Does cost optimisation approximate the real-world energy transition? Retrospective modelling and implications for modelling the future

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Abstract

Widely used bottom-up energy system models are based on the minimisation of the discounted total system costs. This conference paper reviews the origins of this rationale and questions to what extent does cost optimisation approximate the real-world transition. Using the bottom-up D-EXPANSE model for the power system of the United Kingdom, the historic transition between 1990 and 2010 is modelled retrospectively. The cost-optimal transition pathway turns out to be significantly different from the transition that actually occurred. The deviation of 17% in terms of cumulative total system costs between 1990 and 2010 is observed. This is a novel and thought-provoking finding for the bottom-up modelling community because it shows that cost-optimisation does not necessarily approximate the real-world transition. Therefore, the implications of allowing such a high deviation from cost-optimality in modelling the UK future power system transition (2010-2050) are explored. Up to 17% deviation leads to significantly different transition pathways in terms of technology deployment. More caution is thus needed when interpreting the results of the existing bottom-up models that are based solely on cost optimisation. Further research is essential on systematically exploring the near-optimal transition pathways.

1. Introduction

Widely used bottom-up energy system models are based on the minimisation of the discounted total system costs [1, 2]. These bottom-up models evaluate the cost-optimal energy system transition under numerous parametric and structural assumptions. Parametric assumptions are the quantitative modelling inputs, such as technology costs, resource constraints or energy service demand levels, and have been addressed through stochastic approaches or uncertainty analyses, e.g. [3]. Examples of the structural assumptions include cost optimisation, perfect foresight, linearity, reference energy system and many others. While some of these structural assumptions, such as perfect foresight [4], have been addressed, in the recent years there is a growing concern about the cost-optimality assumption [5-8]. Previous

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bottom-up energy system modelling efforts [5-8] showed that, when the cost-optimality assumption is relaxed by exploring near-optimal energy transition pathways (energy scenarios), these resulting pathways may be significantly different in their attributes, such as technology deployment, investment needs etc. In other words, the results of the bottom-up energy system models are highly sensitive to the cost-optimality assumption, which in turn tends to gloss over a range of very different pathways that have a similarly good performance with respect to the total system costs.

While several studies systematically analysed the near-optimal energy system transition pathways for the future [5-8], they commonly assumed a deviation of 10% to 30% in total system costs [5-7, 9-13]. However, there is little evidence of what level of deviation from cost-optimality could be realistic. Empirical evidence from interviews in Switzerland, reported in [9], showed that various stakeholders would accept 30% higher total system costs if the system would match other goals, for instance, related to environmental concerns or energy independence. However, this is the only evidence of its kind and, as it comes from the stated preferences approach, it may still not be an accurate representation of the potential real-world developments.

By means of retrospective modelling, this conference paper therefore investigates to what extent cost optimisation approximates the real-world energy system transition. For this purposes, the D-EXPANSE model (Dynamic version of EXploration of PAtterns in Near-optimal energy ScEnarios) of the power sector of United Kingdom (UK) is used [7]. As the D-EXPANSE model is currently used for modelling the future transition from 2010 to 2050, it is assumed that a similar type of modelling exercise is being conducted in 1990 for the period of 1990-2030. In order to minimise the effects of the parametric uncertainty in data on costs, energy demand etc., the actual historic data are reproduced as closely as possible and are fed into the model for the period 1990-2010. Then, the cost-optimal pathway for the period 1990-2030 is evaluated and compared to the real-world transition from 1990 to 2010 in order to estimate the actual deviation from cost-optimality. While some retrospective studies have been done before [14, 15], this analysis is the first of its kind as it is applied to the bottom-up energy system models and focuses specifically on the structural assumption of cost-optimality. Based on the findings about the retrospective deviation from cost-optimality, the implications for modelling the UK power system transition in the future from 2010 to 2050 are then analysed.

This conference paper is structured as follows: Section 2 provides a short review of the origins of cost optimisation rationale in bottom-up energy system models, Section 3 introduces the D-EXPANSE model and its data for the retrospective and future analyses, Section 3 presents the results and Section 4 discusses the key finds and lists future research needs.

