

The benefits of ambitious short-term targets when decarbonising the coupled electricity and heating energy system in Europe

Abstract

Keywords:

Achieving a climate-neutral European Union in 2050 [1] requires meeting the in-between milestones. Although carbon emissions will most probably curb by 20% in 2020, relative to 1990 [2], it is unclear whether this will be the case for the -40% objective settled for 2030. The national energy plans for the coming decade submitted by member states do not add up the necessary reduction to meet the target [3], while in the context of a *European Green Deal* a more ambitious reduction of -55% is currently under discussion [4]. At the same time and led by young people [5], society is claiming for more ambitious climate actions [6]. Electricity generation is expected to spearhead the transition spurred by the dramatic cost reduction of wind [7] and solar photovoltaics (PV) [8, 9]. A vast body of literature shows that a power system based on wind, solar, and hydro generation can supply hourly electricity demand in Europe as long as proper balancing is provided [10–13]. This can be done reinforcing interconnections among neighbouring countries [14] to smooth renewable fluctuations by regional aggregation or through temporal balancing using local storage [15, 16]. Moreover, coupling the power system with other sectors such as heating or transport could provide additional flexibilities facilitating the system operation and simultaneously helping to abate emissions in those sectors [17–19].

CO₂ emissions from heating in residential and services sector show a more modest historical reduction trend than electricity generation (Fig. 1). Nordic countries have been particularly successful in reducing carbon emissions from the heating sector by using sector-coupling strategies (Supplementary Note 3). Denmark, where more than half of the households are connected to district heating systems [20], has shifted the fuel used in Central Heat and Power (CHP) units from coal to biomass and urban waste incineration [21]. The high penetration of heat pumps in Sweden can be explained by a path-dependence process [20] and it is now supported by high CO₂ prices [22] and low electricity taxes.

Greenfield optimisation of the future European energy system, that is, building the system from scratch, shows that sector-coupling decreases the system cost and reduces the need for extending transmission lines due to the ad-

ditional local flexibility brought by heating and transport sectors [18]. Sector-coupling allows further CO₂ reductions before large capacities of storage become necessary, providing more time to develop further storage technologies [23]. Greenfield optimisation is useful to investigate the optimal configuration of the fully-decarbonised system, but it does not provide insights on how to transition towards it. Today's generation fleet and decisions taken in intermediate steps will shape the final configuration. Alternative transition paths for the European power system have been analysed using myopic optimisation, without full foresight over the investment horizon [24–27]. Myopic optimisation results in higher cumulative system cost than optimising the entire transition period with perfect foresight because the former leads to stranded investments [26, 28]. However, the myopic approach is less sensitive to the assumed discount rate and can capture better short-sighted behaviour of political actors and investors.

Here, we use a sector-coupled networked model of the European energy system and myopic optimisation in 5-years steps from now to 2050 to investigate the impact of different CO₂ restriction paths with the same carbon budget. In every time step, the expansion of generation, storage, and interconnection capacities in every country is allowed if it results cost effective under the corresponding global emissions constraint. We show that a transition path with more ambitious short-term CO₂ targets reduces the cumulative system cost and requires more stable build rates, which are beneficial from the point of view of social acceptance, local industry, and jobs creation. Compared to existing transition paths analyses for the European power system [25–27], our research includes the coupling with the heating (and transport) sector. The use of alternative CO₂ reduction paths with constant cumulative emissions is also a novelty of this work.

Integrated Assessment Models (IAMs) with similar spatial resolution than our model, i.e., one node per country, have also been used to model the sector-coupled decarbonization of Europe [1, 8, 29]. However, IAMs typically use a much lower time resolution, *e.g.* using a few time slices to represent a full year [27, 29–32] or considering the residual load duration curve [8, 33]. The hourly resolution

in our model unveils several effects that are critical to the operation of highly renewable systems, such as the solar and wind non-correlations smoothed by the grid, the role of long-term storage, and the system operation during cold spells, *i.e.* a cold week with low wind and solar generation. By using an open model, we ensure transparency and reproducibility of the results in a discipline with high policy relevance such as it is energy modelling [34, 35].

Carbon budget for electricity and heating in Europe.

