Early decarbonisation of the European energy system pays off

Marta Victoria[a,b,*], Kun Zhu[a], Tom Brown[c], Gorm B. Andresen[a,b], Martin Greiner[a,b]

[a] *Department of Engineering, Aarhus University, Inge Lehmanns Gade 10, 8000 Aarhus, Denmark*
[b] *iCLIMATE Interdisciplinary Centre for Climate Change, Aarhus University*
[c] *Institute for Automation and Applied Informatics (IAI), Karlsruhe Institute of Technology (KIT), Forschungszentrum 449, 76344, Eggenstein-Leopoldshafen, Germany*

Abstract

In a context of increasing public awareness and plummeting costs for wind and solar photovoltaics, discussions on the possibility of increasing CO_2 reduction targets for Europe have started. Here, we model alternative transition paths with equivalent carbon budget for the sector-coupled networked European energy system. We show that realistic costs for wind and solar plus hourly resolution for balancing make climate action with renewables more cost-effective than previously seen. Moreover, we found that ambitious CO_2 reductions in the short term not only trigger a cheaper transition but also incentivise more stable CO_2 prices and build rates for the required new capacities which could be beneficial from the point of view of investors, social acceptance, local economies, and jobs creation.

Keywords: myopic optimisation, carbon dioxide reduction, grid integration of renewable, sector coupling, open energy modelling

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.

A remaining global carbon budget of 800 Gigatons (Gt) of CO_2 can be emitted from 2018 onwards to limit the anthropogenic warming to 1.75°C relative to preindustrial period with a probability of greater than 66% [6]. Different sharing principles can be used to split the global carbon budget into regions and countries [7]. Considering an equal per-capita distribution translates into a quota of 48 $GtCO_2$ 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 $GtCO_2$, [8] and Supplementary Note 2. The budget increases to 33 $GtCO_2$ when transport sector is included.

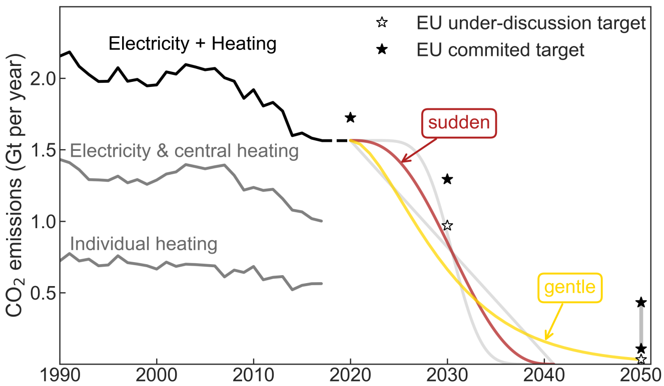

Figure 1: Historical CO_2 emissions from the European power system and heating supply in the residential and services sectors [8]. The various future transition paths shown in the figure have the same cumulative CO_2 emissions, which correspond to the remaining 21 Gt CO_2 budget to avoid human-induced 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 stars mark under-discussion targets.

In this work, we use a sector-coupled networked model of the European energy system and myopic optimisation in 5-years steps from 2020 to 2050 to investigate the impact of different CO_2 reduction 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 realistic costs for wind and solar plus hourly resolution for balancing make climate action with renewables more cost-effective

*Corresponding author
Email address: mvp@eng.au.dk (Marta Victoria)

than previously seen. Furthermore, we found that a transition path with more ambitious short-term CO_2 targets reduces the cumulative system cost and requires more stable CO_2 price and build rates. Our research includes the coupling with heating and transport sectors, which is absent in transition paths analyses for the European power system [9–11], as well as realistic cost assumption for wind and solar PV together with hourly resolution, contrary to most Integrated Assessment Models (IAMs) [12]. 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 [13, 14].

Myoptic optimisation with sector coupling.

Electricity generation is expected to spearhead the transition spurred by the dramatic cost reduction of wind [15] and solar photovoltaics (PV) [12, 16]. 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 [17–20]. This can be done reinforcing interconnections among neighbouring countries [21] to smooth renewable fluctuations by regional aggregation or through temporal balancing using local storage [22–24]. 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 [25–27].