2. Review of the cost optimisation rationale in energy system models

While the practice of cost optimisation is at the core of engineering, there are two interlinked arguments for optimisation in bottom-up energy system models: the social planner's approach and the partial equilibrium assumption. The social planner's approach originates in welfare economics and assumes that there is a single decision maker, who aims to achieve the best outcome for the society as a whole. Such an outcome is reached by maximising the sum of the energy suppliers' and the consumers' surpluses. The surplus maximisation is transformed into an equivalent of minimisation of the total system costs that represent the negative of the surplus [1]. In reality, however, such a social planner does not exist. Energy system, especially with its liberalised market logic and multiple heterogeneous energy suppliers and consumers, is a highly complex system. As Ottino [16] argues, such complex systems can hardly be steered to a single desired (optimal) state anyway. Another rationale for cost optimisation in energy system models originates from the partial equilibrium assumption. The supply-demand equilibrium is reached when the total surplus, as in the social planner's approach, is maximised [1]. However, the equilibrium assumption in economics is easily contested too because the real-world systems are not necessarily at equilibrium due to market heterogeneity, imperfect information etc. [17].

If the energy system optimisation is conducted only in terms of the total system costs, it does capture multiple other objectives that are relevant [5, 11, 12]. While some objectives could be included through optimisation constraints, multi-objective optimisation and evaluation of the Pareto-optimal frontier, it is still hard to steer the complex system towards a single desired state or frontier [16]. Furthermore, some types of objectives that exist in realty cannot be even modelled [5, 11, 12]. Therefore, the cost-optimising rationale and, generally, optimising rationale of energy system models can be contested, especially if the modelling results are highly sensitive to it [5-7]. A comprehensive review of the reasons why near-optimal energy pathways can be at least as probable and reasonable as the cost optimal one is provided in [6].

At the same time, even if the real-world energy system may not evolve in a cost-optimal way, costs are one of the key elements of the transition. Despite all the real-world complexities, it is meaningful to assume that the energy system will not evolve in the most expensive and irrational way. Instead, the actual transition will likely be somewhere close to the cost-optimal pathway, but not necessarily exactly the optimal one [6, 7]. While the afore-mentioned modelling studies allow 10% to 30% deviations in the total system costs [5-7, 9-13], there is little real-world evidence, with the exception of [9], that shows what level of deviation is reasonable. This conference paper, therefore, investigates for the first time to what extent does the rationale of cost optimisation approximate the real-world energy system transition.

3. The model and data

This section describes the D-EXPANSE model, as applied to analysing the UK power system transition retrospectively (1990-2030) and in the future (2010-2050).

3.1. D-EXPANSE model structure and validation

The D-EXPANSE model (Dynamic version of EXploration of PAtterns in Near-optimal energy ScEnarios) is the dynamic extension [7, 18] of the earlier static EXPANSE model [6]. D-EXPANSE has the structure of the conventional, bottom-up, technology rich, cost optimisation energy system model with perfect foresight [1, 2, 19, 20]. In addition, it has two state-of-the-art features. First, it systematically explores the near-optimal energy pathways in line with [5-8]. Second, it generates large numbers of near-optimal pathways in order to draw patterns from them in line with [13, 21-24]. Instead of using varying input parameters to produce multiple pathways as [13, 22-24], D-EXPANSE uses one set of deterministic input parameters. The multiple pathways are generated by allowing a deviation from the cost-optimality assumption. That is, all the pathways generated with D-EXPANSE use the exact same input parameters, but have different total system costs.

