Impact of myopia and disruptive events in power systems planning

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Relative to the need defined by meeting agreed climate targets, the delayed deployment of low-carbon energy technologies, other than wind and solar, is impeding energy system decarbonisation. Current low-carbon technologies are deemed too expensive, and a strategy of waiting for a "unicorn technology" to appear is considered more effective than moving forward with options available today. The implications of disruptive technology change on the power system transition, particularly under myopic decision making, have not yet been explored or quantified. Here we show that myopic strategies which rely on the eventual manifestation of a "unicorn technology" result in an oversized and underutilised power system if decarbonisation objectives are to be achieved, or one which is far from being decarbonised, even if a "unicorn technology" becomes available. Under perfect foresight, disruptive technology innovation can reduce total system cost by 13 %. However, a strategy of waiting for a "unicorn technology" which does not appear, could result in 40-61 % higher cumulative total system cost by mid-century, under perfect foresight or myopic planning respectively,

compared to deploying currently available low-carbon technologies early on.

Introduction

In 2004, Pacala and Socolow proposed that an economy-wide decarbonisation was possible with existing technologies. It was argued then that "the choice today is between action and delay" [6]. More than a decade later, despite ongoing research and technological advancement, we recognize that with respect to many of the "stabilization wedges", the past years were characterized by hesitation and inaction [7]. In 2004, global CO_2 emissions were 27.4 Gt_{CO_2} [8] requiring 7 wedges for economy-wide decarbonisation according to Pacala and Socolow. In 2016, anthropogenic CO_2 emissions were on the order of 33.4 Gt_{CO_2} [8]. Consequently, mitigation actions to achieve a stabilisation of atmospheric CO_2 concentration at 500 ppm is now estimated to require 19 wedges [9] Investment delays are likely to make the 2°C threshold unattainable [1,4]. Moreover, economic and scientific models indicate that a path of inaction will be far more costly than one of action [5,11].

Taking the example of CCS-equipped power generation as one of the stabilisation wedges, the indecisive approach of policy makers has significantly delayed the technology's deployment [10]. The Intergovernmental Panel on Climate Change (IPCC) for instance, found that the possibility of meeting climate targets without Carbon Capture and Storage (CCS) was uncertain and, if possible, would be 138 % more costly [11]. Typically, high technology costs are cited as the main reason for public sector reluctance [2]. This fails to recognise that fist-of-a-kind projects will be particularly costly owing to the commercial risk associated with new business models, and the cross-chain risks associated with the deployment and operation of the CO_2 transport and storage infrastructure [12,13]. Technology learning and cost reduction is primarily achieved via deployment [15,16]. Whilst CCS is technically mature, public sector investment is required to enable its deployment owing to a lack of commercial structure [14]. In spite of this understanding, the current position is one of waiting for a "unicorn technology" as opposed to taking investment decisions today.

The pressures of increasing population and energy demand, and the retreat from multilateralism could lead to a continuation of business-as-usual, meaning the deployment of conventional renewables, wind and solar, in combination with unabated fossil fuels. At best, this will result in a partial decarbonisation scenario [19]. Avoiding this will require commitment and near term action by the public sector, in contrast to the contemporary approach of business-as-usual whilst hoping for a technological breakthrough.

In this contribution we use modelling and optimisation to evaluate the approach of waiting for a "unicorn technology" with the alternative of taking immediate action, using as performance indicators success in meeting climate targets, and the cost of doing so. In the context of the power sector, we ask the question of whether long-term versus myopic planning can lead to a pathway of decarbonisation and what the system-wide consequences are of failing to deploy the important "wedge" of CCS-equipped power plants and large-scale energy storage, while waiting for a "unicorn technology" which might or might not become available.

Compared to existing studies with Integrated Assessment Models [20–22] which evaluate the effect of planning foresight and technology availability on the global economy via macro scale sensitivity analysis, this work presents a systematic modelling approach to integrating myopia and progressive arrival of information into long-term planning tools. Focussing on power sector investment planning, the purpose of this study is to evaluate the adequacy of the current myopic approach to decarbonisation, and contrasting this with the efficiencies that may be obtained by decisive actions today, which will enable the subsequent incorporation of disruptive technologies, should they arise.