CO_2 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 [28], has shifted the fuel used in Central Heat and Power (CHP) units from coal to biomass and urban waste incineration [29]. The high penetration of heat pumps in Sweden can be explained by a path-dependence process [28] and it is now supported by high CO_2 prices [30] 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 additional local flexibility brought by heating and transport sectors [26]. Sector-coupling allows further CO_2 reductions before large capacities of storage become necessary, providing more time to develop further storage technologies [24]. 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. Transition paths for the European power system have been analysed using myopic optimisation, without full foresight over the investment horizon [9–11, 31]. Myopic optimisation results in higher cumulative system cost than optimising the entire transition period with perfect foresight because the former leads to stranded investments [10, 32]. However, the myopic approach is less sensitive to the assumed discount rate and can capture better short-sighted behaviour of political actors and investors.

Alternative transition paths.

Cumulative costs

Here, we investigate the consequences of following two alternative transition paths. The Gentle path represents a cautious approach in which significant emissions reductions are attained in the early years. In the Sudden path, the low initial reduction targets quickly deplete the carbon budget, requiring a sharp reduction later. As in Aesop's fable, making fun of the cautious tortoise, following the hare strategy and delaying climate action requires a later speeding up that will be more expensive and might be unfeasible.

The two alternative paths arrive at a similar system configuration in 2050. Towards the end of the period, under heavy CO_2 restriction, balancing technologies appear in the system. They include large storage capacities comprising electric batteries and hydrogen storage, and methanation. New lignite, coal or nuclear capacity is installed and, at the end of both paths, conventional includes only gas-fueled power plants, CHP and boilers. Cumulative cost for the Gentle path represents 6,994 billion euros (B€), while the Sudden path accounts for 7,341 B€. The newly built conventional capacity for electricity generation is very modest in both cases, Fig. 3 and Supplementary Note 9. Decarbonising the power system has proven to be cheaper than the heating sector [33]. Consequently, although CO_2 allowances differ, the electricity sector gets quickly decarbonised in both paths. More notable differences appear in new conventional heating capacities, Fig. 4. Regarding new renewable generation and power-to-heat capacities, both paths show major differences.

Stranded assets

Neither of the two paths installs new coal, lignite or nuclear capacity. Part of the existing conventional capacities become stranded assets, in particular, coal, lignite, CCGT (which was heavily deployed in Europe in the early 2000s) and gas boilers. As renewable deploy, utilisation factors for conventional power plants reduce and they do not recover their total costs via market revenues, becoming stranded assets. Throughout the full paths, variable costs for conventional are lower than market revenues so they are expected to remain in operation, Supplementary Note 8.1 Unexpectedly, the sum of costs not recovered via market revenues is similar in both paths. In the Sudden path, high CO_2 prices justify producing up to 220 TWh/a of synthetic methane in 2040. This allows CCGT and gas boilers to keep operating avoiding them to become stranded assets, but the consequence is a higher cumulative system cost, as previously discussed. Although, infrautilisation of existing generation capacity might be seen as an unnecessary contribution to a 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 [34].

Transition smoothness

A timely transition is challenging yet doable. Decarbonising the electricity and heating sector using wind and solar PV requires duplicating the historical maximal build rates, Fig. 3 and Supplementary Note 4. Consequently, attaining higher build rates to also decarbonise transport and industry sectors seems possible.Wind and solar PV provides 45% and 40% respectively of the electricity demand in 2050, complemented by hydro generation. Previously, most IAMs have emphasized the importance of bioenergy or carbon capture and storage and failed to identify the key role of solar PV due to their unrealistically high cost assumptions for this technology, see [12, 37] and Supplementary Note 8.

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 Gentle transition path requires a smoother evolution of build rates which could better accommodate the cultural, political, and social aspects of the transition [38]. It will also allow reaching a stationary situation in which installation and decommissioning rates match.

CO_2 prices much higher than those historically attained in the ETS market are necessary throughout the transition, Fig. 5. The Gentle path requires smoother evolution of CO_2 price which will have a positive impact on investors. Due to its large seasonal variation, decarbonisation of the heating sector is known to require higher CO_2 prices than the electricity sector, mainly to push into the system high-efficiency but capital-expensive technologies such as heat pumps [24, 26]. CO_2 price is only an indication of the price gap between polluting and clean technologies and several policies can be established to fill that gap. Among others, sector-specific CO_2 taxes [30], auctions for renewable capacity that reduce the risk, and consequently the investment cost and LCOE of the technology [39], or regulatory frameworks that incentivise the required technologies such those promoting rooftop PV installations or ensuring the competitiveness of district heating systems.