A remaining global carbon budget of 800 Gigatons (Gt) of CO₂ can be emitted from 2018 onwards to limit the anthropogenic to 1.75°C relative to preindustrial period with a probability of greater than 66% [36]. Different sharing principles can be used to split the global carbon budget into regions and countries [37]. We consider an equal per-capita distribution that translates into a quota of 48 GtCO₂ for Europe. Since the historical quota has been much higher this implies that Europe must be more ambitious than other regions. Assuming that sectoral distribution of emissions within Europe remains at present values, the carbon budget for the generation of electricity and provision of heating in the residential and services sector accounts for approximately 21 GtCO₂, [38] and Supplementary Note 2.

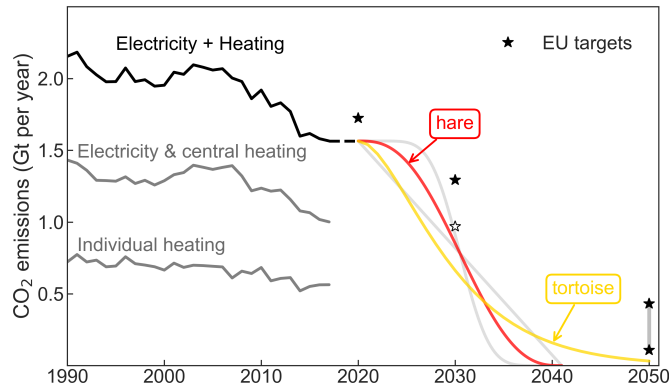


Figure 1: Historical CO₂ emissions from the European power system and heating supply in the residential and services sectors [38]. The various future transition paths shown in the figure have the same cumulative CO₂ emissions, which correspond to the remaining 21 Gt CO₂ budget to avoid human-induced warming above 1.75°C with a probability of greater than 66%, assuming current sectoral distribution for Europe, and equity sharing principle among regions. Black stars indicate committed EU reduction targets, while white star marks under-discussion target.

Stranded assets.

Here we investigate the consequences of following two alternative transition paths. As in Aesop’s fable, the Tortoise pathway represents a cautious approach in which significant emissions reduction are attained in early years. In the Hare pathway, the low initial reduction targets quickly deplete the carbon budget requiring a sharp reduction

later. The two alternative paths arrive at a similar system configuration in 2050. Only in the later years, under heavy CO₂ restriction, balancing technologies significantly appear in the system. They include large storage capacities comprising electric batteries and H₂ storage, methanation, and reinforced interconnections. Cumulative cost for the Tortoise path represents 7,800 billion euros (B€), while the Hare path accounts for 8,100 B€. OCGT and CCGT gas power plants represent the main stranded assets causing the higher cost in the later. The higher CO₂ emissions allowance in 2030 and earlier allow the installation of such plants. However, the drastic change in emissions restriction in subsequent years, avoids the operation of gas power plants. The Europe-averaged utilisation factors shown in Fig. 3 are close to zero from 2040 onwards for the gas units in the Hare path, and they recover less than X% of their cost via market revenues. For both transition paths, even in the initial years the utilisation factor of gas is below 50%. This is a consequence of the role that gas units play as backup technology securing electricity and heat supply when there is a significant deficit of renewable generation, but it is also a consequence of the large capacity of gas recently installed in Europe. The pyramid age of existing electricity generation technologies in Europe, Fig. 4, unveils that most of the ‘younger’ power plants use gas. Since most of the gas capacity in Europe was installed less than 25 years ago, part of this capacity represent a stranded asset during the initial years for both transition paths. Although, infrautilisation of existing generation capacity might be seen as an unnecessary contribution to higher cost of energy it must be remarked that the early retirement of electricity infrastructure has been identified as one of the most cost-effective actions to reduce committed emissions and enable a 2°C-compatible future evolution of global emissions [39].

Build rates and feasibility of transition paths.

During the past decade, several European countries have shown sudden increments in the annual build rate for solar PV, followed by equivalent decrements one or two years later. Italy, Germany, Spain, and UK show clear peaks (see Supplementary Note 4) due to the combination of a fast cost decrease of the technology and unstable regulatory frameworks whose details are country-specific. These peaks are lethal for local businesses. The sudden shrinkage of annual build capacity results into companies bankruptcy and job loss. The Tortoise transition path requires a smoother evolution of build rates which could better accommodate the cultural, political, and social aspects of the transition [40], see Supplementary Note 5. Although none of the build rates required in the Hare path is technological infeasible, the Tortoise path is more compatible to the inertias in the transition such as required time to modify regulatory frameworks or to educate the necessary labour force.

Balancing renewable generation.