Myopic and long-term decision making in power systems planning

There is a disconnect between the time scales embedded in long-term power system planning tools and the time horizon typically relevant for governments and administrations. The strength of computational tools to evaluate implications of different strategies and guide adaptive and robust decisions making has been recognised in many disciplines, e.g., management science [23] or process systems engineering [24].It is common practice in energy systems modelling to consider the full time horizon in a single simulation or optimisation operation, assuming decisions further into the future can be made with the same precision and certainty as decisions in the near future. This approach becomes particularly problematic when a future disruptive technological advancement is assumed with perfect foresight, although in practice such prescience is impossible.

Figure 1 illustrates the different approaches as perfect foresight, myopia, and myopia with limited foresight. In the latter two cases also the length of the limited foresight (number of time steps) and the overlap influences the results. Whereas in the perfect foresight case, decisions are made for the entire time horizon at once, in a model with limited foresight and overlapping time steps, decisions are typically recursively adjusted in subsequent iterations. The occurrence of a disruptive event (*e.g.*, technology innovation) is anticipated in different planning horizons depending on the foresight options.

[Figure 1 here.]

While some studies on myopic decision making exist [29,33], the effects in combination with disruptive technology innovation have not yet been explored. The present work aims to fill this gap and investigate the consequences of different power sector investment and planning strategies. The supplementary online material provides a review of energy system models with myopic decision making option and describes in detail the modelling approach of this study.

Technology incumbents and unicorns

In a power systems context, we define a unicorn or super technology as a power generation technology which has proven itself on a demonstration scale level but is not yet commercially deployed. We hypothesize the features of such a super technology as being highly flexible in operation, CO_2-free (with reference to the power plant's operation rather than the life-cycle emissions), highly efficient, and capable of providing system ancillary services, at low investment and operational cost, and short construction time. With respect to the maturity level such "unicorns" are distinct from technologies which are available today, *i.e.*, where large scale power plants exist. With reference to the technology readiness levels (TRL) defined by the U.S. Department of Energy [34], technologies classified as "unicorns" fall between TRL 3-7 and technologies available today are at TRL 8-9 (highest readiness level, proven via successful operation). Table 1 provides some examples.

[Table 1 here.]

With regard to the technology's cost reduction potential, incumbents expect little to no future cost reduction, whereas technologies available today and certainly "unicorns" have significant potential for cost reduction and technology learning upon deployment, depending on their maturity level [16,38]. Solar photovoltaic and onshore wind power plants, however, might still experience significant cost reduction [39].

For emerging technologies, it is important to distinguish between those requiring the development of infrastructure and those which can be easily integrated into existing power systems. An example for an infrastructurally intensive technology is CCS-equipped power capacity. The development of a CO_2 transportation network and storage sites is vital to the deployment of large-scale CCS projects. Electric battery storage systems or small modular nuclear reactors (SMR), however, could be imagined to have main manufacturing and supply-chain components abroad (from a local perspective) and could, as deployment becomes economically feasible, be "plugged into" the power system [40].

Scenarios

We analyse the optimal investment timing and deployment volume of power supply and energy storage technologies on the basis of three main scenarios as defined in table 2. The "go" and "wait" strategies are characterised by the readiness to deploy commercially available low-carbon power technologies. In a "go" scenario, the deployment of wind power generators which are able to provide reserve services as a fraction of their installed capacity is possible from 2015, large-scale battery storage from 2020, CCS-equipped coal and gas-fired power plants from 2025, and bioenergy with CCS from 2030. Hence, the "go" scenario describes a world where the implementation of ready to use technologies is made possible and supported by policy institutions, investors, and the public; yet all investment decisions are determined by the cost-minimising program. The "wait" scenarios represent inaction by prohibiting the deployment of these technologies. Finally, the scenarios are characterised by different decarbonisation strategies. A committed decarbonisation refers to a strict CO_2 emission reduction trajectory reaching a zero-carbon power system by 2050. This target is in line with the UK's efforts to achieving the Paris agreement, translated by the Committee on Climate Change into a reduction in carbon intensity to below 100 g_{CO_2}/kWh by 2030 and absolute carbon emissions of 3-6 $Mt_{CO_2-eq.}$/year by 2050 [41]. The market driven approach refers to a carbon price as the single driver to decarbonisation, increasing from £18/t_{CO_2} in 2015 to £220/t_{CO_2} by 2050 [42].

[Table 2 here.]

Scenarios 1a and 1b represent the committed decarbonisation action under perfect foresight and myopic planning conditions. The wait scenarios 2a and 2b rely on market driven decarbonisation and experience a disruptive technological advancement with a "super technology" becoming available. Finally, 3a and 3b refer to wait scenarios where a breakthrough technology remains unavailable, however, a path of committed decarbonisation is followed. The supplementary online material provides more detail on the scenarios and underlying input data.

