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\title{How much flexibility is available for a just energy transition?

- A global sensitivity analysis of European countries CO$\_2$ targets}

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\maketitle

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\subsection\*{Abstract}

The transition of the European energy supply towards a zero-emission future should be efficient, fair, and fast. The efficiency of the transition is ensured by the European Emissions Trading System, where emission allowances are traded, allowing market forces to operate. The free market forces are moderated to account for fairness by national targets on emission reductions determined by the Effort Sharing legislation. These two pieces of legislation are the backbone of the transition of the European energy supply, attempting to balance the trade-off between efficiency and fairness. In this work, 30.000 Monte Carlo simulations of national emission targets dispositions have been performed and evaluated using an advanced energy system optimization model of the European electricity supply in 2030. Results reveal a group of countries where emission reductions beyond the national targets are economically favorable in most scenarios. On the other side, there are countries where large abatement costs are unavoidable. An efficient transition may be achieved by allowing large emissions where abatement costs are high and reducing emissions to almost zero in countries with good renewable resources.

\section\*{Main text}

\subsection\*{Introduction}

The European Green Deal raises the ambition level for decarbonization of the European energy sector, in combination with goals of ensuring a just transition \cite{green\_deal}. The quality of a just transition is, however, not easily measured and has in recent years become a topic of much debate \cite{jenkins\_2016,maguire\_2021}.

Emissions from the energy sector are currently governed by the EU Emission Trading System (EU ETS) \cite{eu\_ets}, operating on the cap-and-trade principle, requiring that all power generators in Europe buy emission allowances. The Just Transition Mechanism combined with the Just Transition Fund is introduced to ensure equity in the transition \cite{just\_transition\_mechanism}. Since 2013, a fixed amount of emission allowances has been auctioned off to power plants each year, thereby putting a price on CO$\_2$ emission encouraging a reduction of emissions \cite{eu\_2030\_framework}. By controlling the number of quotas on auction every year, the EU ETS is capable of controlling the overall rate of emission reductions of the EU member states. The rate of emission reductions is governed by the recently accepted 2030 Climate Target plan, where the European Union commits to reducing emission by 55\% by 2030 \cite{EU\_2030\_Climate\_target\_plan}. The burden of reducing emissions is shared among EU member states by setting national reduction targets. Emissions from the sectors not covered by the EU ETS is controlled through the Effort Sharing Legislation \cite{EU\_effort\_sharing}, translating the combined 55\% reduction target into national targets for the member states. The national targets are based on Member States’ relative wealth, measured by gross domestic product (GDP) per capita, and are put in place to ensure a just transition \cite{EU\_effort\_sharing}. Several European nations have chosen to implement additional national targets for emissions already governed by the EU ETS. Implementing national CO$\_2$ targets entails national CO$\_2$ prices, undermining the global CO$\_2$ price given by the EU ETS. Distributed CO$\_2$ prices can lead to carbon leakage among EU nations \cite{schlott2021carbon}, but more importantly it will decrease the global welfare \cite{nordhaus2019}.

The European power sector is on the verge of a major transition from a fossil-based system to reliance primarily on renewable resources \cite{victoria\_2020}. However, the starting situation is far from even, with some countries already attaining high shares of carbon-neutral energy sources, and other countries still heavily reliant on fossil fuels \cite{eurostat\_2019}.

The transition of the national energy supply can be encumbered by several factors of a technical, economic or political character. The availability of renewable resources \cite{levenda\_2021}, currently installed plants, and strengths of international transmission connections \cite{golubchikov\_2020} are a few of the technical challenges. Figure \ref{fig:starting\_point} a) shows the capacity of plants installed today that are expected to be in operation in 2030. It is clear, that the starting point for rapid decarbonization of the energy supply is very diverse, with some countries relying heavily on coal and oil, and other countries having already installed some extend of renewable energy generators. Figure \ref{fig:starting\_point} b) shows the effective renewable potentials, calculated as the geographical potential times the average capacity factor (reference for geographical potentials). The figure clearly shows how the distribution of renewable potentials far from follow neither country sizes nor energy demands.

The vastly different starting points of the member states should be capture by the EU ETS in the Effort Sharing Regulation \cite{EU\_effort\_sharing} if a just transition is to be achieved.

\begin{figure\*}[!htb]

\includegraphics[width=1\textwidth,trim={0cm 0cm 0cm 0cm},clip]{./figures/starting\_point.pdf}

\caption{a) Currently installed technology capacity that will be in service in 2030. b) Effective renewable energy potentials, calculated as the maximum geographical potential times the local capacity factor for the given technology. Wind turbine capacity is specified as offshore and onshore. Hydro-power is separated as either run-of-river (ROR), pumped-hydro-storage (PHS), and hydro. Two types of gas-turbines are included. These closed-cycle-gas-turbines (CCGT) and open-cycle-gas-turbines (OCGT). Transmission capacities are indicated either as high voltage AC or DC transmissions lines. The majority of countries has both brownfield and renewable potentials to cover several times their annual electricity demand. }

\label{fig:starting\_point}

\end{figure\*}

The use of a single global CO$\_2$ price is argued by economists to be the most effective way of achieving emission reductions \cite{nordhaus2019}. Relying solely on a global CO$\_2$ price, justice of the transition can not be ensured. Sovacool \cite{sovacool2014we} argues that there is a need to move towards human-centered exploration of the energy transition if fairness is to be ensured. Distributing the global carbon budget to ensure equity is however a difficult task with many outcomes. In a review by Zhou and Wang \cite{Zhou\_2016} a range of allocation schemes based on different philosophies is identified. Some of the principal considerations in the allocation schemes are sovereignty, egalitarianism, efficiency, horizontal equity, vertical equity and polluter pays. Other studies combine these philosophies to create more complex allocation schemes, such as the Model of Climate Justice per capita \cite{alcaraz\_2018}, where historical emissions along with population growth are considered. Choosing a single right allocation scheme is inherently difficult as it is not a question about costs but rather one of morality \cite{sovacool2015energy}. A study by Markowitz \cite{markowitz2012climate} even states that the human moral is ill-equipped to make this decision given the complexity of the problem, and our own complicity in causing it.

In a conceptual review, Jenkins et. al. \cite{jenkins\_2016} identified three core tenants of energy justice: Distributional, recognition, and procedural. Distributional justice recognizes the unequal distribution of environmental benefits and will be the core focus of this work.

In a study by Schwenk-Nebbe et. al. \cite{Schwenk\_2020}, three effort sharing schemes for selecting national CO$\_2$ targets are studied in a European context. In the paper, emissions are allocated based on cost efficiency, sovereignty (local-load), and grandfathering (local-1990). The efficiency scenario utilizes a global CO$\_2$ price, the sovereignty scenario allocates emissions proportional to national electricity demand, and the grandfathering scenario allocates emissions proportional to historical emissions.

