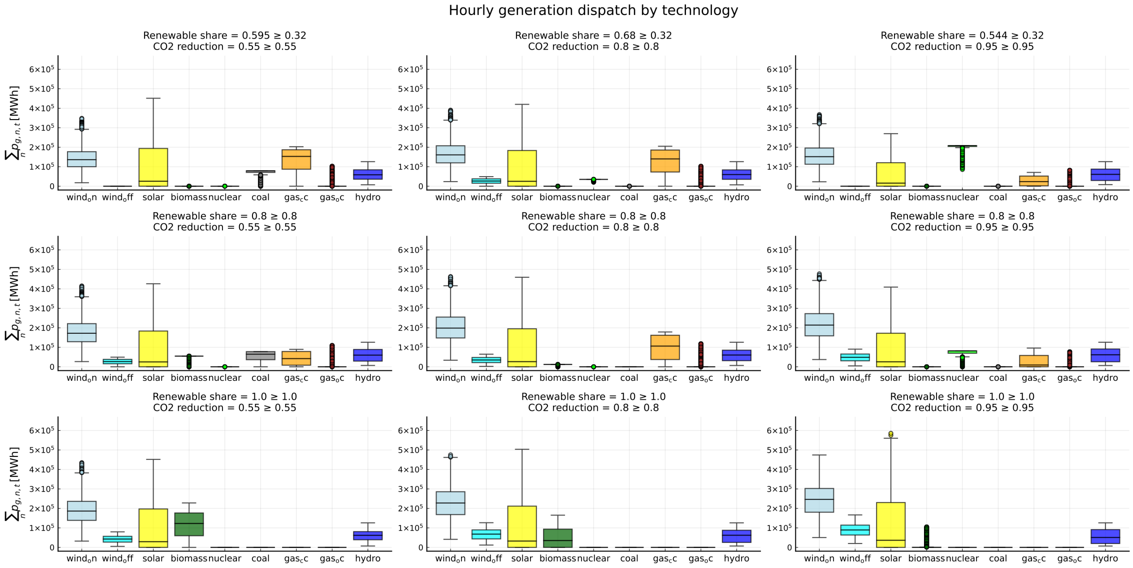

Figure 6: Hourly generation dispatch

storage too, but it is still mainly concentrated in the nodes that use solar. Combined with 95% carbon reduction, a fully renewable system requires a massive 665GWh of storage, compared to only 21.6GWh for the non-renewable low carbon system.

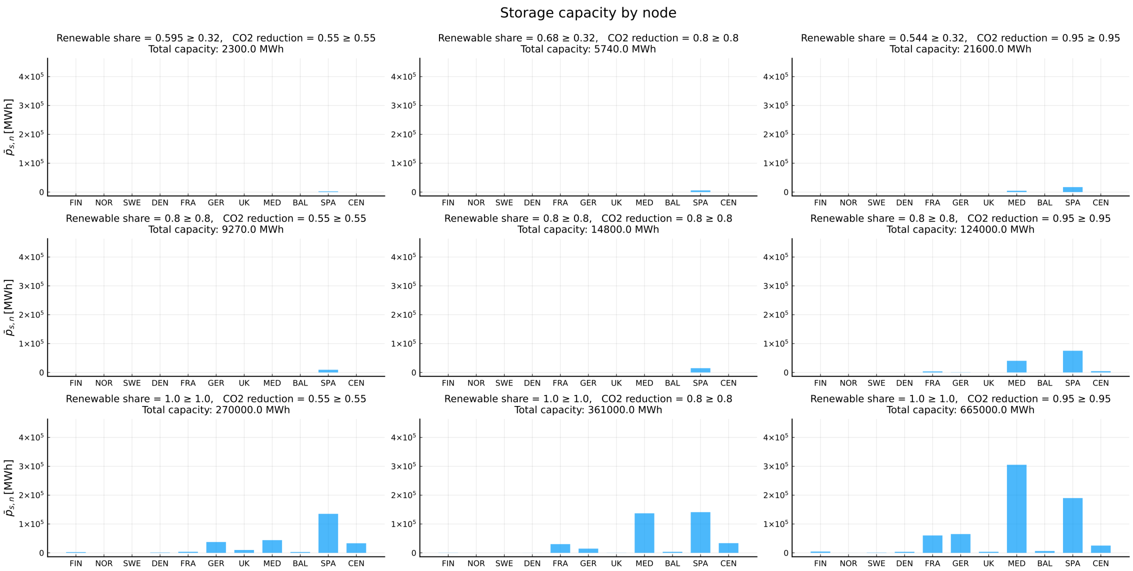

Figure 7: Storage capacities

3.4 Transmission

Transmission line capacities and yearly transmission through them are presented in figures 8 and 9, respectively. As can be seen from figure 5, in the 32% renewable scenarios the difference between demand and energy produced is small in most nodes.