For this analysis we have parametrised a super technology as Chemical Looping Combustion (CLC) in a Natural Gas Combined Cycle (NGCC) in combination with CCS (hereafter referred to as CLC-CCS). This technology represents an infrastructurally intense case, where initial costs for supply chain development are high but they are substantially reduced for subsequent projects. These cost reductions associated with the transportation and storage network are explicitly modelled via an endogenous cost curve. Analogous to technology learning theory, the cost reductions are modelled as percent reduction per doubling of cumulative installed capacity [16,38].

The findings for the CLC-CCS technology are contrasted with small modular nuclear reactors (SMRs) and an increased availability of energy storage in form of grid-scale lead-acid batteries. SMRs are modelled as "plug-in" technology without significant requirements for infrastructure development [44]. The technology costs are modelled either at a constant level or as a declining cost curve following the learning curve theory [16] at current expert estimates of a 10 % learning rate [17,18]. Battery technologies, though commercially available today *(i.e.*, not in the "unicorn" category), have seen limited grid-scale applications [43,45]. We model a high deployment potential to simulate a regulatory or market push. Costs for lead-acid batteries are assumed to have matured [46], and remain constant over the relevant planning horizon of this study. The scenarios with SMR and increased battery storage availability are discussed in detailed in the supplementary online material.

Main results

The main results and full scenario sets (figures 2, 3, and 4), are discussed for the case of CLC-CCS as a super technology. The potential consequences of a decarbonisation committed "go" strategy are contrasted with a typical "wait" strategy of myopic planning while waiting for a disruptive super technology to become available in figure 2 (left, scenario 1b, 2a, 2b). The impact of myopic planning under committed decarbonisation on the optimal power capacity expansion is shown by comparison of scenarios 1b, 1a, and 3a, in figure 2 (right).

[Figure 2 here.]

No decarbonisation without committed action. Scenario 1b, enables a full decarbonisation of the power sector by 2050 via strict CO_2 emission targets and the deployment of CCS-equipped power plants, advanced wind farms, and battery storage. More than 3 GW of capacity are added to the existing capacity stock in some years and total capacity installed has increased 1.5-fold by 2050 compared to 2015. Myopic power systems planning under a progressive decarbonisation agenda (1a) increases in particular the deployment rate of offshore wind and solar capacity in order to meet emission targets, while the future availability of CCS-equipped power plants is yet unknown (compare figure 2, right, scenario 1b, 1a). The total capacity stock increases 1.6-fold by 2050.

Scenarios 2a and 2b show a 1.4 and 1.2-fold capacity increase under myopic and perfect foresight conditions. The carbon intensity is reduced from 0.38 in 2015 to 0.092 and 0.1 t_{CO_2}/MWh, respectively. Despite the super technology becoming available from 2035 onwards, foregoing the opportunity to deploy existing low-carbon technologies (advanced wind, CCS, grid-scale storage) as soon as possible prohibits full decarbonisation. The CO_2 emission target for 2050 estimated at 3-6 $Mt_{CO_2-eq.}$/yr [41] which is achieved in scenario 1b (3 $Mt_{CO_2-eq.}$/yr) would be missed by 41-48 $Mt_{CO_2-eq.}$/yr in scenario 2a and 2b, respectively.

The myopic planning (2a) leads to a larger total capacity stock compared to long-term foresight (2b) and a smaller volume of the super technology is deployed. This is due to lock-in effects from wind and solar power capacity, as well as electric interconnectors, built in earlier planning years where the future availability of emerging technologies and the super technology is unknown. A key consequence of myopic planning is that the optimal capacity mix shifts towards solutions which are least-cost in the short-term, rather than enabling the development of an efficiently integrated system.

Figure 2 (right, scenario 3a), visualises that a committed strategy to complete decarbonisation without today's commercially available low-carbon technologies, leads to a 2.3-fold increase in total capacity installed by 2050 compared to 2015. This translates to an additional annual average spending of £34 bn. on capital investment to ensure sufficient power supply capacity mainly in form of wind, solar, nuclear, and interconnector capacity. Such an acceleration in capacity build-up, if not physically impossible due to resource constraints, could have economy-wide infrastructural implications.