These three scenarios will also be referenced throughout this work. In their analysis, Schwenk-Nebbe et. al. find that the Efficiency solution leads to the location of emissions in a small selection of countries where the cost of decarbonization is highest. Allocating emissions after the Sovereignty or Grandfathering principle will distribute emissions more uniformly, but lead to uneven CO$\_2$ abatement costs and higher total system cost. Bauer et. al. \cite{Bauer\_2020} have studied the trade-off to be made between economic efficiency and sovereignty in a global context using a multi-objective approach. Their findings indicate a highly non-linear trade-off between efficiency and sovereignty, indicating that choosing an intermediate scenario will lead to an increased sum of total benefits.

The studies by Schwenk-Nebbe and Bauer \cite{Schwenk\_2020, Bauer\_2020} do, however, only analyze a fraction of the possible ways national CO$\_2$ reduction targets can be distributed. As found in \cite{Zhou\_2016}, there are numerous philosophies that can be applied towards effort sharing resulting in a vast number of emission distribution schemes.

In this work, a Markov Chain Monte Carlo (MCMC) method \cite{haario\_2001} will be employed in combination with a techno-economic optimization model of the European power supply to study a broad range of CO$\_2$ target dispositions. The allocation dispositions come in the form of a set of national emission reduction targets for the modeled countries. Two criteria are required of the CO$\_2$ target dispositions. First, a combined CO$\_2$ reduction of at least 55\% must be achieved by the model countries according to the EU 2030 Climate Target Plan \cite{EU\_2030\_Climate\_target\_plan}. Second, the total system cost of enforcing the CO$\_2$ target disposition must not increase by more than 18\% relative to the cost-optimal allocation of national targets. This constraint is based on the principles from Modeling to Generate Alternatives (MGA) where economically near-optimal model solutions are studied \cite{brill1982}. Applying MGA methods to energy system optimization models has gained a lot of attention \cite{neumann2021broad, lombardi2020policy}. MGA has, however, mainly been used to study technical flexibility among the near-optimal solutions \cite{neumann2021}.

The method employed in this work consists of two steps. First, using a MCMC method to draw a random set of national CO$\_2$ reduction targets for the model countries. Second, the total system cost and combined CO$\_2$ reductions of the CO$\_2$ target disposition are then evaluated using an energy system optimization model. If the CO$\_2$ target disposition satisfies the two afore-mentioned criteria, it is accepted and stored. If not, the CO$\_2$ target disposition is rejected. This process is iterated until a sufficient sample size is obtained. The result is a set of CO$\_2$ target dispositions that resembles all possible CO$\_2$ target dispositions that will satisfy the two criteria.

The novelty of this work lies in the combination of a power system optimization model and MCMC methods to study possible CO$\_2$ target dispositions in a European context. Where previous studies have used scenario-based modeling or multi-objective optimization to study a small range of possible solutions, the method applied in this work is capable of identifying a much larger range of possible scenarios. Furthermore, detailed information about each CO$\_2$ target disposition is obtained as the power system optimization model is solved for each allocation scheme.

\subsection\*{Method}

The aim of this paper is to analyze the impact of changing national CO$\_2$ targets and their effect on the European power system.

Feasibility of the CO$\_2$ target dispositions is accomplished if a disposition satisfies the criteria listed in Table \ref{tab:feasa}. In addition to the two previously mentioned criteria, it is further required that the energy system optimization model is solvable under the target disposition and national emission must not surpass the equivalent emissions of covering 150\% of national energy demand with coal power. These additional criteria prevent very unrealistic scenarios from being found feasible.

\begin{table\*}[htb]

\centering

\caption{CO$\_2$ disposition scheme feasibility criteria}

\label{tab:feasa}

\begin{tabularx}{.9\textwidth}{lX}

\hline

%\multicolumn{2}{c}{Feasibility criterion's} \\

a) & Combined CO$\_2$ reductions must be equal or grater than 55\%. \\

b) & Total system cost of the scenario does not surpass the cost of the cost optimal scenario + 18\% \\

c) & A technically feasible solution to the model exists. \\

d) & National emissions must be less than the equivalent emissions of covering 150\% of national energy demand with coal power

\end{tabularx}

\end{table\*}

To draw possible CO$\_2$ target dispositions a modified version of the Adaptive Metropolis-Hastings (AMH) sampler is used \cite{haario\_2001}. The sampler falls under the broad umbrella of MCMC samplers. Using the AMH sampler to efficiently sample possible CO$\_2$ target dispositions, and rejecting the dispositions considered infeasible, it is possible to approximate the distribution of feasible CO$\_2$ target dispositions. The sampled variables are the national CO$\_2$ reduction targets for the model countries. Using the AMH sampler, distributions approximating the distributions of all feasible CO$\_2$ target dispositions are obtained. A detailed description of the sampler is available in the appendix.

The sampled CO$\_2$ target dispositions are evaluated using an energy system optimization model of the European power sector. The model uses the PyPSA-Eur-Sec framework \cite{PyPSA-EUR-SEC} to define a model spanning 33 ENTSO-E member countries. A 2030 brownfield scenario is modeled, where all installed generator capacities as of 2019 that are expected to be in operation in 2030 are included. To cover energy demands the model will install new generation capacity, where it is economically optimal. Model countries are the EU-27 excluding Cyprus and Malta, but including Great Britain, Norway, Switzerland, Serbia, and Bosnia and Herzegovina. The model uses a one node pr. synchronous zone setup, with the nodes connected by high voltage AC and DC lines. Using one year of energy demand and weather data resolved in 3 hour time-steps, the model determines the cost-optimal dispatch, power flows, and investment in new generator capacity.

Transmission line capacities included in the model are the currently installed capacities, plus the planned capacities from the Ten Year Network Development Plan (TYNDP) \cite{tyndp\_2018}. The energy-generating technologies included are run-off-river, onshore wind, offshore wind, solar PV, CCGT, OCGT, coal, lignite, nuclear, and oil. Furthermore, two storage technologies are included. These are hydrogen and battery storage. The technology parameters are found in Table \ref{tab:tech\_data}. Brownfield capacities are seen in Figure \ref{fig:starting\_point} and in Table \ref{tab:brownfield\_cap}.

The national CO$\_2$ reduction targets given by the AMH sampler are included as constraints in the model, limiting the CO$\_2$ emissions from energy generation in the modeled countries. Modeled countries are free to overperform on the national CO$\_2$ reduction target if it is economically favorable.

Technology cost predictions for 2030 are used for all expandable generator types. All technology costs can be found in Table \ref{tab:tech\_cost}.

Hourly energy demand and weather data from 2013 are used. 2013 is chosen as the reference year, as the demand and weather profile is a good representation of an average year.

A single model evaluation can be completed in approximately 15 minutes on a 4 core machine with sufficient memory.