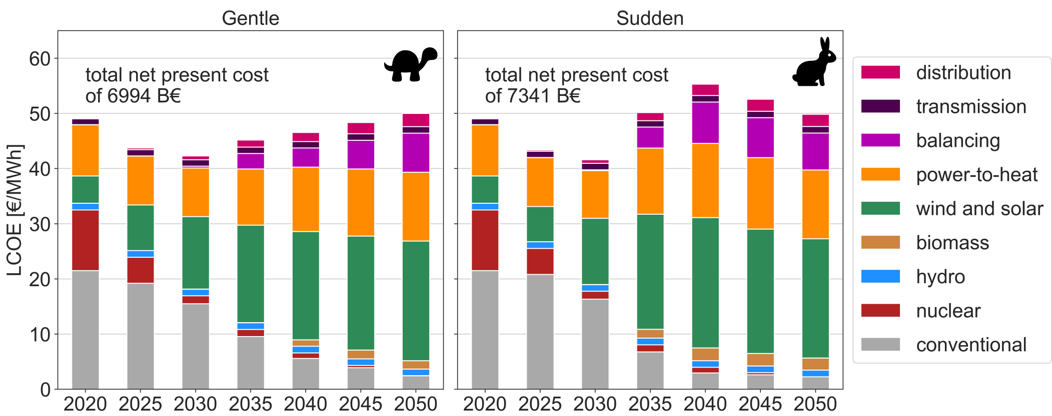

Figure 2: Levelized Cost of Energy (LCOE) for the European electricity and heating system throughout transition paths Gentle and Sudden shown in Fig. 1. Conventional includes costs associated with coal, lignite, and gas power plants producing electricity as well as costs for fossil-fueled boilers and CHP units. Power-to-heat category includes costs associated with heat pumps and heat resistors. Balancing includes cost of electric batteries, H_2 storage, and methanation.