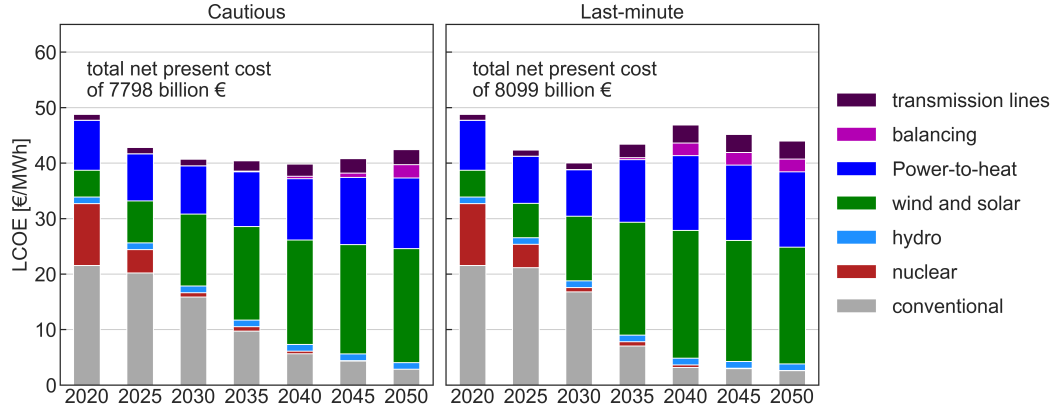


Figure 2: Levelized Cost of Energy (LCOE) for the European electricity and heating system throughout transition paths cautious and last-minute shown in Fig. 1. Conventional includes costs associated with coal, lignite, and gas power plants producing electricity as well as gas consumed in gas boilers and CPH units. Power-to-heat category includes costs associated with heat pumps and heat resistors. Balancing includes cost of electric batteries, H₂ storage and methanation.

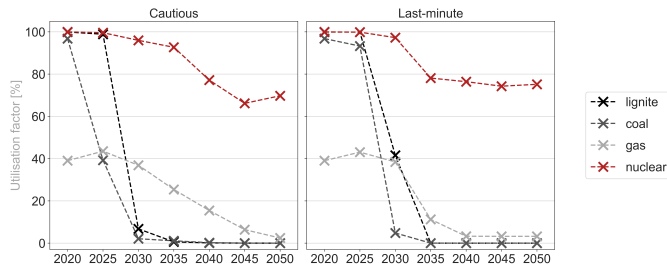


Figure 3: Utilisation factors for lignite, coal, gas, and nuclear power plants throughout transition paths shown in Fig. 1. The figure also depicts the percentage of cost that those technologies recover via market revenues.

TODO: Write paragraph discussing the country-specific mix of primary energy and reference previous results regarding balancing. Add reference to MGA results. Add figure with Fourier power spectra. Discuss also the difference between the 2050 results with the cautious path and using greenfield optimization, using the spatial plot figure in the Supplementary Materials.

Policy incentives are needed.

TODO: Write paragraph discussing evolution of CO₂ price. Include caveat due to not modelling biomass. Add comment on possible alternative to setting CO₂ price such as economic aids for certain technologies. We use CO₂ price here, other measures can also be efficient.

Transitioning without grid expansion.

TODO: Write paragraph discussing the different results obtained when the expansion of transmission lines after 2030 is not allowed.

Early action allows room for decision-making later.

TODO: Run cautious path banning the use of coal and lignite after 2025/2030 and write paragraph discussing the results

The challenging decarbonisation of the heating sector.

TODO: Run cautious path banning new district heating and write paragraph discussing the results

Impact of building retrofitting.

TODO: Run cautious path including path for reduction of heating demand, e.g. 3% per year and write paragraph discussing the results

Coupling the transport sector.

TODO: Run cautious path including path representing the electrification of the transport sector and write paragraph discussing the results.

Heterogeneity among European countries.

TODO: Discuss final system configuration obtained as a result of the path vs. greenfield optimization in 2050.

1. Methods

The system configuration is optimised by minimising annualised system cost in every time step (one every 5 years), under the global CO₂ emissions cap imposed by the transition path under analysis (Fig. 1). This can be considered a myopic approach since the optimisation has no information about the future. The cumulative CO₂ emissions for all the different transition paths is equal to a carbon budget of 21 GtCO₂. In every time step, generation, storage, and transmission capacities in every country are optimised assuming perfect competition and long-term market equilibrium. Besides the global CO₂ emission cap, other constraints such as the demand-supply balance in every node, and the maximum power flowing through the links are imposed to ensure the feasibility of the solution, see Supplementary Note 6.