Between these nodes, transmission is done back and forth only to balance the system due to the differences in hourly wind, solar and hydro availability. However, Norway produces more than twice the amount of energy it needs, while Sweden, Germany and UK do not produce enough for themselves. This leads to the largest transmission happening from Norway to Sweden, Germany and UK, and consequently the most capacity being needed for these lines. Generally, as the carbon cap is decreased, total transmission increases slightly. However, a little less capacity is needed in the 95% carbon reduction scenario than in the 80% carbon reduction scenario, because the 95% scenario includes less renewables and more nuclear, which reduces the variation in transmission needs.

Raising the renewable share to 80% causes the total transmission capacity to increase by 33%, 42% and 67% for the 55%, 80% and 95% carbon reduction scenarios respectively, and the total transmission amount to increase by 48%, 53% and 76%. Additional wind capacity deployments in Sweden and the Baltics cause Sweden to cut most of its imports from Norway, and the Baltics to become a major exporter to Central Europe.

The fully renewable systems rely more on transmission, as generation capacity is concentrated in the nodes that have more availability for the renewable technologies. Compared to the 80% renewable systems, the total transmission capacity is increased by 12%, 30% and 21% for the 55%, 80% and 95% carbon reduction scenarios respectively. In the 55% carbon reduction scenario the total transmission amount actually decreases by 5.1% despite the higher capacity, indicating less average transmission but larger peaks during low renewable availability hours. In the 80% and 95% carbon reduction scenarios, however, the total transmission increases by 35% and 34%, respectively. Norway maintains its position as a major exporter to Germany, but as more wind capacity is installed in the UK, the trade between Norway and UK becomes more even, and UK starts exporting to Germany and France. Spain also starts exporting to France and the Mediterranean due to having installed extra wind capacity.

In all of the 80% and 100% renewable scenarios, Germany imports the most electricity. In the fully renewable, 95% carbon reduction scenario Germany produces only 46% of its electricity itself compared to 91% in the 32% renewable scenario, where most of Germany's electricity is produced with nuclear power. This is notable, because while Germany seems to struggle the most without nuclear power in the low carbon scenarios, it plans to completely phase out its real-world nuclear capacity (World Nuclear Association, 2020).