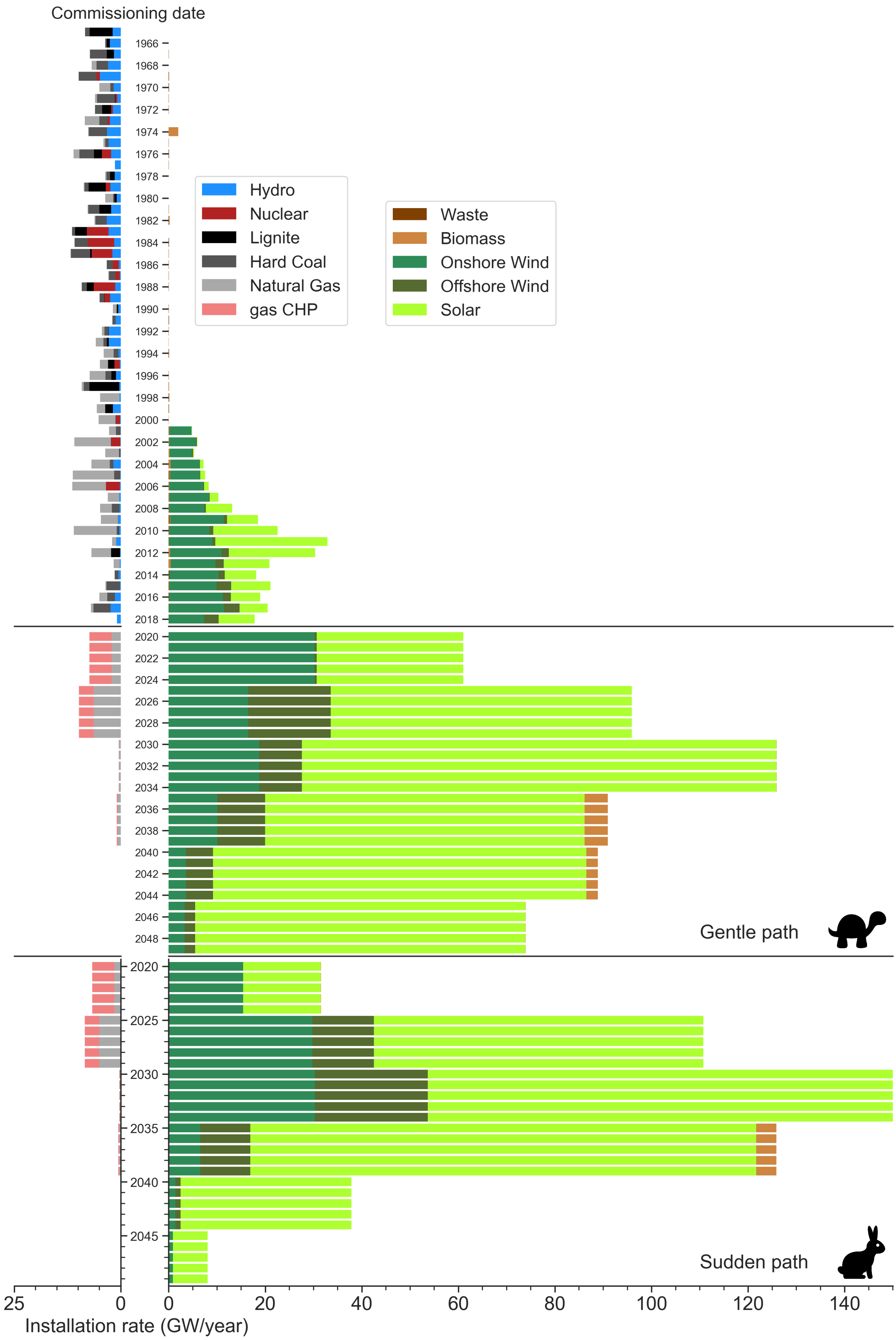

Figure 3: Age distribution of European power plants in operation [35, 36] and required annual installation throughout the Gentle path.

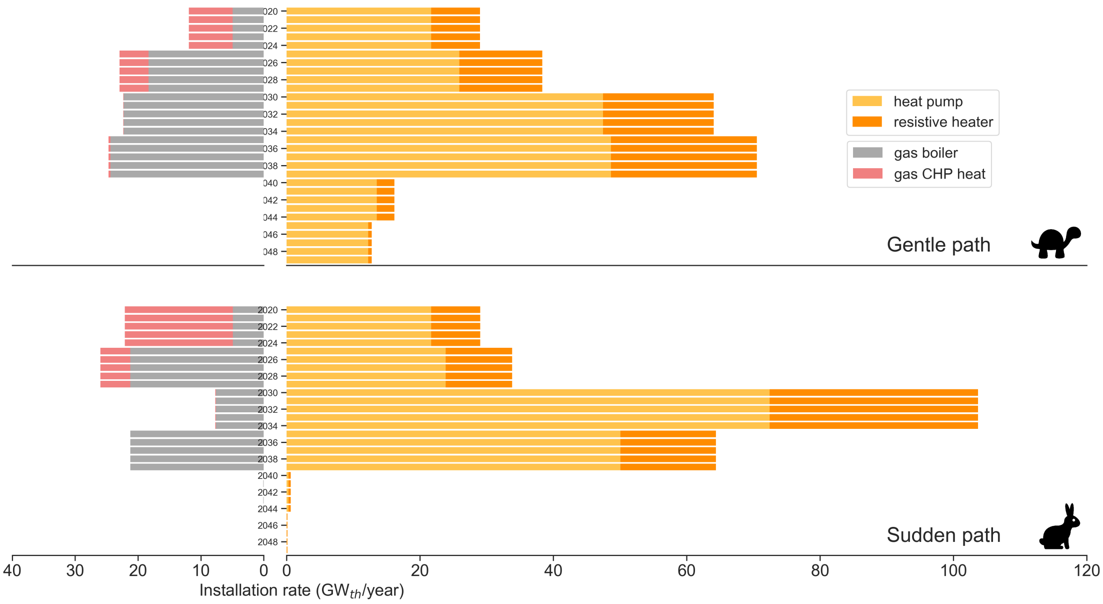

Figure 4: Required expansion of heating capacities in both paths. Maximum heating capacities are shown for CHP plants.