The D-EXPANSE model and its mathematical formulation is introduced in detail in [7]. Figure 1 summarises the general procedure. First, D-EXPANSE is run in cost-optimisation mode to find the least cost solution (transition pathways) using a set of technology and cost data as well as the constraints on the annual and peak electricity demand, resource bounds, carbon emission targets and others. Second, the total system costs of the cost-optimal pathway are used as the anchor point for analysing the near-optimal pathways. A certain deviation in the total system costs is allowed from the optimal level of costs. In this way, costs become a constraint rather than the objective function for the model. The technique of efficient random generation [11, 12] is then used to produce a large number (e.g. one thousand) of pathways that all meet the constraint on the near-optimal costs. Third, this large set of near-optimal pathways is analysed either by eliciting a smaller number of maximally-different pathways or by extracting the patterns in these pathways. The small number of maximally-different pathways is formed by the adapted distance-to-selected technique [6-8, 25], that finds pathways that are most different in their elements (e.g. technology deployment levels). Alternatively, simple descriptives [6] or advanced quantitative techniques [8, 21, 26] can be used to draw patterns from the large number of pathways.

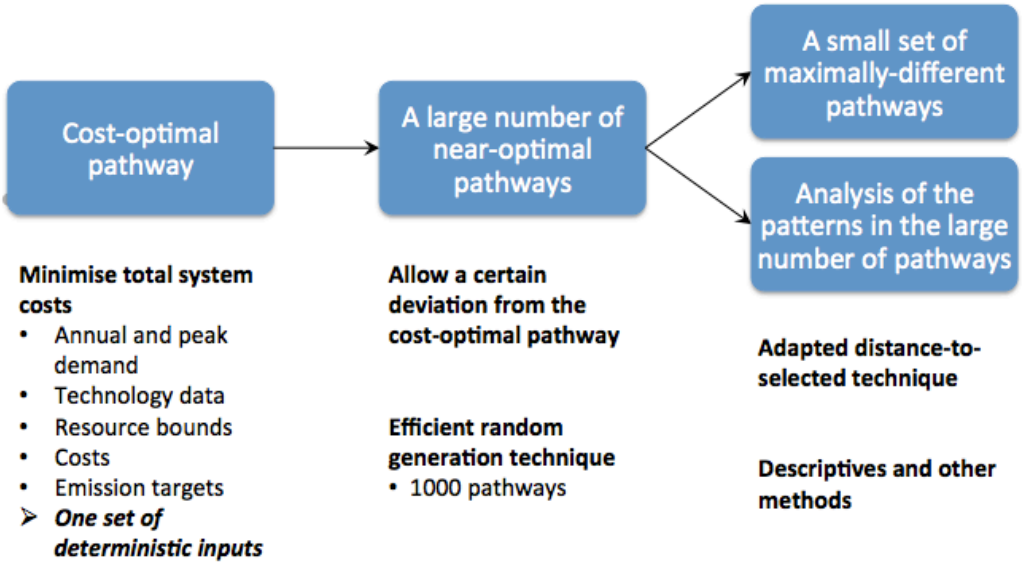


Figure 1. The general procedure of the D-EXPANSE model

The D-EXPANSE model is currently set up for analysing the UK power system transition for the period of 2010-2050 [7]. For validation reasons, the D-EXPANSE cost-optimal pathway was compared to the results of the well-established models [3, 20] and matches them with a reasonable level of precision. As compared to a detailed power system model, D-EXPANSE has a relatively coarse representation of the power system. In line with the state-of-the-art practice to soft-link and validate models [27], D-EXPANSE has been validated by soft-linking it with the detailed FESA model. FESA [28, 29] is a single-year UK power generation and demand model, incorporating one-hour time step for dispatch modelling and using real weather data of temperature, wind speeds, wave height and solar radiation. Thus, FESA helped to test whether the pathways generated with D-EXPANSE are technically feasible. D-EXPANSE was also embedded in the multi-model comparison [30] with seven other models, that ranged from detailed power sector models to economic or environmental impact assessment models. This allowed for validating the other features of D-EXPANSE that could not be covered by FESA.

3.2. Data

For the analysis of the future UK power system transition in the period 2010-2050, the original D-EXPANSE model builds on the data from the well-established UK energy system models [3, 18, 20, 31], filling the minor data gaps from other sources. The range of technologies to be considered and the electricity demand assumptions are taken from the Realising Transition Pathways project [32, 33], that D-EXPANSE is embedded into. As the electricity demand is an exogenous assumption in D-EXPANSE, it is taken from the so-called “Central Co-ordination” transition pathway from this project [29, 34], where the demand evolution was analysed in detail in terms of annual demand evolution, load curves and peak demands.