Solving the optimization problem 30.000 times, requiring 15 minutes each, was performed using 10 parallel threads, resulting in roughly 30 days of computation.

By evaluating the result of the energy system optimization model for a given CO$\_2$ target disposition it is possible to determine if the target disposition fulfills the criterion's in Table \ref{tab:feasa}. The CO$\_2$ target dispositions can then be accepted or rejected bases on the result.

\begin{table\*}[htb]

\caption{Strategies for CO$\_2$ target disposition}

\label{tab:scenarios}

\begin{tabularx}{1\textwidth}{XXX}

Name & Interpretation & Rule \\ \hline

Grandfathering & All nations have equal right to pollute & Distribute emissions proportional to historic emissions \\

Sovereignty & All nations have equal right to pollute & Distribute emissions proportional to energy demand \\

Efficiency & Maximize global welfare & Distribute emissions to reduce total socio-economic costs \\

Egalitarianism & All people have equal right to pollute & Distribute emissions proportional to population size \\

Ability to pay & Nations with higher welfare should take on a larger part of the task & Distribute emissions inversely to GPD per population \\ \hline

\end{tabularx}

\end{table\*}

\subsubsection\*{Method limitations}

In the model a single year is used for weather and demand data is used. Weather and demand patterns are expected to change as a result of global warming and general electrification of energy use. Investigating these effects is, however, beyond the scope of this paper.

Only the electricity sector has been modeled in this work where a 2030 scenario is modeled. The effects of sector coupling are only expected to be moderate by 2030, thus this simplification is believed to give a minor source of error. If sector coupling were implemented, the electricity sector is expected to achieve higher decarbonization levels then the 55\% target, as the electricity sector is considered as easier to decarbonize than other sectors. Emissions from northern countries, that have achieved a high decarbonization in the electricity sector (Norway, Sweden, Finland) will rise, as they are still relying on oil and gas for heating, industry and transportation.

\subsection\*{Results}

Throughout the results, there will be referred to five national CO$\_2$ target strategies. Based on the strategies described in \cite{Zhou\_2016}, these are grandfathering, sovereignty, efficiency, egalitarianism, and ability to pay. The interpretation and rule for the distribution of emissions for the strategies are found in Table \ref{tab:scenarios}

Applying the described MCMC method, a total of 30.000 random dispositions were drawn, with an acceptance rate of $\approx 80\%$. All samples were saved allowing for analysis of emitted CO$\_2$, technology investments, and electricity prices.

In Figure \ref{fig:co2red\_cost}, the global CO$\_2$ emission from all samples is shown, plotted against the total system cost of the samples. The reference scenario (Efficiency) with the lowest total system cost is indicated with the red cross. The Pareto optimal front was calculated by continuously decreasing the allowed global CO$\_2$ emissions, and is indicated by the blue line.

\begin{figure}[htbp]

\includegraphics[width=0.49\textwidth,trim={0 0 0 0},clip]{./figures/cost\_vs\_co2\_2030\_elec\_f.pdf}

\caption{Histogram showing the CO$\_2$ reduction relative to 1990 and cost increase of all feasible CO$\_2$ target dispositions relative to the cost-optimal solution. The minimum required CO$\_2$ reduction and maximum allowable cost increase is marked with red lines. The blue line marks the Pareto-optimal front of a dual objective optimization problem using total system cost and CO$\_2$ reduction as the two objective functions. The cost-optimal solution is marked with a red X, and the CO$\_2$ target scenarios Grandfathering, Ability-to-pay, Egalitarianism, and Sovereignty are marked with orange. }

\label{fig:co2red\_cost}

\end{figure}

In the figure, a gap between the Pareto optimal front and the samples can be observed. There is nothing preventing the sampler from drawing samples on the Pareto optimal front, it is, however, very unlikely. Because probability of the sampler drawing the exact combination of the 33 variables that will lead to a Pareto optimal solution is very low. This also shows that the optimal solution is an extreme scenario that is very hard to obtain without extensive collaboration and agreement between model countries. This is, very unlikely as countries have individual national targets and agendas. Therefore, we argue that solutions located in the dark blue regions of Figure \ref{fig:co2red\_cost} can be considered as significantly more probable outcomes, because they can be realized with many different national dispositions.

All CO$\_2$ disposition strategies except the Efficiency strategy are seen having a higher CO$\_2$ reduction than what is required. This over-performance on emissions reduction is a result of several countries finding it cost-optimal to reduce emissions beyond their assigned national target. In the Efficiency scenario, a global CO$\_2$ emission constraint is used, and is thus binding for all countries. In all other scenarios national CO$\_2$ emission constraints are used. In all scenarios with higher than 55\% reductions the national CO$\_2$ constraint is not binding in one or more countries.

The Grandfathering and Ability to pay schemes are located close to the Pareto-optimal front, whereas the Sovereignty and Egalitarianism are found to deviate significantly from the Pareto-optimal front.

Looking at the marginal distribution of the global CO$\_2$ reduction, it is clear that the probability of achieving reductions close to the global target (marked by the red line) is more probable than overachieving. The marginal distribution of the system cost reveals that an increase in the total system cost of a minimum 5\% relative to the optimal scenario is almost unavoidable, since, to obtain the lowest possible total system cost, the burden of transitioning must be shared in a very exact way. It is, nevertheless, very unlikely that this will happen as countries have different national ambitions. Therefore a cost increase of the entire system is expected. What Figure \ref{fig:co2red\_cost} tells us is that this cost increase with a 75\% chance will be above 4.6\% and has a 50\% chance of being between 4.6\% and 12.2\%.

\begin{figure\*}[htb]

\includegraphics[width=1\textwidth,trim={1cm 0.3cm 2cm 0cm},clip]{./figures/co2\_mwh\_box\_2030\_elec\_f.jpeg}

\caption{ National CO$\_2$ emissions relative to 1990 values for all modeled scenarios. The scenarios Grandfathering, Sovereignty, Efficiency, Egalitarianism, and Ability to pay is highlighted.}

\label{fig:co2\_mwh\_box}

\end{figure\*}

Figure \ref{fig:co2\_mwh\_box} shows the emitted CO$\_2$ from the modeled countries relative to 1990 values and weighted by national energy production. In the figure, emissions from the CO$\_2$ target dispositions are also plotted. As seen in the figure, all countries have zero emissions in one or more scenarios. Countries such as Norway and Sweden have zero emissions in all scenarios. This is not because they are given a very low CO$\_2$ reduction target, but simply because it is cost-optimal to rely fully on renewable or nuclear energy. On the other end, there are countries such as Poland and Macedonia with large emissions per MWh energy produced. By analyzing the CO$\_2$ target disposition in the Efficiency scheme, it is seen that higher than average shares are allocated to countries that generally have high emissions and fewer than average shares to the countries with low emissions. In other words, the Efficiency scheme favors assigning low CO$\_2$ reduction targets to countries that have a hard time reducing emissions and cuts emissions drastically in countries where CO$\_2$ reduction is easier. This intuitively reduces total system cost. In the Sovereignty scenario, CO$\_2$ reduction targets are distributed equally based on the national energy demand. Naturally, a much more even emission per unit of produced energy is seen for this scenario. In the Ability to pay scenario emissions are distributed inversely proportional to national GDP. This redistribution of emissions in the Ability to pay scheme is clearly seen in Figure \ref{fig:co2\_mwh\_box}, where wealthy countries such as Germany and the Netherlands have low emissions and countries such as Romania, Macedonia, and Bulgaria have higher emissions. \\

\begin{figure\*}[htb]