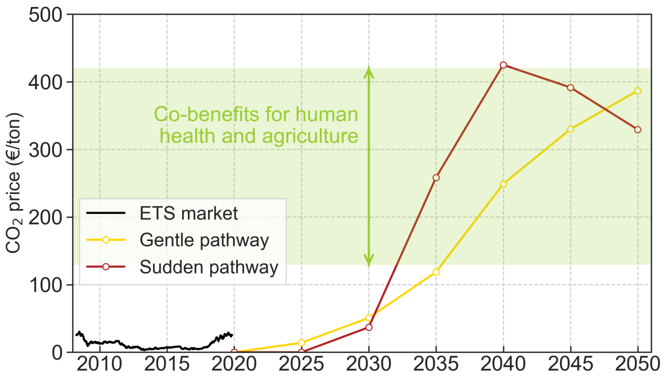

Figure 5: Historical evolution of CO_2 price in the European Trading System [40] and required CO_2 price obtained from the model throughout transition paths shown in Fig. 1. Co-benefits of reducing CO_2 emissions in Europe due to avoided premature mortality, reduced lost work days, and increased crop yields are estimated in the range of 125-425 €/ton CO_2 [41].

Hourly time resolution and renewable balancing. Modelling an entire year with hourly resolution unveils the strong links among renewable generation technologies and balancing strategies. For countries and time steps in which large solar PV capacities are deployed, it is also cost-effective to install large battery capacities to smooth the strong daily solar generation pattern. Conversely, onshore and offshore wind capacities require H_2 storage and reinforced interconnections to balance wind synoptic fluctuations [18, 21, 22, 24]. This can also be appreciated by looking at the dominant dispatch frequencies exposed by the Fourier power spectra of the dispatch time series, Fig. 6. IAMs with similar spatial resolution than our model, *i.e.*, one node per country, have also been used to investigate the sector-coupled decarbonisation of Europe [1, 12, 42]. However, IAMs typically use a much lower time resolution, *e.g.*, using a few time slices to represent a full year [11, 42–45] or considering the residual load duration curve [12, 46]. 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.

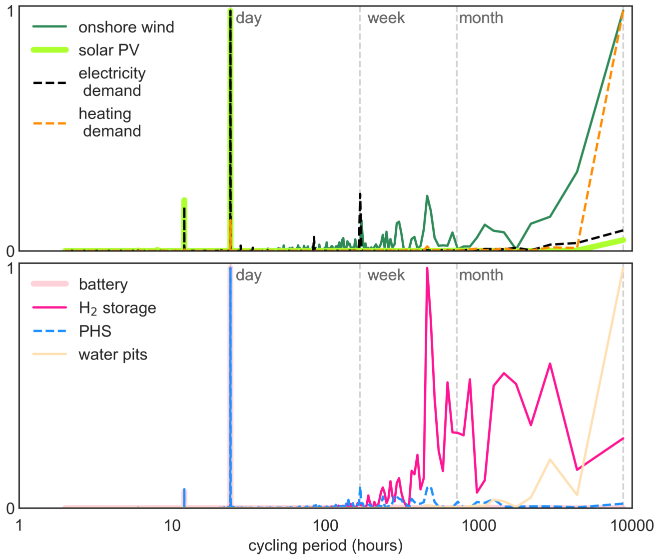

Figure 6: Fourier power spectra of wind and solar PV generation, electricity and heating demand, as well as storage technologies dispatch time series. The time series represent the Europe-aggregated generation/demand for the Gentle path in 2050.

The optimal renewable mix in every country depends on the local resources and the already existing capacities, see Fig. 14 in Supplementary Note 9. Nevertheless, it should be remarked that the analysis of near-optimal solutions has recently shown that country-specific mixes can vary significantly while keeping the total system cost only slightly higher than the minimum [47].

Transport?.