Asset underutilisation as unwanted side effects. A power system built without foresight and without possibilities to pursue the deployment of new low-carbon technologies (3a) could require a total capacity stock nearly three times higher than annual peak demand. Its inefficient operation becomes apparent in figure 3, which illustrates the annual average utilisation factor for several technologies in the "go" scenarios (1a/1b) and the myopic "wait" scenario (3a). Striving for decarbonisation while minimising total system cost, could steadily reduce the operation of nuclear power plants which are making way for low-cost renewable power generation. Most significantly in the myopic waiting scenario (3a), the operation of inflexible nuclear and intermittent wind power generators collide, as sufficient balancing (in form of abated fossil fuel power plants or battery storage) is missing. The wind and solar curtailment rates due to supply-demand mismatch reach 24% in 2050 in 3a, compared to 7%/5% in 1a/1b, respectively.

[Figure 3 here.]

Waiting means more cost or more carbon. Finally, we compare cumulative total system cost (TSC) for the "go" and "wait" strategy under committed decarbonisation action considering the possibility of a super technology becoming available for deployment in 2035. Our analysis shows that the difference in TSC between hesitation and moving forward is significantly more pronounced than the effect of a super technology on power sector cost (see figure 4). In both decarbonisation scenarios 1 and 3, initially analysed without super technology (see figure 2), its deployment could reduce cumulative TSC in 2050 compared to the respective cases 1b and 3b. A waiting strategy where no super technology becomes available, however, could increase cumulative TSC by 61%, owing to overbuilding and underutilising power supply capacity (compare 1b and 3b). Considering a market driven decarbonisation scenario (2a), waiting could also cost the British economy an additional 283-190 Mt_{CO_2} in cumulative emissions in the period 2015-2050, depending on the availability of the super technology. The costs of removing this CO_2 from the atmosphere in the future are uncertain but likely to be much greater than not emitting in the first place [11]; not to mention the implications for the climate.

[Figure 4 here.]

Other unicorn technologies. Performing this analysis with SMR as the super technology delivers qualitatively analogous results. SMR unit capital costs are high compared to CLC-CCS, £3567/kW in the constant cost case, and £3567/kW - £2126/kW in the cost learning case compared to £2132/kW - £1066/kW for CLC-CCS. The costs for CLC-CCS are assumed to reduce upon deployment accounting for the development of the CO_2 transport and storage network. These results are described in more detail in the SOM. Hence, in a market driven decarbonisation scenario (2a, 2b) SMR deployment is uneconomical and carbon intensity levels are not reduced beyond 0.15 t_{CO_2}/MWh. Under committed decarbonisation action, where SMRs become implementable (analogous to 1b with SMR availability in 2035), an SMR integration up to 9.4 GW (compared to 19.4 GW for CLC-CCS) is part of the least-cost solution. The consideration of capital cost reduction for SMR units at a 10 % learning rate leads to an increased deployment of up to 14.6 GW by 2050. The high availability of grid-scale lead-acid batteries (instead of CLC-

CCS or SMR capacity) is also profitable in such a scenario, increasing the share of intermittent renewable capacity but also balancing capacity requirements. In the case of SMR or increased energy storage availability cumulative TSC by 2050 are 12 % and 14 % higher, respectively. In a "go" scenario, a different capacity deployment strategy can achieve similar CO_2 emission reductions. Hence, this analysis should not be seen as an advocacy for a specific technology but rather a thought experiment on the sensibility of investment action versus delay. The validity of the overall results is further strengthened via a sensitivity analysis on electricity demand and fuel prices which can be found in the SOM.

Conclusion

Myopic planning leads to power system capacity expansion which is inefficient in terms of cost and resources. We have shown that even in an optimistic case of technically and economically highly favourable power technologies becoming available for deployment in 2035, CO_2 emission targets aligned with the Paris agreement for 2050 estimated at 3-6 $Mt_{CO_2-eq.}$/yr could be missed by 41-49 Mt_{CO_2}/yr in 2050, or 190-202 Mt_{CO_2} in cumulative emissions from 2015 to 2050. If in a strategy of waiting, the unicorn technology fails to materialise, total capacity requirements by 2050 are 55-58 % higher and cumulative system cost by 2050 are 40-61 % greater to achieve CO_2 mitigation than if today commercially available low-carbon technologies are deployed early on. If in such a scenario, decarbonisation efforts are not committed, annual CO_2 emission from the power sector could be as high as 83 Mt_{CO_2}/yr in 2050 or reach a cumulative 280 Mt_{CO_2} overshoot by 2050.

To pursue a "go" strategy, institutional and policy influence has to bridge the phase of technology uncertainty [47]. Incumbencies have to be overcome; rather than near-term low-cost options, long-term planning foresight and predictable policies can foster a system-wide optimal pathway.