We use a one-node-per-country network, including 30 countries corresponding to the 28 European Union member states as of 2018 excluding Malta and Cyprus but

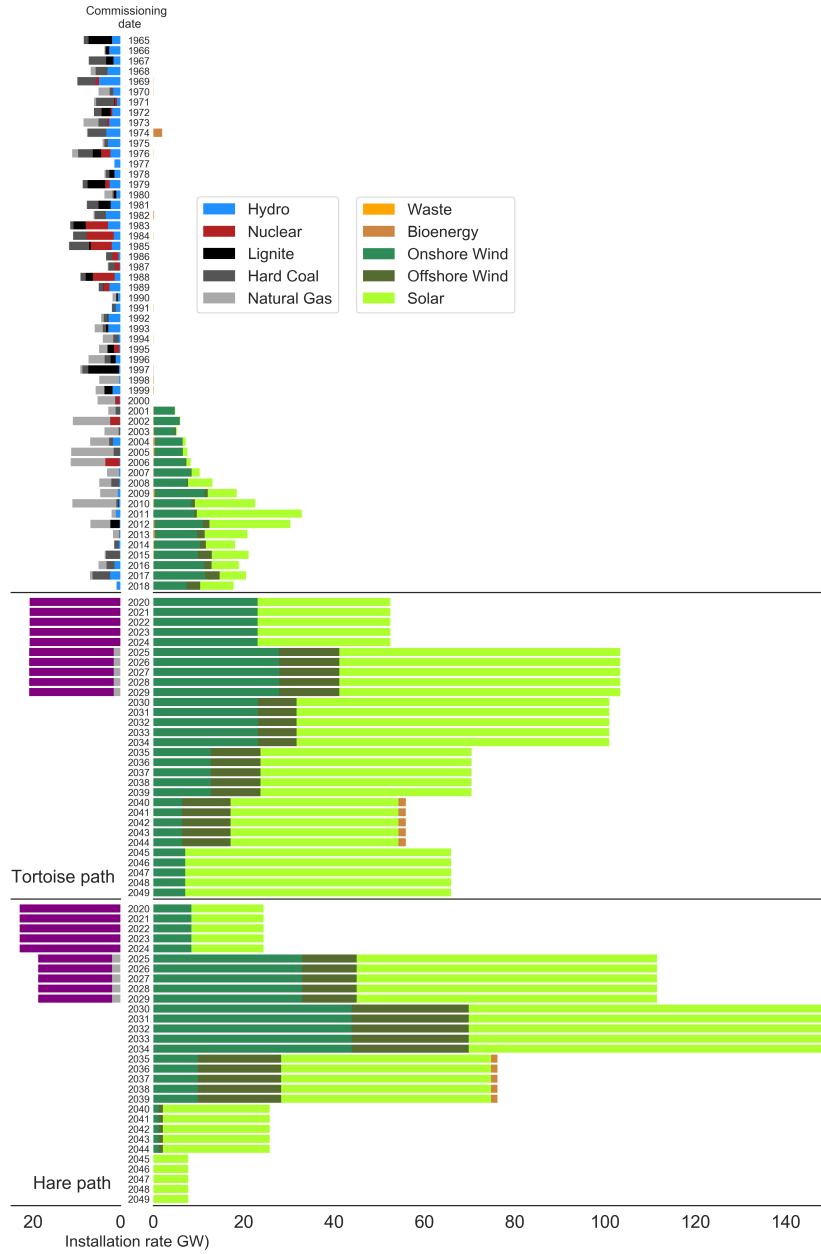


Figure 4: Age distribution of European power plants in operation [41, 42] and required installation in both pathways.

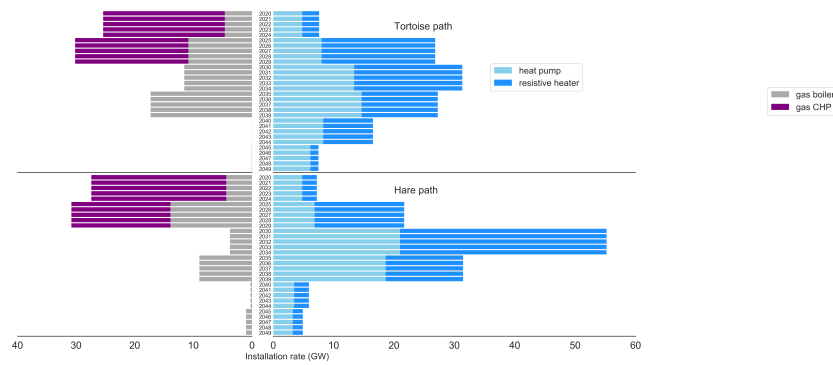


Figure 5: Required heating capacities expansion in both pathways.