As the current version of D-EXPANSE is set up for 40 years, the retrospective modelling exercise has been conducted for the period of 1990-2030. The initial modelling year was chosen as 1990 due to the satisfactory availability of historical data. In order to minimise the influence of parametric uncertainty on the modelling results, the existing power plant capacity in 1990 and its phase-out, the annual produced electricity amounts and the peak demand requirements for the period 1990-2010 were assumed equal to the historic values. This data was reconstructed from the Digest of UK Energy Statistics [35-37]. Reconstruction of the historical investment costs, operation and maintenance and fuel costs proved to be the biggest challenge in this analysis. While the fuel and investment costs were relatively easier to find [38-40], hardly any data was available on the operation and maintenance costs. Thus, these costs were assumed as equal to the current estimates. The data for the period 2010-2030 where then assumed as in the afore-described future modelling of the “Central Co-ordination” transition pathway.

The future modelling exercise assumes that the UK’s legally binding target [41] to reduce its carbon emissions from the energy sector by 80% until 2050, as compared to the emissions of 1990, will be met. Retrospectively, the discussion about climate change mitigation in the power sector existed in the UK from the UN Framework Convention on Climate Change at Rio in June 1992 at the latest [39]. However, the very strict and ambitious commitment to mitigate emissions occurred only with the Climate Change Act in 2008 [41]. Due to a rapid switch from coal to gas in the UK power sector, the emission intensity decreased about twice from 1990 to 2010. In order to reflect this situation in the retrospective modelling, it was assumed that, regardless how committed the UK actually was to carbon emission reductions between 1990 and 2010, the modelled cost-optimal power sector emission intensity in 2010 was not higher than the actual value of 0.444kgCO_2/kWh. Afterwards, the emission target follows the assumptions of the future modelling exercise.

4. Results

4.1. Results of the retrospective modelling (1990-2030)

When the D-EXPANSE model was run for the period 1990-2030 with the historic data, the UK power system transition pathway with the minimal discounted total system costs is shown in Figures 2 and 3. The cost-optimal pathway captured many elements of the actual transition: especially the gradual phase-out of coal power plants and the increasing deployment of onshore wind power after 2005. However, significant differences can be observed too. The "dash for gas" that occurred in the UK after 1990 with a rapid and extensive uptake of gas CCGT technology [37] was not reproduced by the model. The D-EXPANSE cost-optimal solution included more nuclear power rather than gas for the period 1990-2030. This is not surprising. First, the "dash for gas" was a complex process, where multiple aspects—not only costs—had influence, for example, technology expectations at that time, energy independence goals, nuclear safety-related concerns etc. [37]. As D-EXPANSE is the model with perfect foresight, it also considered the substantial increase in the gas price after 2000. Moreover, in the 1990s the estimates of the levelised costs for nuclear power were higher than the estimates for gas CCGT, while the investment cost estimates for nuclear dropped in the subsequent years [38]. Second, the construction of interconnectors for electricity import appeared much earlier in the D-EXPANSE cost-optimal pathway rather than in reality, although these interconnectors served the role of the back-up capacity. All of these considerations show that the actual power system transition in 1990-2010 was not exactly the same as the cost-optimal pathway, modelled with D-EXPANSE.

Figures 2 and 3 show the levels of investment and annual total system costs for the cost-optimal and actual transition pathways. The costs of the actual pathway are calculated based on the same cost assumptions from D-EXPANSE rather than using the historical expenditure data, which was not available. While Figure 2 shows that the investment costs of the actual transition in the year 2000 and 2010 were lower than of the cost-optimal pathway, the total annual system costs were higher in 1995, 2005 and 2010. The deviation from the cost-optimal pathway in terms of total cumulative system costs was thus evaluated as $(C_{actual}-C_{optimal})/C_{optimal}$. The deviation in 10 years (1990-2000) was relatively minor and equal to 3.8%. However, the deviation in 20 years (1990-2010) was as high as 17.2%. The earlier studies show that, when deviation of 20% from the cost-optimal solution is allowed, the resulting energy transition pathways can be significantly different in the technology deployment levels [6, 7]. This explains why the cost-optimal D-EXPANSE transition pathway for the period 1990-2010 was so significantly different from the actual development.