\includegraphics[width=0.5\textwidth,trim={3.2cm 3cm 1.1cm 2cm} ,clip] {./figures/co2\_correlation\_map\_2030\_elec\_f.pdf}

\includegraphics[width=0.5\textwidth,trim={1cm 1.5cm 1.5cm 1.5cm} ,clip]{./figures/co2\_emis\_correlations\_2030\_elec\_f.pdf}

\caption{The data used to create this figure is the Pearson correlation of the national CO$\_2$ emission across all samples. a) CO$\_2$ emission correlations shown on a map of the model countries. Correlation strength and direction is indicated by the link color and size. Correlations below 0.2 has been removed for clarity. b) A matrix plot of CO$\_2$ emission correlation for all model countries.}

\label{fig:co2\_correlation}

\end{figure\*}

By analyzing correlations between actual national CO$\_2$ emissions from all the samples, Figure \ref{fig:co2\_correlation} is generated. On Figure \ref{fig:co2\_correlation} a) it is very evident that neighboring countries have a great effect on each other. The strong positive correlation between Sweden and Norway's emissions is however an artifact as these two countries have zero-emission in almost all scenarios. Germany is found to play a central role in the emissions of many central European countries. Strong negative correlations are seen between Germany and the neighbors France, Austria, Denmark, Luxembourg, and the Netherlands. This indicates that in scenarios where Germany has low emissions, the neighboring countries are likely to have higher than average emissions. A likely explanation is that the neighboring countries are providing dispatchable energy when Germany is capable of providing this itself due to tight national CO$\_2$ reduction targets and vice versa.

A cluster of tightly correlated countries is, furthermore, found among the northeastern countries Poland, Estonia, Lithuania, and Latvia. Here Poland appears to be dominating, with strong negative correlations to the three other countries. This reveals a dynamic where CO$\_2$ emitting dispatchable energy is moved between these countries depending on where national emission reduction targets are tightened. In this region of Europe renewable, resources are less favorable, and this strong correlation could indicate that the countries located here are strongly dependent on energy from dispatchable resources from each other.

Another cluster with similar dynamics is found in southeastern Europe between the countries Greece, Bosnia and Herzegovina, Albania, Montenegro, and Serbia. The correlation pattern here is however not easily understood.

\\

\begin{figure\*}[htb]

\includegraphics[width=1\textwidth,trim={0cm 0.3cm 0cm 0cm},clip]{./figures/unused\_co2\_2030\_elec\_f.jpeg}

\includegraphics[width=1\textwidth,trim={0cm 0cm 0cm 0cm},clip]{./figures/co2\_vs\_co2\_['PL', 'NL', 'AT', 'FI', 'SE'].jpeg}

\caption{Data from all sample points. a) a box plot of the utilization of the national reduction targets for the individual couturiers across all scenarios. A value of 100\% means that the country is emitting as much CO$\_2$ as their reduction target allows, whereas 0\% indicates that the country has no emissions although the CO$\_2$ reduction target is not 0.

b) Example countries. Reduction target utilization plotted against the total amount of target emissions.}

\label{fig:unused\_co2}

\end{figure\*}

In this study, CO$\_2$ reduction targets were assigned to countries giving the countries the option to either use all allowable emission or simply leave them unused if it is found economically optimal. The top panel of Figure \ref{fig:unused\_co2} shows a box plot of the utilization of the national reduction targets for the individual couturiers across all scenarios. Here, a value of 100\% means that the country is emitting as much CO$\_2$ as their reduction target allows, whereas 0\% indicates that the country has no emissions although the CO$\_2$ reduction target is not 0.

Below the box plot, the reduction target utilization has been plotted against the total amount of target emissions for five example countries. The top panel of Figure \ref{fig:unused\_co2} clearly shows three distinct behavioral patterns for the countries. The countries either a) emit as much as the national target allows no matter what, b) sometimes overperform on the target or c) never have any emission. These different patterns are clearly highlighted in the lower panels: Poland is seen always emitting as much as the national target allows. The Netherlands, Austria, and Finland can be seen over-performing as when they have higher allowable emissions. The curved lines appearing in these figures correspond to the countries capping-out at a certain emission level. Finland can be seen having a clear upper bound to how much CO$\_2$ they prefer to emit, whereas Austria appears to have several preferable levels. This behavior is very likely a result of the strong correlation between Austria's emissions with the emission from Germany and France found in Figure \ref{fig:co2\_correlation}. In scenarios where Germany is assigned less than their preferred amount of emissions, Austria can provide dispatchable power resources and therefore have higher emissions. In scenarios where Germany and its neighbors have high allowable emissions, the demand for dispatchable resources from Austria drops, and it becomes cost-optimal for Austria not to use all allowable emissions.

Studying how the five CO$\_2$ disposition schemes from Table \ref{tab:scenarios} are distributed on Figure \ref{fig:unused\_co2} reveals that the Efficiency scheme ensures that all national targets are utilized 100\%. In the Efficiency scheme no country is allocated more emissions than needed, whereas the other disposition schemes result in inefficient allocations increasing total system cost. Especially the Grandfathering scheme leads to a large share of allocated emissions being unused.

It is important to note that as only the electricity sector is considered in this work, the 55\% emission reduction target applied is a bit conservative, considering that the electricity sector is expected to be the first to be decarbonized. As several countries already have decarbonized their electricity sector to a high extend, they will find it economically optimal not to use all the emissions they are allocated. Norway, Sweden, and Switzerland are seen not using any of their allocated emissions in most scenarios. This is compliant with the findings from Figure \ref{fig:co2\_mwh\_box}.

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\begin{figure\*}[htb]

\includegraphics[width=1\textwidth,trim={1cm 0.3cm 2cm 0cm},clip]{./figures/co2\_price\_2030\_elec\_f.jpeg}

\includegraphics[width=1\textwidth,trim={1cm 0.3cm 2cm 0cm},clip]{./figures/elec\_price\_2030\_elec\_f.jpeg}

\caption{The top panel show the national CO$\_2$ price for all countries across all scenarios. The countries are sorted after average emission per Mwh produced. The lower panel shows the average electricity price for the individual countries across all scenarios. }

\label{fig:prices}

\end{figure\*}

Enforcing a national limit on CO$\_2$ emissions naturally entails a price on abating emissions for the given region. In a linear optimization model such as the one used in this paper, the Lagrange/Kuhn-Tucker multiplier of the national CO$\_2$ constraints serves as a proxy for the national CO$\_2$ abatement cost. The Lagrange multiplier measures the change in objective function value caused by a change in the given constraint. Thus, the Lagrange multiplier associated with the national emission limits measures the increase in total system cost when the given node is constrained on its emissions.