Future research could investigate the role of time and space representation in energy system models, the effect of the timing of emission targets and specific technology incentives, as well as the uncertainty and optionality around disruptive events. Undoubtedly, technology innovation plays a major role in tackling the energy transition. Nevertheless, a "waiting" strategy could be costly in terms of cost, carbon, and resources. Low-carbon technologies which are available today allow for power sector decarbonisation, and are "wedges" that should not be overlooked.

Methods

A mathematical description of the underlying power systems model, assumptions, data references, and additional methods are presented in detail in the supplementary online material. Input data and the model formulation in GAMS 24.8.3 are also available for download under the MIT (Massachusetts Institute of Technology) open-source license at Zenodo with the identifier *DOI 10.5281/zenodo.1048943* (myopic model formulation will be added in due course).

We have conducted this analysis based on a bottom-up least-cost optimisation model representing the capacity expansion and unit-wise operation of the British power system [38,48,49]. The Electricity Systems Optimisation (ESO) modelling framework offers the possibility to investigate optimal power supply capacity investment timing, system-wide capacity and generation mix, CO_2 emission, and cost, on an hourly granular time scale in 5 yearly intervals from 2015 to 2050. To represent the integration of intermittent renewables and the operation of energy storage technologies a few time slices, as is common practise in many power systems models, are not sufficient [50,51]. We present a temporally detailed, however spatially aggregated sample model for a national scale system in transition. The full hourly time sets of demand, onshore wind, offshore wind, solar PV [52,53], and electricity import price are reduced via k-means clustering and energy preserving profiling as described in Heuberger et al. [38,49]. The model typically has a size of $2.4 \cdot 10^5$ variables, of which $3.2 \cdot 10^4$ are discrete resulting in approximately 45 minutes solution time on an Intel i7-4770 CPU, 3.4 GHz machine with 8 GB RAM with the CPLEX 12.3 solver. The model size and solution time can be further reduced by the replacement of the integer scheduling constraints with their convex hull reformulation. The distinguishing features of the ESO models are a detailed technical and economic representation of technologies, the high time granularity in a long-term planning tool, the modelling of power system reliability and operability, and the option to represent endogenous technology learning [38]. Although frequency and voltage control relate to a sub-hourly time scale, we approximate these options on the hourly time scale to ensure sufficient access to ancillary services. Especially at high levels of intermittent renewable power integration, such services are essential to maintain power system operability and should be explicitly accounted for in power system models [54].

Model assumptions. A set of model assumptions are made to enable computational tractability and sensitivity analyses. The most salient simplifications are: (a) electricity demand and electricity import prices are inelastic, (b) uncertainty in the input parameters is not considered, (c) the electric transmission system is represented as a single-node network, but overall losses are accounted for.

Myopic decision making. The ESO model is implemented as perfect foresight and myopic option with limited foresight. The perfect foresight options treats all structural and operational decisions in a single solution process, whereas the myopic version is implemented in a rolling horizon fashion. Here each 5-yearly planning time is solved iteratively with limited information about future system constraints.

Disruptive technological change. We introduce a technology maturity parameter indicating the year in which a technology becomes available for commercial deployment. The rolling horizon optimisation approach allows for iterative updating of the technology maturity parameter. Under myopic decision making this procedure is able to simulate the sudden availability of a new technology.

Data Availability The model formulation and data that support the findings of this study are available at Zenodo with the identifiers *DOI 10.5281/zenodo.1048943* and *DOI ...* (myopic model formulation will be added in due course).

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Authors Contribution NMD conceived and led this study. CFH developed the model formulation, implementation, and carried out the analyses. CFH wrote the paper, NMD, IS, and NS contributed to the text and edited the paper.

References

1. Luderer, G. Economic mitigation challenges: How further delay closes the door for achieving climate targets. *Environ. Res. Lett.* **8**, 034033 (2013)

2. House of Commons, United Kingdom. The future of carbon capture and storage in the UK: Government Response to the Committee's Second, Appendix: Government response. `https://publications.parliament.uk/pa/cm201617/cmselect/cmenergy/497/49704.htm#footnote-001` (2017)

3. Rockström, J. *et al.* The Worlds Biggest Gamble. *Earth's Future* **4**, 465-470 (2016)

4. Dessens, O.; Anandarajah, G.; Gambhir, A. Review of existing emissions pathways and evaluation of decarbonisation rates. `http://tinyurl.com/ybgyemql` (2014)