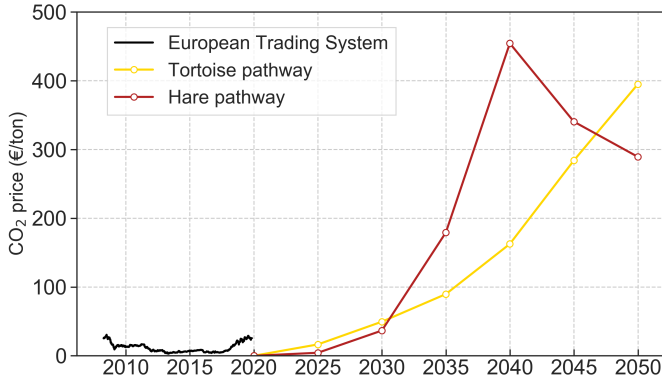


Figure 6: Historical evolution of CO₂ price in the European Trading System [43] and required CO₂ price obtained from the model throughout transition paths shown in Fig. 1

including Norway, Switzerland, Bosnia-Herzegovina, and Serbia (Fig. X in the Supplementary Notes). Countries are connected by High Voltage Direct Current (HVDC) links whose capacities can be expanded if it is cost-effective. In the power sector, electricity can be supplied by onshore and offshore wind, solar photovoltaics (PV), hydroelectricity, Open Cycle Gas Turbines (OCGT), Combined Cycle Gas Turbines (CCGT), Coal, Lignite, and Nuclear power plants, and Combined Heat and Power (CHP) units using gas. Electricity can be stored using Pumped Hydro Storage (PHS), static electric batteries, and hydrogen storage. Hydrogen is produced via electrolyzers and converted back into electricity using fuel cells. Methane can be produced by combining Direct Air Captured (DAC) CO₂ and electrolysed-H₂ in the Sabatier reaction. Heating demand is split into urban heating, corresponding to regions whose population density allows centralised solution, and rural heating where only individual solutions are allowed. Heating can be supplied via central heat pumps, heat resistors, gas boilers, solar collectors, and CHP units for urban regions, while only individual heat pumps, electric boilers, and gas boilers can be used in rural areas. Centralised and individual thermal energy storage can also be installed. A detailed description of all the sector is provided in the Supplementary Note 7.

Costs assumed for the different technologies depend on time (Supplementary Note 8) but not on the cumulative installed capacity since we assume that they will be influenced by the forecast global installation rates and learning curves. The financial discount rate applied to annualise costs is equal to 7% for every technology and country. Although it can be strongly impacted by the maturity of a technology and the rating of a country [44], we assumed European countries to be similar enough to use a constant discount rate. The already installed capacities, *i.e.* existing capacities in 2020 or capacities installed in a previous year whose life time has not concluded, are exogenously included in the model. For every time step, the total system cost includes two components. First, the costs of newly

installed assets, which exactly recover their investment by market revenues. Second, the stranded costs for the exogenously fixed capacities. They are determined as the difference between the annualised costs and the revenues that those assets get from the market. To estimate the cumulative cost of every transition path, the annualised cost for all year are added assuming a social discount rate of 2%. This rate represents the value at which we, as European society, discount investments in far-future years when comparing them with present investments. We have selected a social discount rate of 2%, which is similar to the inflation rate in the European Union, that averaged 2.4% in the past 20 years. It is worth remarking that the cumulative cost remains lower for the last-minute path provided that discount rates lower than 11% are assumed. The CO₂ price is not an input to the model, but a result that is obtained via the Lagrange/Karush-Kuhn-Tucker multiplier associated with the global CO₂ constrain.