CO$\_2$ abatement costs are highly dependent on local CO$\_2$ reduction targets and the availability of renewable resources. An abatement cost will only occur if the national emission reduction constraint is binding. Thus, in a scenario where a given country is only utilizing parts of the allocated CO$\_2$ target, an abatement cost of 0 will be obtained. In Figure \ref{fig:unused\_co2} it is seen that a large number of the model countries are not utilizing the entire share of allocated emissions. Therefore, CO$\_2$ abatement costs of zero are seen for several countries in many of the scenarios in Figure \ref{fig:prices}. Comparing the group of countries observed to always utilize their allocated emissions on Figure \ref{fig:unused\_co2}, with the CO$\_2$ abatement cost on Figure \ref{fig:prices}, these countries are found to always have non-zero abatement cost.

The abatement cost for these countries are ranging from 30 to 40 €/t CO$\_2$ in most scenarios, but with outliers ranging much higher.

On the top panel of Figure \ref{fig:prices} the Efficiency scheme is seen having almost similar CO$\_2$ abatement costs for all model countries. The significantly higher abatement costs in the Efficiency scheme of the five countries RO, BG, MK, GR, and SI, is caused by the constraint on maximum emissions relative to using only coal power seen in Table \ref{tab:feasa} (d).

Electricity prices are found to have a smaller spread for the individual countries as seen on the lower panel of Figure \ref{fig:prices}. The robustness of the electricity price does, however, depend on the country observed with countries at each end of the figure having more robust prices, and countries towards the center having larger deviations. The countries observed to have constantly high prices are to a large extent the same countries that had high abatement costs. The countries observed to have high fluctuations in the electricity price are also the countries observed having strong correlations in national CO$\_2$ emissions on Figure \ref{fig:co2\_correlation}.

The observed electricity prices on the lower panel of Figure \ref{fig:prices} span from 10 €/MWh all the way to above 70 €/MWh for some outlier scenarios. This span in power prices is rather large compared to current power prices which are around 50 €/MWh for most European countries.

\subsection\*{Discussion (Policy implications)}

- 55\% target is not very ambitious when only considering the electricity sector. Several studies show that the electricity sector will be the first to decarbonize. Therefore, the electricity sector should have reached higher decarbonization levels by 2030. \\

- The entire cost of electricity is not captured in the electricity price plots, as brownfield costs are not included in model cost\\

- Perspective to PRIMES model \\

- EU ETS/effort sharing scenarios.

\subsection\*{Conclusion}

In this study a Markov Chain Monte Carlo simulation of 30.000 emission allocation schemes of the European power supply has been performed for the model year of 2030. Results reveal that a cost increase of 5\% from the cost-optimal solution is almost inevitable. Furthermore, strong correlation between emissions from three groups of countries located in central, North Eastern, and South-Eastern Europe was identified. These correlation reveal that enforcing a tight CO$\_2$ limit on one cluster country will move emissions to the other countries in the cluster. Analyzing the utilization of allocated emissions reveal a group of countries where it will be economically favorable to decorbonize the power-sector, thus having zero emissions although emissions are allocated to the given country. A large group of countries do however favor some level of emissions from the power sector, but the level of favored emissions do in many cases depend on emissions from neighboring countries. The national CO$\_2$ abatement cost associated with the sampled emission allocation schemes reveal large inequality with some countries being likely to have significantly higher abatement costs. A similar picture is found when studying power prices. The key take-away from this study is the fact that the burden of transitioning our power supply is inequitably distributed, and actions must be taken to compensate.

\clearpage

\onecolumn

\section\*{Appendix}

\subsection\*{Sampling method}

To draw possible CO$\_2$ target dispositions the Adaptive Metropolis-Hastings (AMH) sampler is implemented \cite{haario\_2001}. The AMH sampler is based around a Markov Chain process where samples are continuously drawn from a proposal distribution centered around the previous sample point. By controlling the width of the proposal distribution continuously the AMH sampler ensures efficient sampling.

\begin{figure\*}[!htb]

\includegraphics[width=0.9\textwidth,trim={5cm 4cm 0cm 0cm},clip]{./figures/Method\_figure.pdf}

\caption{Sampling method schematic}

\label{fig:method}

\end{figure\*}

An arbitrary CO$\_2$ target disposition can be denoted as the vector $\mathbf{x}$, with each component of this vector $x\_i$ representing the national CO$\_2$ emission target of the $i$'th country relative to the total CO$\_2$ emission target. The allowed emission for a given country can be determined as $x\_i \cdot CO2\_{CAP}$, where the $CO2\_{CAP}$ is the total global amount of CO$\_2$ emissions allowed in tonnes of CO$\_2$. Realizations of the variables are denoted with subscript $\mathbf{x}\_t$. \\

Given a starting point $\mathbf{x}\_0$ the AMH sampler will continuously generate new sample proposals $\mathbf{x}'$. New samples are drawn from the proposal distribution centered around the previous sample. The proposal distribution is defined as a uniform distribution around the previous sample point with the width $\sigma$. Thus the maximal change in each variable $x\_i$ per iteration is $\sigma/2$. There are however a few caveats. As the variables considered $\mathbf{x}$ are fractions of a total CO$\_2$ budget, they are constrained to be between 0 and 1. Therefore, the uniform distribution is bounded not to exceed this area.

\begin{equation}

\mathbf{x}' \sim \mathcal{U}[\max(\mathbf{x}\_i-\frac{\sigma}{2} ,0) , \min(\mathbf{x}\_i+\frac{\sigma}{2} ,1) ]

\end{equation}

The distribution width $\sigma$ can be tuned continuously as more information about the solutions space is obtained. By setting $\sigma$ too low, the sampler will need an excessive amount of samples to explore the entire solution space. On the other hand, setting $\sigma$ too high will result in the rejection of too many samples.

By continuously monitoring the acceptance rate, it is possible to determine if the chain is taking either too short or long steps. If the acceptance rate is very high $\sigma$ should be increased, and if the acceptance rate is low $\sigma$ should be decreased. In practice, this is implemented by letting the sampler run for a number of iterations and evaluating the acceptance rate in that batch of samples. In this implementation of the AMH sampler, $\sigma$ is updated by continuously monitoring the acceptance ratio of the samples. When the acceptance ratio is below a user-specified value, $\sigma$ is incremented by a small amount $\epsilon$, and vice versa when the acceptance ratio is too high. An $\epsilon$ value of 0.05 was used throughout this work. In this work, a desired acceptance ratio of 80\% has been used.