District heating (DH) has proven to be extremely useful to decarbonise the heating sector. It allows cheaper centralised technologies such as heat pumps and CHP units, enables a faster conversion because it is easier to substitute one central heating unit than a myriad of individual domestic systems, and facilitates long-term thermal energy storage, via cheap large water pits, Fig.6, that help to balance the large seasonal variation of heating demand, Supplementary Note 6. When DH is assumed to expand linearly so that it supplies the entire urban heat demand in every country, cumulative system cost for the Gentle path reduces by 259 B€ which roughly offsets the cost of extending and maintaining the DH networks and avoids the additional expansion of gas distribution networks. When a 2% reduction of space heating per year is assumed due to the retrofitting of building stock, cumulative system cost decreases by 858 B€ compared to paths with constant heating demand. When the model is allowed to optimised transmission capacities after 2030 together with the generation and storage assets, the optimal configuration at the end of the paths includes a transmission volume approximately three times larger than that of 2030. Although the cumulative system cost is 79 B€ lower, it is unclear that it compensates the social acceptance issues associated with increasing transmission capacities. No nuclear capacity is installed. For nuclear to be selected in 2050: the nuclear cost must be 25% lower of the reference, renewable cost must remain fixed at 2030 values, transmission capacity must be fixed at today's values. Cuando se añade el transporte, el LCOE no aumenta, porque el aumento de demanda trae felxibilidad en forma de baterías

Conclusions. When comparing alternative transition paths for the European energy system with the same carbon budget, we found that those including a gentle CO_2 reduction path are considered around 300 B€ cheaper than those paths where low targets in the initial period demand a sharper reduction later. These findings could contribute to the on-going discussing regarding increasing CO_2 reduction targets for 2030. Early action not only allows room for decision-making later but it is also found to pay off.

1. Methods

The system configuration is optimised by minimising annualised system cost in every time step (one every 5 years), under the global CO_2 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 CO_2 emissions for all the different transition paths is equal to a carbon budget of 21 $GtCO_2$. In every time step, generation, storage, and transmission capacities in every country are optimised assuming perfect competition and foresight as well as long-term market equilibrium. Besides the global

CO_2 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 5.

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 including Norway, Switzerland, Bosnia-Herzegovina, and Serbia (Fig. 12 in Supplementary Note 9). 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, coal or biomass. Electricity can be stored using Pumped Hydro Storage (PHS), static electric batteries, and hydrogen storage. Hydrogen is produced via electrolysers and converted back into electricity using fuel cells. Methane can be produced by combining Direct Air Captured (DAC) CO_2 and electrolysed-H_2 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 6.

Costs assumed for the different technologies depend on time (Supplementary Note 7) 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, including the country-specific experience on it, and the rating of a country [48], we assumed European countries to be similar enough to use a constant discount rate. For decentral solutions, such as rooftop PV, heat resistors and gas boilers, a discount rate equal to 4% is assumed. The already installed capacities, *i.e.* existing capacities in 2020 or capacities installed in a previous year whose lifetime 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 CO_2 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 CO_2 constrain.

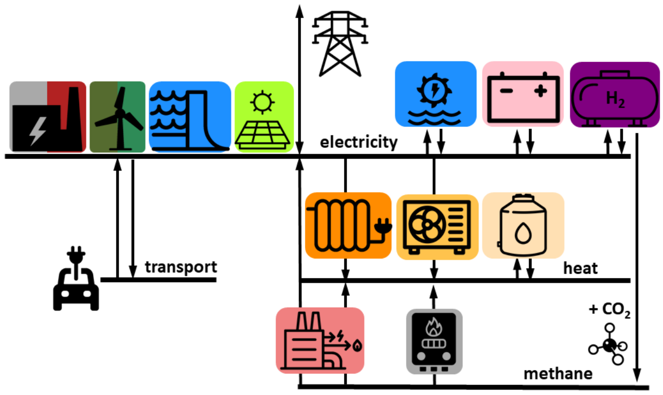

Figure 7: Model diagram representing the main technologies and links in every country.

2. Data availability and code availability

The model is implemented in the open-source framework Python for Power System Analysis (PyPSA) [49]. The model and data used in this paper can be retrieved from XXX

3. Authors contribution

M. Victoria designed the analysis, drafted the manuscript and contributed to the data acquisition, analysis and interpretation of data. K. Zhu contributed to the data acquisition, modelling, analysis and interpretation of data. T. Brown, G. B. Andresen and M. Greiner contributed to the initial idea, findings, and made substantial revisions of the manuscript.