2. Data availability and code availability

3. References

- [1] In-depth analysis in support of the Comission Communication COM(2018) 773 A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, Tech. rep. (Nov. 2018). URL https://ec.europa.eu/clima/news/commission-calls-climate-neutral-europe-2050_en
- [2] Total greenhouse gas emissions, trends and projections, EEA. URL <https://www.eea.europa.eu/data-and-maps/indicators/greenhouse-gas-emission-trends-6/assessment-2>
- [3] EU comission appraisal on national energy and climate plans, 2019. URL https://europa.eu/rapid/press-release_IP-19-2993_en.htm
- [4] The European Green Deal. URL https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf
- [5] M. Warren, Thousands of scientists are backing the kids striking for climate change, *Nature* 567 (2019) 291–292. doi:10.1038/d41586-019-00861-z. URL <http://www.nature.com/articles/d41586-019-00861-z>
- [6] A. Rinscheid, R. Wüstenhagen, Germanys decision to phase out coal by 2038 lags behind citizens timing preferences, *Nature Energy* 4 (10) (2019) 856–863. doi:10.1038/s41560-019-0460-9. URL <https://www.nature.com/articles/s41560-019-0460-9>
- [7] E. Lantz, R. Wiser, M. Hand, The Past And Future Cost Of Wind Energy, Tech. rep., NREL (2012). URL <https://www.nrel.gov/docs/fy12osti/53510.pdf>
- [8] F. Creutzig, P. Agoston, J. C. Goldschmidt, G. Luderer, G. Nemet, R. C. Pietzcker, The underestimated potential of solar energy to mitigate climate change, *Nature Energy* 2 (9). doi:10.1038/nenergy.2017.140. URL <https://www.nature.com/articles/nenergy2017140>
- [9] N. M. Haegel, H. Atwater, T. Barnes, C. Breyer, A. Burrell, Y.-M. Chiang, S. D. Wolf, B. Dimmler, D. Feldman, S. Glunz, J. C. Goldschmidt, D. Hochschild, R. Inzunza, I. Kaizuka, B. Kroposki, S. Kurtz, S. Leu, R. Margolis, K. Matsubara, A. Metz, W. K. Metzger, M. Morjaria, S. Niki, S. Nowak, I. M. Peters, S. Philipps, T. Reindl, A. Richter, D. Rose, K. Sakurai, R. Schlattmann, M. Shikano, W. Sinke, R. Sinton, B. J. Stanbery, M. Topic, W. Tumas, Y. Ueda, J. v. d. Lagemaat, P. Verlinden, M. Vetter, E. Warren, M. Werner, M. Yamaguchi, A. W. Bett, Terawatt-scale photovoltaics:

- Transform global energy, *Science* 364 (6443) (2019) 836–838. doi:10.1126/science.aaw1845.
URL <https://science.sciencemag.org/content/364/6443/836>
- [10] E. H. Eriksen, L. J. Schwenk-Nebbe, B. Tranberg, T. Brown, M. Greiner, Optimal heterogeneity in a simplified highly renewable European electricity system, *Energy* 133 (Supplement C) (2017) 913–928. doi:10.1016/j.energy.2017.05.170.
URL <http://www.sciencedirect.com/science/article/pii/S0360544217309593>
- [11] D. P. Schlachtberger, T. Brown, S. Schramm, M. Greiner, The benefits of cooperation in a highly renewable European electricity network, *Energy* 134 (Supplement C) (2017) 469–481. doi:10.1016/j.energy.2017.06.004.
URL <http://www.sciencedirect.com/science/article/pii/S0360544217309969>
- [12] H. C. Gils, Y. Scholz, T. Pregger, D. L. de Tena, D. Heide, Integrated modelling of variable renewable energy-based power supply in Europe, *Energy* 123 (2017) 173 – 188. doi:https://doi.org/10.1016/j.energy.2017.01.115.
URL <http://www.sciencedirect.com/science/article/pii/S0360544217301238>
- [13] T. W. Brown, T. Bischof-Niemz, K. Blok, C. Breyer, H. Lund, B. V. Mathiesen, Response to burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems, *Renewable and Sustainable Energy Reviews* 92 (2018) 834–847. doi:10.1016/j.rser.2018.04.113.
URL <http://www.sciencedirect.com/science/article/pii/S1364032118303307>
- [14] R. A. Rodríguez, S. Becker, G. B. Andresen, D. Heide, M. Greiner, Transmission needs across a fully renewable European power system, *Renewable Energy* 63 (2014) 467–476. doi:10.1016/j.renene.2013.10.005.
URL <http://www.sciencedirect.com/science/article/pii/S0960148113005351>
- [15] M. G. Rasmussen, G. B. Andresen, M. Greiner, Storage and balancing synergies in a fully or highly renewable pan-European power system, *Energy Policy* 51 (2012) 642 – 651. doi:https://doi.org/10.1016/j.enpol.2012.09.009.
URL <http://www.sciencedirect.com/science/article/pii/S0301421512007677>
- [16] F. Cebulla, T. Naegler, M. Pohl, Electrical energy storage in highly renewable European energy systems: Capacity requirements, spatial distribution, and storage dispatch, *Journal of Energy Storage* 14 (2017) 211–223. doi:10.1016/j.est.2017.10.004.
URL <http://www.sciencedirect.com/science/article/pii/S2352152X17302815>
- [17] D. Connolly, H. Lund, B. V. Mathiesen, Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union, *Renewable and Sustainable Energy Reviews* 60 (2016) 1634–1653. doi:10.1016/j.rser.2016.02.025.
URL <http://www.sciencedirect.com/science/article/pii/S1364032116002331>
- [18] T. Brown, D. Schlachtberger, A. Kies, S. Schramm, M. Greiner, Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system, *Energy* 160 (2018) 720–739. doi:10.1016/j.energy.2018.06.222.
URL <http://www.sciencedirect.com/science/article/pii/S036054421831288X>
- [19] M. Child, C. Kemfert, D. Bogdanov, C. Breyer, Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe, *Renewable Energy* 139 (2019) 80–101. doi:10.1016/j.renene.2019.02.077.
URL <http://www.sciencedirect.com/science/article/pii/S0960148119302319>
- [20] R. Gross, R. Hanna, Path dependency in provision of domestic heating, *Nature Energy* 4 (5) 358–364. doi:10.1038/s41560-019-0383-5.
URL <https://www.nature.com/articles/s41560-019-0383-5>
- [21] Regulation and planning of district heating in Denmark, Tech. rep., Danish Energy Agency (2015).
URL https://ens.dk/sites/ens.dk/files/contents/material/file/regulation_and_planning_of_district_heating_in_denmark.pdf
- [22] State and Trends of Carbon Pricing 2019, World Bank Group, Tech. rep. (2019).
URL <https://openknowledge.worldbank.org/handle/10986/31755>
- [23] M. Victoria, K. Zhu, T. Brown, G. B. Andresen, M. Greiner, The role of storage technologies throughout the decarbonisation of the sector-coupled European energy system, *Energy Conversion and Management* 201 (2019) 111977. doi:10.1016/j.enconman.2019.111977.
URL <http://www.sciencedirect.com/science/article/pii/S0196890419309835>
- [24] D. Bogdanov, J. Farfan, K. Sadovskaia, A. Aghahosseini, M. Child, A. Gulagi, A. S. Oyewo, L. Barbosa, C. Breyer, Radical transformation pathway towards sustainable electricity via evolutionary steps, *Nature Communications* 10 (1) (2019) 1–16. doi:10.1038/s41467-019-08855-1.
URL <https://www.nature.com/articles/s41467-019-08855-1>
- [25] G. Pleßmann, P. Blechinger, How to meet EU GHG emission reduction targets? A model based decarbonization pathway for Europe’s electricity supply system until 2050, *Energy Strategy Reviews* 15 (2017) 19–32. doi:10.1016/j.esr.2016.11.003.
URL <http://www.sciencedirect.com/science/article/pii/S2211467X16300530>
- [26] C. Gerbaulet, C. von Hirschhausen, C. Kemfert, C. Lorenz, P. Y. Oei, European electricity sector decarbonization under different levels of foresight, *Renewable Energy* 141 (2019) 973–987. doi:10.1016/j.renene.2019.02.099.
URL <http://www.sciencedirect.com/science/article/pii/S0960148119302538>
- [27] K. Poncelet, E. Delarue, D. Six, W. D’haeseleer, Myopic optimization models for simulation of investment decisions in the electric power sector, in: 13th International Conference on the European Energy Market (EEM), 2016, pp. 1–9. doi:10.1109/EEM.2016.7521261.
- [28] C. F. Heuberger, I. Staffell, N. Shah, N. M. Dowell, Impact of myopic decision-making and disruptive events in power systems planning, *Nat Energy* 3 (8) (2019) 634–640. doi:10.1038/s41560-018-0159-3.
URL <https://www.nature.com/articles/s41560-018-0159-3>
- [29] S. Simoes, W. Nijs, P. Ruiz, A. Sgobbi, D. Radu, P. Bolat, C. Thiel, S. Peteves, The JRC-EU-TIMES model, assessing the long-term role of the SET plan energy technologies.
URL <https://ec.europa.eu/jrc/en/scientific-tool/jrc-eu-times-model-assessing-long-term-role-energy-technologies>
- [30] K. Löffler, T. Burandt, K. Hainsch, P.-Y. Oei, Modeling the low-carbon transition of the European energy system - A quantitative assessment of the stranded assets problem, *Energy Strategy Reviews* 26 100422. doi:10.1016/j.esr.2019.100422.
URL <http://www.sciencedirect.com/science/article/pii/S2211467X19301142>
- [31] C. McGlade, P. Ekins, The geographical distribution of fossil fuels unused when limiting global warming to 2°C, *Nature* 517 (7533) (2015) 187–190. doi:10.1038/nature14016.
URL <https://www.nature.com/articles/nature14016>
- [32] S. Babrowski, T. Heffels, P. Jochem, W. Fichtner, Reducing computing time of energy system models by a myopic approach 5 (1) 65–83. doi:10.1007/s12667-013-0085-1.
URL <https://doi.org/10.1007/s12667-013-0085-1>
- [33] F. Ueckerdt, R. Pietzcker, Y. Scholz, D. Stetter, A. Gianousakis, G. Luderer, Decarbonizing global power supply under region-specific consideration of challenges and options of integrating variable renewables in the REMIND model, *Energy Economics* 64 665–684. doi:10.1016/j.eneco.2016.05.012.
URL <http://www.sciencedirect.com/science/article/pii/S014098831630130X>