5. Gambhir, A. Assessing the Feasibility of Global Long-Term Mitigation Scenarios. *Energies* **10**, 89 (2017)

6. Pacala, S. & Socolow, R. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science* **305**, 968-972 (2014)

7. Stern, N. H. Why are we waiting? The logic, urgency, and promise of tackling climate change (MIT Press, 2015)

8. BP plc. Statistical Review of World Energy. `http://tinyurl.com/yaok2dzo` (2017)

9. Davis, S., Cao, L., Caldeira, K., Hoffert, M. I. Rethinking wedges. *Environ. Res. Lett.* **8**, 011001 (2013)

10. Reiner, D. M. Learning through a portfolio of carbon capture and storage demonstration projects. *Nature Energy* **1**, 15011 (2016)

11. Edenhofer, O. *et al*. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Technical Summary (2014)

12. International Energy Agency. Energy Technology Perspectives 2017. `http://www.iea.org/etp/` (2017)

13. Bassi, S. *et al.* Bridging the gap: improving the economic and policy framework for Carbon Capture and Storage in the European Union. `http://admin.indiaenvironmentportal.org.in/files/file/briding%20the%20gap.pdf` (2015)

14. Hackett, L. Commercialisation of CCS: What needs to happen? http://industriamundum.com/wp-content/uploads/2016/12/IChemE-CCS-Commercialisation-L.-A.-Hackett-2016.pdf (2016)

15. Kahouli-Brahmi, S. Technological learning in energyenvironmenteconomy modelling: A survey. *Energy Policy* **36**, 138-162 (2008)

16. Rubin, E. S., Azevedo, I. M. L., Jaramillo, P., Yeh, S. A review of learning rates for electricity supply technologies. *Energy Policy* **86**, 198-218 (2015)

17. Abdulla, A., Azevedo, I. L., Morgan, M. G. Expert assessments of the cost of light water small modular reactors. *PNAS* **110**, 96869691 (2013)

18. Roulstone, T. SMRs will transform the nuclear industry. http://www.buildoffsite.com/presentation/next-generation-infrastructure/?view=1394 (2016)

19. Heuberger, C. F., Staffell, I., Shah, N., Mac Dowell, N. Quantifying the value of CCS for the future electricity system. *Energy Environ. Sci.* **9**, 2497-2510 (2016)

20. Tavoni, M., de Cian, E., Luderer, G., Steckel, J. C., Waisman, H. The value of technology and of its evolution towards a low carbon economy *Climatic Change* **14**, 39-57 (2012)

21. Bertram, C. et al. The value of technology and of its evolution towards a low carbon economy *Technological Forecasting and Social Change* **90**, 62-72 (2015)

22. Pye, S., Li, F. G. N., Price, J., Fais, B. Achieving net-zero emissions through the reframing of UK national targets in the post-Paris Agreement era *Nat. Energy* **2**, 17024 (2017)

23. Lempert, R. J., Groves, D. G., Popper, S. W., Bankes, S. C. A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios *Management Science* **53**, 514-528 (2006)

24. Bertsimas, D., Litvinov, E., Sun, X. A., Zhao, J., Zheng, T. Adaptive Robust Optimization for the Security Constrained Unit Commitment Problem *IEEE Transaction on Power Systems* **28**, 52-63 (2013)

25. Levin, N., Tishler, A., Zahavi, J. Time Step vs. Dynamic Optimization of Generation-Capacity-Expansion Programs of Power Systems. *Operations Research* **31**, 891-914 (1983)

26. U.S. Energy Information Administration. Model Documentation Report: System for the Analysis of Global Energy Markets (SAGE), Model Documentation. `http://www.globaloilwatch.com/reports/mdr-system-analysis-global-energy-markets-eia-082003.pdf` (2003)

27. Martinsen, D., Krey, V., Markewitz, P., Vögele, S. A Time Step Energy Process Model for Germany - Model Structure and Results. *Energy Studies Review* **14**, 33-57 (2014)

28. Li, F. G. N., Strachan, N. BLUE: Behaviour Lifestyles and Uncertainty Energy model, Online Documentation Revision 03. `https://www.ucl.ac.uk/energy-models/models/blue/blue-documentation-feb-2017` (2017)

29. Li, F. G. N. Actors behaving badly: Exploring the modelling of non-optimal behaviour in energy transitions. *Energy Strategy Reviews* **15**, 57-71 (2017)

30. Waisman, H., Guivarch, C., Grazi, F., Hourcade, J. C. The IMACLIM-R model: Infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight. *Climatic Change* **114**, 101-120 (2012)