The feasibility of a proposed sample $\mathbf{x}'$ is evaluated using the energy system optimization model. If the solution to the energy system optimization model given $\mathbf{x}'$ as input satisfies all criteria from Table \ref{tab:feasa} the sample is accepted. Otherwise, the sample is rejected and a new proposal sample is drawn. When a proposed sample is accepted it is assigned index $t$, such that $\mathbf{x}\_t = \mathbf{x}'$. If a sample is rejected the previous sample point is stored instead $\mathbf{x}\_t = \mathbf{x}\_{t-1}$.

The process of drawing samples from the proposal distribution and either accepting or rejecting them is repeated until sufficient sample size is reached. The process is illustrated in Figure \ref{fig:method}.

%The feasibility of any arbitrary CO$\_2$ target disposition can be determined by evaluating the proportional probability function $p(\mathbf{x})$. The proportional probability function $p(\mathbf{x})$ will return a value of $1$ if $\mathbf{x}$ satisfies all criterion's from table \ref{tab:feasa}, otherwise it will be $0$. Thus, the output of $p(\mathbf{x})$ is a binary.

%By combing these tools the AMH sampler can be described using the schematic on \ref{fig:method}. Starting at $t=0$ a starting point $\mathbf{x}\_t$ that satisfies $p(\mathbf{x}\_0)>0$ is provided. For each iteration the sampler will draw a proposal sample $\mathbf{x}'$ from the proposal distribution $g(\mathbf{x}',\mathbf{x})$. The optimization problem is then solved in order to obtain a model solution for the proposed sample. If the proportional probability of the proposed sample $p(\mathbf{x}')$ is 1 the sample is accepted, otherwise, it is rejected. If the samples is accepted it is stored as $\mathbf{x}\_t = \mathbf{x}'$. Otherwise $\mathbf{x}\_t = \mathbf{x}\_{t-1}$. $t$ is incremented and this process is repeated until the desired number of samples $T$ is obtained. \\

The result is a set of realizations of $\mathbf{x}$ that can ensure feasible operation of the model, global emission reductions higher than the base scenario, and a total system cost that is no more than 18\% higher than that of the base scenario. If enough samples are drawn the distribution of the set of realizations will approximate all solutions satisfying the above-mentioned criteria.

In practice, the above algorithm is implemented as a parallel process with multiple chains running simultaneously. The samples from the parallel chains can then be merged at the end of the sampling process.

The starting point for all chains is the optimal solutions $\mathbf{x}\_1$ is the same. Therefore, the correlation between the chains and auto-correlation within the chains themselves is unavoidable at the start. As these starting samples would skew the result towards the starting scenario, a burn-in period is implemented. By discarding the first samples from the chains any bias towards the start solution is avoided.

!!! Include the following: \\

- MCMC starting point \\

- Argue for choice of mcmc method

%\begin{enumerate}

% \item Select the starting point $\mathbf{x}\_1$ to be the base scenario. (This step could be improved to select a random %starting point)

% \item For each iteration $t$:

% \begin{enumerate}[label\*=\arabic\*.]

% \item Draw a proposal for the next sample point $\mathbf{x}'$ from the proposal distribution $g(\mathbf{x}',y)$

% \item Optimize the model using the proposed sample point as input.

% \item Accept the sample point if the optimized solutions satisfies the following criteria:

% \begin{enumerate}

% \item A feasible solution to the model exists

% \item Global CO$\_2$ reductions must be equal or grater than that of the base scenario

% \item Total system cost does not surpass the cost of the base scenario + 10\%

% \end{enumerate}

% \item If the sample is accepted, set $\mathbf{x}\_t = \mathbf{x}'$.

% \item If the sample cannot be accepted then set $\mathbf{x}\_t = \mathbf{x}\_{t-1}$.

% \end{enumerate}

%\end{enumerate}

\subsection\*{Energy system optimization model}

The energy system optimization model used in this work is based on the PyPSA-Eur-sec model \cite{PyPSA-EUR-SEC}. The PyPSA-Eur-sec model to a high extend depends on data imports from the PyPSA-Eur model \cite{horsch2018pypsa}. The model formulated in this work represents a 2030 scenario of the European electricity supply. The model spans the EU-27 countries excluding Cyprus and Malta, but including Great Britain, Norway, Switzerland, Serbia, and Bosnia and Herzegovina. The electricity transmission grid is represented by a one node pr. power trading region network, connected with links representing existing and planned international AC and DC transmission lines. All existing plus the planned transmission capacities in the Ten Year Network Development Plan (TYNDP) \cite{tyndp\_2018} is included. (!! Make a figure of transmission capacities !!)

A brown-field scenario is generated where existing capacities that are planned to be in operation by 2030 are included in the model. The included brown-field capacities are seen in Table \ref{tab:brownfield\_cap}. Existing conventional capacities are found from the power-plant matching database \cite{powerplantmatching}, while renewable capacities are found from the IRENA annual statistics \cite{IRENA}.

Some technology capacities can be expanded to meet energy demand at a certain cost. Cost of the expandable technologies are given in Table \ref{tab:tech\_cost}. Efficiency and emission data are available in Table \ref{tab:tech\_data}. Technology costs are primarily based on the 2030 cost prediction given by the Danish Energy Agency in their technology data catalog \cite{Data\_catalogue}. A discount rate of 7\% has been used to calculate annualized costs using the annuity factor given in Equation \ref{eq:annuity}. Here $r$ is the discount rate and $n$ is the technology lifetime.

\begin{equation}\label{eq:annuity}

a = \frac{1 - (1+r)^{-n}}{r}

\end{equation}

The model of the European power sector is formulated as a linear optimization problem, consisting of an objective function along with a set of constraints. Throughout this description of the model, the model variables are split in two vectors namely $\mathbf{x}$ and $\mathbf{y}$. Where $\mathbf{x}$ describes the national CO$\_2$ reduction target given by the MCMC sampler $\mathbf{x} = {r\_n \; \forall \; n}$. Here $r\_n$ is the national CO$\_2$ target in ton CO$\_2$ for all model countries $n$. The remaining variables $\mathbf{y}$ represent technology capacities and dispatch $\mathbf{y} = \{ \mathbf{g}\_{n,s,t} , \mathbf{G}\_{n,s} , \mathbf{F}\_{l} \}$.

Here index $s$ is indexing the technology for all technologies included in the model, index $t$ is indexing the hour for all hours in the year, and $l$ is the transmission line. The variables determined in the optimization process is thus:

\begin{itemize}

\item $\mathbf{g}\_{n,s,t}$ : Hourly dispatch of energy from the given plants in the given countries with the marginal cost $\mathbf{o}\_{n,s}$.