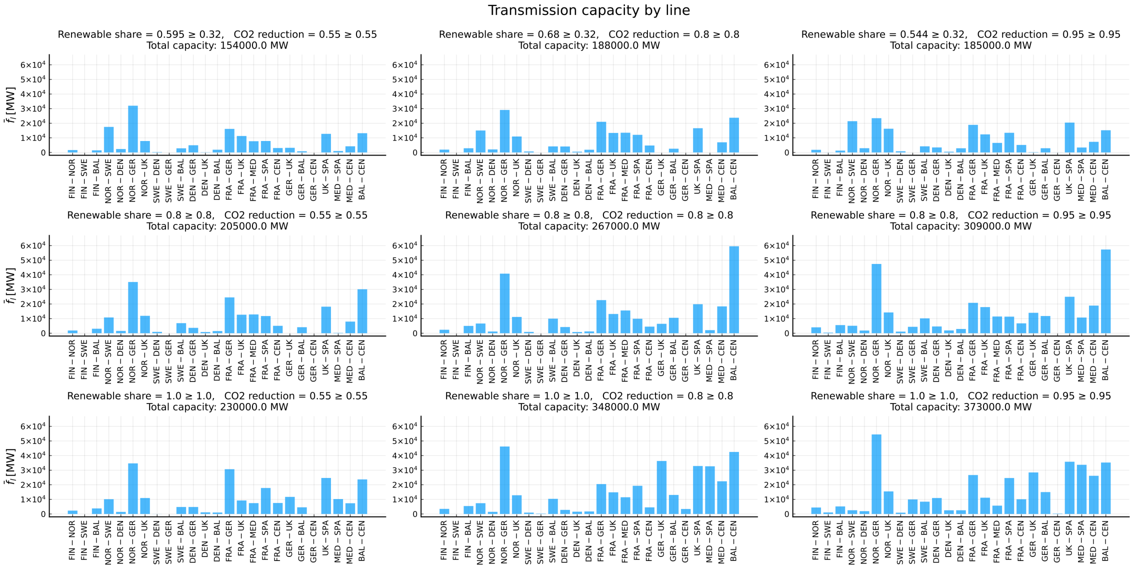

Figure 8: Transmission line capacities

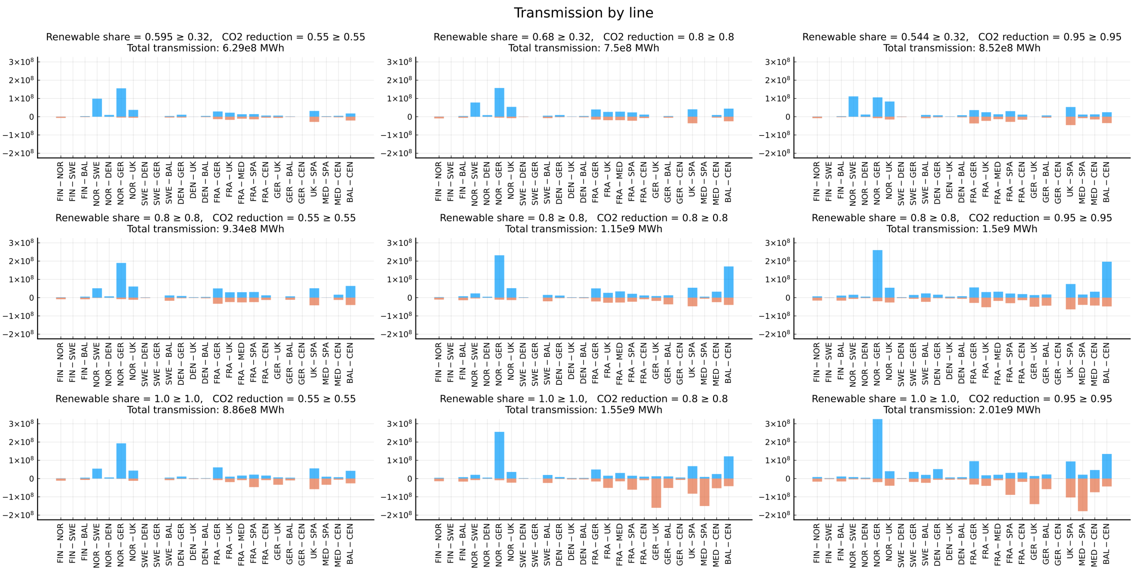

Figure 9: Transmission trough the lines. Positive values indicate transmission from node 1 to node 2 in the pair forming the line, and negative values indicate transmission in the opposite direction.

4 Conclusions

We implemented a power system capacity expansion optimization model and solved it for the European energy system using 11 aggregated nodes, using 9 scenarios involving a carbon cap ranging from 55% to 80% and 95% carbon reduction and a renewable share requirement ranging from 32% to 90% and 100%.

Compared to a scenario depicting the 2030 climate target of the European Union involving a cut in CO2 emissions by at least 55% and a renewable share of at least

32%, a carbon neutral system with a 32% renewable share was 19% more expensive, and a fully renewable system with a 55% cut in carbon emissions was 21% more expensive, while a fully renewable carbon neutral system was 50% more expensive. Somewhat surprisingly, the cost of combining both of the restrictions is therefore more than the combined cost of having both of them active on their own. This indicates that an economical low carbon system is not just a small step away from an economical fully renewable system or vice versa, but that they are at least partly competing objectives.

A low carbon system is composed of mainly nuclear, wind and hydro, with some solar and combined cycle gas, while a fully renewable system is composed of mainly biomass, wind, hydro and solar. Combining a low carbon cap and a high renewable share prevents the large-scale usage of nuclear and biomass. The system is therefore forced to build considerable amounts of additional wind and solar capacity, storage for the nodes that use solar, as well as transmission capacity, to handle low availability periods. This causes the high cost of the system.

Lowering the carbon cap does not guarantee a higher renewable share, nor does raising the renewable share guarantee lower carbon emissions if emissive renewable technologies, such as biomass, are not constrained separately. Raising the renewable share can actually have negative effects on the energy mix, as the capacity and dispatch of cheaper, more emissive technologies, such as coal, get reduced less than those of cleaner technologies. Separate policies, such as ones penalizing emission-intensive technologies, are needed in order to avoid this.

A limitation of the model used is that it does not consider possible indirect or non-monetary benefits that a highly renewable system can have, such as making the system less reliant on imported fuel and nuclear material. The value of indirect benefits should be studied and assessed in any future analysis alongside the direct monetary cost of the system.

Typical to energy system models, the model contains many simplifications in order to maintain the solving time reasonable. The generation technologies chosen are general representations of multiple technologies, that each have slightly different properties and could therefore be better solutions in specific situations and locations. The representation of thermal technologies is unrealistic in that their efficient load ranges and minimum up- and downtimes are completely discarded. This makes the technologies more adaptable than they are in reality.

The model is likely to to underestimate the cost of transmission, since Europe is divided into relatively few large nodes, and intra-node transmission is excluded. On the other hand, the inclusion of transmission from outside Europe could lower the system cost slightly by making it possible to import and export energy out of the system when needed.

One of EU's key strategies in achieving carbon neutrality is its "cap-and-trade" emissions trading scheme. While our model includes a carbon cap, in terms of emissions it considers the whole Europe as a single region, so emissions trading is not explicitly modeled. Assuming good will and mutual goals on behalf of all of the European countries, this is sufficient for providing an optimal emission division for the continent. In reality, however, countries are likely to act also on their own interests.

Therefore, explicitly modeling emissions trading would be a next logical step in expanding the model to give a more realistic picture of the future European energy system, and to make the model more suitable for more specialized and localized studies.

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