31. Keppo, I., Strubegger, M. Short term decisions for long term problems The effect of foresight on model based energy systems analysis. *Energy* **35**, 2033-2041 (2010)

32. Babrowski, S., Heffels, T., Jochem, P., Fichtner, W. Reducing computing time of energy system models by a myopic approach. *Energy Systems* **5**, 65-83 (2014)

33. Fuso Nerini, F., Keppo, I., Strachan, N. Myopic decision making in energy system decarbonisation pathways. A UK case study. *Energy Strategy Reviews* **17**, 19-26 (2017)

34. U.S. Department of Energy. Technology Readiness Assessment Guide. https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04a (2011)

35. Hanna, R., Gross, R., Speirs, J., Heptonstall, P., Gambhir, A. Innovation timelines from invention to maturity: A rapid review of the evidence on the time taken for new technologies to reach widespread commercialisation. http://www.ukerc.ac.uk/programmes/technology-and-policy-assessment.html (2015)

36. Bento, N., Wilson, C. Measuring the duration of formative phases for energy technologies. *Environmental Innovation and Societal Transitions* **21**, 95-112 (2016)

37. Loftus, P. J., Cohen, A. M., Long, J. C. S., Jenkins, J. D. A critical review of global decarbonization scenarios: what do they tell us about feasibility? *Wiley Interdisciplinary Reviews: Climate Change* **6**, 93-112 (2015)

38. Heuberger, C. F., Rubin, E. S., Staffell, I., Shah, N., Mac Dowell, N. Power Capacity Expansion Planning Considering Endogenous Technology Cost Learning, *Applied Energy* **204**, 831-845 (2017)

39. International Renewable Energy Agency. The power to change: Solar and wind cost reduction potential to 2025. http://www.irena.org/DocumentDownloads/Publications/IRENA_Power_to_Change_2016.pdf (2016)

40. Iyer, G., Hultman, N., Fetter, S., Kim, S. H. Implications of small modular reactors for climate change mitigation. *Energy Economics* **45**, 144-154 (2014)

41. Committee on Climate Change. UK climate action following the Paris Agreement. https://www.theccc.org.uk/wp-content/uploads/2016/10/UK-climate-action-following-the-Paris-Agreement-Committee-on-Climate-Char pdf (2016)

42. Committee on Climate Change. Power sector scenarios for the fifth carbon budget. https://www.theccc.org.uk/wp-content/uploads/2015/10/Power-sector-scenarios-for-the-fifth-carbon-budget.pdf (2015)

43. Poullikkas, A. Techno-economic investigation of a chemical looping combustion based power plant. *Faraday Discussions* **192**, 437-457 (2016)

44. Atkins for Energy Technology Institute LLP. Power Plant Siting Study: Project Summary Report. https://d2umxnkyjne36n.cloudfront.net/insightReports/PPSS-Summary-Report-with-Peer-Review.pdf?mtime=20160908160324 (2015)

45. Doughty, D. H., Butler, P. C., Akhil, A. A., Clark, N. H., Boyes, J. D. Batteries for Large-Scale Stationary Electrical Energy Storage. *The Electrochemical Society* 49-53 (2010)

46. Schmidt, O., Hawkes, A., Gambhir, A., Staffell, I. The future cost of electrical energy storage based on experience rates. *Nature Energy* **2** 17110 (2017)

47. Jacobsson, S., Bergek, A. Transforming the energy sector: The evolution of technological systems in renewable energy technology. *Industrial and Corporate Change* **13**, 815-849 (2004)

48. Heuberger, C. F., Staffell, I., Shah, N., Mac Dowell, N. Levelised Value of Electricity - A Systemic Approach to Technology Valuation. *26th European Symposium on Computer Aided Process Engineering* **38**, 721-726 (2016)

49. Heuberger, C. F., Staffell, I., Shah, N., Mac Dowell, N. A systems approach to quantifying the value of power generation and energy storage technologies in future electricity networks. *Computers & Chemical Engineering* in press, (2017)

50. Merrick, J. H. On representation of temporal variability in electricity capacity planning models. *Energy Economics* **59**, 261-274 (2016)

51. Pfenninger, S., Staffell, I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy* **114**, 1251-1265 (2016)

52. Staffell, I., Pfenninger, S. Using Bias-Corrected Reanalysis to Simulate Current and Future Wind Power Output. *Energy* **114**, 1224-1239 (2016)