\item $\mathbf{G}\_{n,s}$: Total installed capacity of the given technologies in the given countries with the capital cost $\mathbf{c}\_{n,s}$.

\item $\mathbf{F}\_{l}$: Total installed transmission capacity for all lines with the fixed annualized capacity cost $\mathbf{c}\_{l}$.

\end{itemize}

The model is then formulated as a linear problem following the standard formulation given as:

\begin{equation}\label{eq:ConvexOptimization}

\begin{split}

\text{minimize} \;&\; \mathbf{f}\_0(\mathbf{y}) \; \\

\text{subject to} \; &\; \mathbf{f}\_i(\mathbf{x,y}) \leq 0 \; \; i=1..m\\

\; &\; \mathbf{h}\_i(\mathbf{x,y}) = 0 \; \; i=1..p\\

\end{split}

\end{equation}

The national CO$\_2$ targets $\mathbf{x}$ are given by the MCMC sampler and is thus not optimized in the model. Only the technical variables $\mathbf{y}$ are optimized in the optimization problem.

The objective function of the model is to minimize total system cost and can be formulated as follows:

\begin{equation}

\text{minimize} \; f\_0(\mathbf{x,y}) = \sum\_{n,s} \mathbf{c}\_{n,s} \mathbf{G}\_{n,s} + \sum\_l \mathbf{c}\_l \mathbf{F}\_l + \sum\_{n,s,t} \mathbf{o}\_{n,s} \mathbf{g}\_{n,s,t}

\end{equation}{}

For all model nodes and all hours in the year, a power balance constraint is enforced requiring that the energy demand $\mathbf{d}\_{n,t}$ is fulfilled.

Energy demand data is taken from the ENTSO-E data portal \cite{ENTSOE} and decomposed in industrial and residential demand following the method given in \cite{horsch2018pypsa}.

The incidence matrix describing the line connections is given by $\mathbf{K}\_{n,l}$ and the hourly transmission in each line is described as $\mathbf{f}\_{l,t}$. The nodal power balance constraint can then be formulated as:

\begin{equation} \label{eq:equality\_constraint}

\sum\_s \mathbf{g}\_{n,s,t} - \mathbf{d}\_{n,t} - \sum\_l \mathbf{K}\_{n,l} \mathbf{f}\_{l,t} = 0 \; \; \forall n,t

\end{equation}

The dispatch of each technology $\mathbf{g}\_{n,s,t}$ is limited by the installed technology capacity $\mathbf{G}\_{n,s}$. The dispatch of renewable energy generators such as wind and solar are furthermore limited by the hourly capacity factor $\mathbf{\overline{g}}\_{n,s,t}$. The capacity factor for conventional power plants is 1, whereas it is generated from weather data for the renewable generators. A detailed explanation of the derivation of renewable generation potentials is given in \cite{horsch2018pypsa}.

\begin{equation}

0 \leq \mathbf{g}\_{n,s,t} \leq \mathbf{\overline{g}}\_{n,s,t} \mathbf{G}\_{n,s} \; \forall n,s,t

\end{equation}

Similarly, transmission in transmission lines is also limited by the installed capacity. As the direction of the transmission is without significance it is the absolute transmission $|\mathbf{f}\_{l,t}| $ that is limited.

\begin{equation}

|\mathbf{f}\_{l,t}| \leq \mathbf{F}\_l \; \forall l,t

\end{equation}

The maximum capacity allowed for each technology is determined by geographical potentials available $\mathbf{G}\_{n,s}^{max}$ [REFERENCE].

\begin{equation}

0 \leq \mathbf{G}\_{n,s} \leq \mathbf{G}\_{n,s}^{max} \; \forall n,s

\end{equation}

CO$\_2$ emissions can be constrained in two ways. Either through a global constraint on emissions, or by national constraints on emissions. The global CO$\_2$ reduction constraint is formulated as:

\begin{equation}\label{eq:global\_co2}

\sum\_{n,s,t} \frac{1}{\mathbf{\eta}\_s}\mathbf{g}\_{n,s,t} \mathbf{e}\_s -CAP\_{CO\_2} \leq 0 \;

\end{equation}

Here the $CAP\_{CO\_2}$ is the global emissions limit given in ton CO$\_2$. Note that only a single constraint is given here. Limiting emissions through national constraints can be done by defining a constraint for each country in the model. The national emissions targets $\mathbf{r}\_n$ are given by the MCMC sampler.

\begin{equation}\label{eq:national\_co2}

\sum\_{s,t} \frac{1}{\mathbf{\eta}\_s}\mathbf{g}\_{n,s,t} \mathbf{e}\_s - \mathbf{r}\_n \leq 0 \; \forall \; n

\end{equation}

The global CO$\_2$ constraint (Equation \ref{eq:global\_co2}) is only used in the Efficiency scenario. In all other scenarios, the national CO$\_2$ targets are explicitly given, either by the sampler or following a certain allocation scheme.

% CO2 prices

When the model is solved Lagrange multipliers associated with each constraint are introduced. The value of these Lagrange multipliers represents the cost increase/decrease associated with tightening/loosening the constraint by one unit. Thus be evaluating the Lagrange multipliers associated with the energy balance constraint (Equation \ref{eq:equality\_constraint}) a proxy for the nodal hourly electricity price can be obtained. Similarly, the Lagrange multiplier of the national CO$\_2$ target constraint (Equation \ref{eq:national\_co2}) provides a proxy for the national CO$\_2$ abatement cost. \\

THE FOLLOWING SHOULD BE ADDED HERE:

- Total CO2 budget

- Table over national CO2 targets in scenarios

- Renewable potential calculation

- 150\% coal limit

\begin{table}[h]

\caption{Technology costs of new technologies.}

\label{tab:tech\_cost}

\begin{tabularx}{1\textwidth}{Xrrrr}

\hline

%\multicolumn{2}{c}{Feasibility criterion's} \\

Technology & Capital cost & FOM & VOM & Lifetime \\

& Eur/kW & \%/year & Eur/MWh & years \\ \hline

OCGT & 435.2 & 1.78 & 4.5 & 25 \\

Offshore wind turbine & 1573.2 & 2.29 & 2.67 & 30 \\

Offshore wind AC connection submarine & 2685.0\* & 0 & 0 & 30 \\

Offshore wind AC connection underground & 1342.0\* & 0 & 0 & 30 \\

Offshore wind AC station & 250.0 & 0 & 0 & 30 \\

Offshore wind DC connection submarine & 2000.0\* & 0 & 0 & 30 \\

Offshore wind DC connection underground & 1000.0\* & 0 & 0 & 30 \\

Offshore wind DC connection underground & 1000.0\* & 0 & 0 & 30 \\

Offshore wind DC station & 400 & 0 & 0 & 30 \\

Onshore wind & 1035.6 & 1.22 & 1.35 & 30 \\

Utility scale solar PV & 376.3 & 1.93 & 0 & 40 \\

Electrolysis & 550.0 & 5.0 & 0 & 25 \\

Fuel Cell & 1100.0 & 5.0 & 0 & 10 \\

Hydrogen storage tank & 44.0\*\* & 1.11 & 0 & 30 \\

Hydrogen underground storage & 2.0\*\* & 0 & 0 & 100 \\

Battery inverter & 160.0 & 0.34 & 0 & 25 \\

Battery storage & 142.0\*\* & 0 & 0 & 25 \\ \hline

\* Eur/MW/km \\

\*\* Eur/kWh \\

\end{tabularx}

\end{table}

\begin{table}[h]