- [34] S. Pfenninger, [Energy scientists must show their workings](#), Nature News 542 (7642) 393. doi:10.1038/542393a.
URL <http://www.nature.com/news/energy-scientists-must-show-their-workings-1.21517>
- [35] S. Pfenninger, L. Hirth, I. Schlecht, E. Schmid, F. Wiese, T. Brown, C. Davis, M. Gidden, H. Heinrichs, C. Heuberger, S. Hilpert, U. Krien, C. Matke, A. Nebel, R. Morrison, B. Mller, G. Plemann, M. Reeg, J. C. Richstein, A. Shivakumar, I. Staffell, T. Tröndle, C. Wingenbach, [Opening the black box of energy modelling: Strategies and lessons learned](#), Energy Strategy Reviews 19 63–71. doi:10.1016/j.esr.2017.12.002.
URL <http://www.sciencedirect.com/science/article/pii/S2211467X17300809>
- [36] Global Warming of 1.5°C, Intergovernmental Panel on Climate Change (IPCC), Tech. rep. (2018).
URL <https://www.ipcc.ch/sr15/>
- [37] M. R. Raupach, S. J. Davis, G. P. Peters, R. M. Andrew, J. G. Canadell, P. Ciais, P. Friedlingstein, F. Jotzo, D. P. Vuuren, C. L. Quéré, [Sharing a quota on cumulative carbon emissions](#), Nature Climate Change 4 (10) (2014) 873–879. doi:10.1038/nclimate2384.
URL <https://www.nature.com/articles/nclimate2384>
- [38] National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism , EEA.
URL <https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-15>
- [39] D. Tong, Q. Zhang, Y. Zheng, K. Caldeira, C. Shearer, C. Hong, Y. Qin, S. J. Davis, [Committed emissions from existing energy infrastructure jeopardize 1.5 °c climate target](#), Nature 572 (7769) 373–377. doi:10.1038/s41586-019-1364-3.
URL <https://www.nature.com/articles/s41586-019-1364-3>
- [40] F. W. Geels, B. K. Sovacool, T. Schwanen, S. Sorrell, [Sociotechnical transitions for deep decarbonization](#), Science 357 (6357) (2017) 1242–1244. doi:10.1126/science.aao3760.
URL <https://science.sciencemag.org/content/357/6357/1242>
- [41] [powerplantmatching](#).
URL <https://github.com/FRESNA/powerplantmatching>
- [42] Renewable Capacity Statistics 2019, IRENA.
URL <https://www.irena.org/publications/2019/Mar/Renewable-Capacity-Statistics-2019>
- [43] Carbon price viewer.
URL <https://sandbag.org.uk/carbon-price-viewer/>
- [44] F. Egli, B. Steffen, T. S. Schmidt, [Bias in energy system models with uniform cost of capital assumption](#), Nature Communications 10 (1) 1–3. doi:10.1038/s41467-019-12468-z.
URL <https://www.nature.com/articles/s41467-019-12468-z>