4. Acknowledgements

M. Victoria, K. Zhu, G. B. Andresen and M. Greiner are fully or partially funded by the RE-INVEST project, which is supported by the Innovation Fund Denmark under grant number 6154-00022B. T.B. acknowledges funding from the Helmholtz Association under grant no. VH-NG-1352. The responsibility for the contents lies solely with the authors.

5. References

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] Global Warming of 1.5°C, Intergovernmental Panel on Climate Change (IPCC), Tech. rep. (2018).
URL https://www.ipcc.ch/sr15/

[7] 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

[8] 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

[9] 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

[10] 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

[11] 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.

[12] 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) (Aug. 2017). doi:10.1038/nenergy.2017.140.
URL https://www.nature.com/articles/nenergy2017140

[13] 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

[14] 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. Müller, G. Pleßmann, 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

[15] 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

[16] 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. Schlatmann, 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

[17] 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

[18] 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

[19] 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

[20] 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

[21] 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

[22] 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

[23] 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

[24] 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

[25] D. Connolly, H. Lund, B. V. Mathiesen, Smart Energy Eu-

rope: 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

[26] 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

[27] 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

[28] 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

[29] 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

[30] State and Trends of Carbon Pricing 2019, World Bank Group, Tech. rep. (2019).
URL https://openknowledge.worldbank.org/handle/10986/31755

[31] 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

[32] 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

[33] K. Zhu, M. Victoria, T. Brown, G. B. Andresen, M. Greiner, Impact of CO2 prices on the design of a highly decarbonised coupled electricity and heating system in Europe, Applied Energy 236 (2019) 622–634. doi:10.1016/j.apenergy.2018.12.016.
URL http://www.sciencedirect.com/science/article/pii/S030626191831835X

[34] 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

[35] powerplantmatching.
URL https://github.com/FRESNA/powerplantmatching

[36] Renewable Capacity Statistics 2019, IRENA.
URL https://www.irena.org/publications/2019/Mar/Renewable-Capacity-Statistics-2019

[37] V. Krey, F. Guo, P. Kolp, W. Zhou, R. Schaeffer, A. Awasthy, C. Bertram, H.-S. de Boer, P. Fragkos, S. Fujimori, C. He, G. Iyer, K. Keramidas, A. C. Köberle, K. Oshiro, L. A. Reis, B. Shoai-Tehrani, S. Vishwanathan, P. Capros, L. Drouet, J. E. Edmonds, A. Garg, D. E. H. J. Gernaat, K. Jiang, M. Kannavou, A. Kitous, E. Kriegler, G. Luderer, R. Mathur, M. Muratori, F. Sano, D. P. van Vuuren, Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models, Energy 172 (2019) 1254–1267. doi:10.1016/j.energy.2018.12.131.
URL http://www.sciencedirect.com/science/article/pii/S0360544218325039

[38] 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

[39] E. Vartiainen, G. Masson, C. Breyer, D. Moser, E. R. Medina, Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity, Progress in Photovoltaics: Research and Applications (2017). doi:10.1002/pip.3189.
URL https://onlinelibrary.wiley.com/doi/abs/10.1002/pip.3189

[40] Carbon price viewer.
URL https://sandbag.org.uk/carbon-price-viewer/

[41] T. Vandyck, K. Keramidas, A. Kitous, J. V. Spadaro, R. V. Dingenen, M. Holland, B. Saveyn, Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges, Nature Communications 9 (1) (2018) 1–11, number: 1 Publisher: Nature Publishing Group. doi:10.1038/s41467-018-06885-9.
URL https://www.nature.com/articles/s41467-018-06885-9

[42] 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

[43] 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

[44] 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

[45] 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

[46] F. Ueckerdt, R. Pietzcker, Y. Scholz, D. Stetter, A. Giannousakis, 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

[47] F. Neumann, T. Brown, The Near-Optimal Feasible Space of a Renewable Power System Model, arXiv:1910.01891 (2019).
URL http://arxiv.org/abs/1910.01891

[48] 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

[49] T. Brown, J. Hörsch, D. Schlachtberger, PyPSA: Python for Power System Analysis, Journal of Open Research Software 6 (2018). doi:10.5334/jors.188.
URL https://doi.org/10.5334/jors.188