53. Pfenninger, S. Dealing with multiple decades of hourly wind and PV time series in energy models. *Applied Energy* **197**, 1-13 (2017)

54. Clack, C. T. M. *et al.* Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. *PNAS* **114**, 6722-6727 (2017)

55. Gonzalez-Longatt, F., Chikuni, E., Stemmet, W., Folly, K. Effects of the synthetic inertia from wind power on the total system inertia after a frequency disturbance. *Power Engineering Society Conference and Exposition in Africa* DOI:10.1109/PowerAfrica.2012.6498636 (2012)

56. Teng, F., Trovato, V., Strbac, G. Stochastic Scheduling With Inertia-Dependent Fast Frequency Response Requirements. *IEEE Trans. Power Syst.* **31**, 1557-1566 (2016)

Incumbents	Available today	"Unicorns"
Nuclear, coal, oil and natural gas-based, pumped hydro, run-of-river hydro, onshore wind, solar photovoltaic	Offshore/advances wind, battery storage, CCS-equipped power generation, bioenergy (+CCS), geothermal	Advanced batteries, small modular nuclear reactor (SMR), advanced CCS-equipped power generation, hydrogen + fuel cells, nuclear fusion

Table 1: Classification of several power generation and storage technologies by maturity level. 'Incumbents' refers technologies which have been deployed for more than 50 years; 'available today' are proved technologies which have been deployed on a large scale for less then 20 years; 'unicorns' are high potential technologies at lab scale or pilot plant scale today. Advanced wind turbines refer to power plants which are able to provide ancillary services, e.g., capacity reserve, synthetic inertia [55,56]

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		Tech deployment	Foresight	Decarbonisation	Super Tech
1	a	go	myopic	committed	no
	b	go	perfect	committed	no
2	a	wait	myopic	market driven	yes
	b	wait	perfect	market driven	yes
3	a	wait	myopic	committed	no
	b	wait	perfect	committed	no

Table 2: Scenario definition. From all possible combinations of scenario characteristics the ones most relevant to this study were chosen. More detail can be found in the supplementary online material. Note scenarios 1b and 3b are also analysed with "super technology" availability in figure 4.

Figure 1 Schematic of different model foresight options with disruptive technology becoming available in a later time step. In the 'myopic, limited foresight' case, decisions for the overlapping time frame are recursively taken in the latter model iteration. Note that the foresight time horizon does not necessarily coincide with the model decision time horizon.

Figure 2 Bar chart on optimal capacity mix from 2015 to 2050 for scenarios 1b, 1a, 3a from left to right (left chart), and 1b, 2a, 2b (right chart). Scenario set 1 refers to a "go" strategy with regards to technology deployment (advanced wind turbines, CCS-equipped power generation, and energy storage capacity are promoted) under committed decarbonisation efforts; scenarios 2 and 3 are defined as "wait" strategies, the first under market driven decarbonisation the latter under committed decarbonisation. It is distinguished between perfect foresight and myopic planning, denoted by b and a, respectively. Curves of system carbon intensity refer to respective right hand side axes. Integrated gasification combined cycle (IGCC), combined cycle gas turbine (CCGT), open cycle gas turbines (OCGT), carbon capture and storage (CCS), post-combustion CCS (PostCCS), bio-energy with CCS (BECCS), photovoltaic (PV), high voltage electric interconnector (Interconn.), chemical looping combustion (CLC).

Figure 3 Annual average utilisation factor for power generation technologies under perfect foresight and myopic planning from 2015 to 2050. The "foresight-go" scenario refers to a perfect foresight planning under a “go” strategy with regards to technology deployment (advanced wind turbines, CCS-equipped power generation, and energy storage capacity are promoted) and full decarbonisation by 2050 (1b, full lines). The “myopic-go” scenario (1a, dashed lines) is defined as the above but under myopic foresight. The “myopic-wait” scenario does not enable the deployment of the technologies mentioned above (3a, dotted lines).

Figure 4 Cumulative total system cost for scenario 1b, 3b, and 1b and 3b with a “super technology” becoming available in 2035. Scenario 1b refers to perfect foresight planning under a “go” strategy with regards to technology deployment (advanced wind turbines, CCS-equipped power generation, and energy storage capacity become available) and full decarbonisation by 2050. Scenario 3b does not enable the deployment of the above mentioned technologies. The “super technology” refers to a dispatchable, zero-CO_2 emitting, and inexpensive technology which is parametrised as chemical looping combustion with natural gas combined cycle and CO_2 capture and sequestration.