\caption{Technology data}

\label{tab:tech\_data}

\begin{tabularx}{.9\textwidth}{XXX}

\hline

%\multicolumn{2}{c}{Feasibility criterion's} \\

Technology & Efficiency & Emissions \\

& \% & T CO$\_2$/MWh \\ \hline

OCGT & 41 & 0.49 \\ % 0.2 (efficiency2) / 0.41 efficiency = 0.49

CCGT & 58 & 0.34 \\

Coal & 33 & 1.00 \\

Lignite & 33 & 1.24 \\

Oil & 35 & 0.77 \\

Electrolysis & 66 & 0 \\

Fuel Cell & 50 & 0 \\

Battery inverter & 96 & 0 \\ \hline

\end{tabularx}

\end{table}

\begin{table}[h]

\caption{Existing generator technology capacities by 2030 in MW}

\label{tab:brownfield\_cap}

\begin{tabularx}{1.1\textwidth}{lXXXXXXXXXX}

& Offshore wind & Onshore wind & Run off river & Solar PV & CCGT & OCGT & Coal & Lignite & Nuclear & Oil \\ \hline

AT & 0.0 & 3132.7 & 4478.5 & 1438.6 & 4278.7 & 3203.7 & 3004.7 & 0.0 & 0.0 & 0.0 \\

BA & 0.0 & 50.6 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\

BE & 1185.9 & 2074.8 & 59.0 & 3984.5 & 6555.0 & 3562.5 & 4620.5 & 0.0 & 17957.0 & 0.0 \\

BG & 0.0 & 691.0 & 22.4 & 1029.0 & 0.0 & 1907.3 & 15041.5 & 12100.0 & 6060.6 & 0.0 \\

CH & 0.0 & 63.0 & 5280.0 & 2171.0 & 0.0 & 0.0 & 0.0 & 0.0 & 10393.9 & 0.0 \\

CZ & 0.0 & 316.2 & 40.2 & 2074.3 & 580.7 & 0.0 & 21772.0 & 2199.2 & 8060.6 & 0.0 \\

DE & 6396.0 & 52447.0 & 2997.0 & 45179.0 & 31242.9 & 19620.2 & 85058.7 & 63131.8 & 47843.8 & 10561.1 \\

DK & 1708.1 & 4431.2 & 0.0 & 991.0 & 172.4 & 3481.6 & 10999.8 & 0.0 & 0.0 & 1900.0 \\

EE & 0.0 & 329.8 & 0.0 & 25.4 & 298.3 & 609.8 & 0.0 & 0.0 & 0.0 & 6031.4 \\

ES & 0.0 & 23433.1 & 16.4 & 4753.5 & 41972.9 & 7177.0 & 19756.7 & 9336.8 & 22947.2 & 10095.5 \\

FI & 67.0 & 1971.3 & 1289.6 & 123.0 & 1117.2 & 1652.9 & 9211.2 & 0.0 & 8436.4 & 3501.1 \\

FR & 0.0 & 14898.1 & 5780.8 & 9604.0 & 9674.2 & 2600.0 & 13010.0 & 0.0 & 191303.0 & 20491.8 \\

GB & 8212.7 & 13553.9 & 685.2 & 13107.3 & 56593.6 & 2247.6 & 43863.6 & 0.0 & 34124.2 & 8005.4 \\

GR & 0.0 & 2877.5 & 103.1 & 2650.6 & 7727.6 & 1017.1 & 4697.0 & 11833.3 & 0.0 & 0.0 \\

HR & 0.0 & 580.3 & 278.7 & 67.4 & 637.3 & 201.2 & 922.0 & 0.0 & 0.0 & 1851.0 \\

HU & 0.0 & 335.0 & 19.7 & 724.0 & 2171.0 & 5777.3 & 128.2 & 3576.4 & 5717.6 & 1171.4 \\

IE & 25.2 & 3650.9 & 216.0 & 21.8 & 5079.3 & 3219.5 & 2590.9 & 0.0 & 0.0 & 2591.4 \\

IT & 0.0 & 10230.2 & 6563.7 & 20073.6 & 59376.1 & 15833.6 & 33110.5 & 0.0 & 0.0 & 17557.1 \\

LT & 0.0 & 532.0 & 0.0 & 81.9 & 0.0 & 3841.5 & 0.0 & 0.0 & 0.0 & 0.0 \\

LU & 0.0 & 114.2 & 30.9 & 124.7 & 604.3 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\

LV & 0.0 & 62.9 & 642.1 & 0.0 & 1767.2 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\

ME & 0.0 & 118.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\

MK & 0.0 & 37.0 & 41.6 & 17.0 & 0.0 & 0.0 & 0.0 & 2497.0 & 0.0 & 0.0 \\

NL & 957.0 & 3491.0 & 0.0 & 4522.0 & 23417.2 & 9734.1 & 16942.4 & 0.0 & 1490.9 & 0.0 \\

NO & 0.0 & 1708.0 & 0.0 & 53.4 & 775.9 & 1885.6 & 0.0 & 0.0 & 0.0 & 0.0 \\

PL & 0.0 & 5762.1 & 14.4 & 562.0 & 562.1 & 2519.3 & 65419.7 & 28503.0 & 0.0 & 985.7 \\

PT & 0.0 & 5172.4 & 1615.5 & 665.4 & 6601.7 & 0.0 & 5321.2 & 0.0 & 0.0 & 0.0 \\

RO & 0.0 & 3243.0 & 870.4 & 1385.7 & 1862.1 & 5565.9 & 4563.6 & 14482.5 & 3933.3 & 250.1 \\

RS & 0.0 & 25.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\

SE & 204.0 & 7097.0 & 1955.9 & 481.0 & 1220.7 & 0.0 & 393.9 & 0.0 & 28884.8 & 6100.0 \\

SI & 0.0 & 0.0 & 861.3 & 251.8 & 1434.5 & 1095.1 & 745.5 & 2860.6 & 2203.0 & 410.2 \\

SK & 0.0 & 0.0 & 641.3 & 533.0 & 1117.2 & 0.0 & 1333.3 & 1472.7 & 5878.8 & 0.0 \\\hline

\end{tabularx}

\end{table}

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