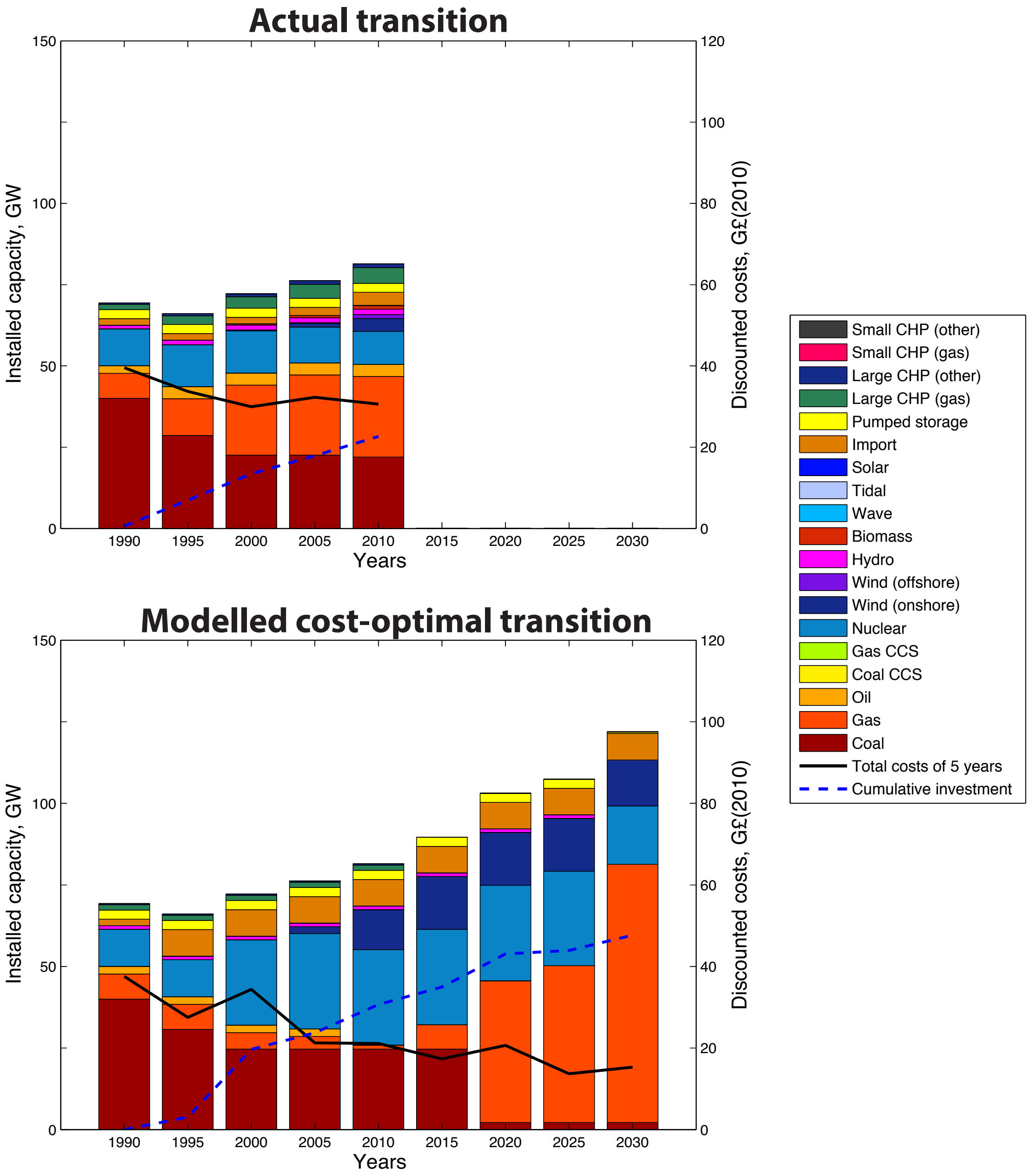
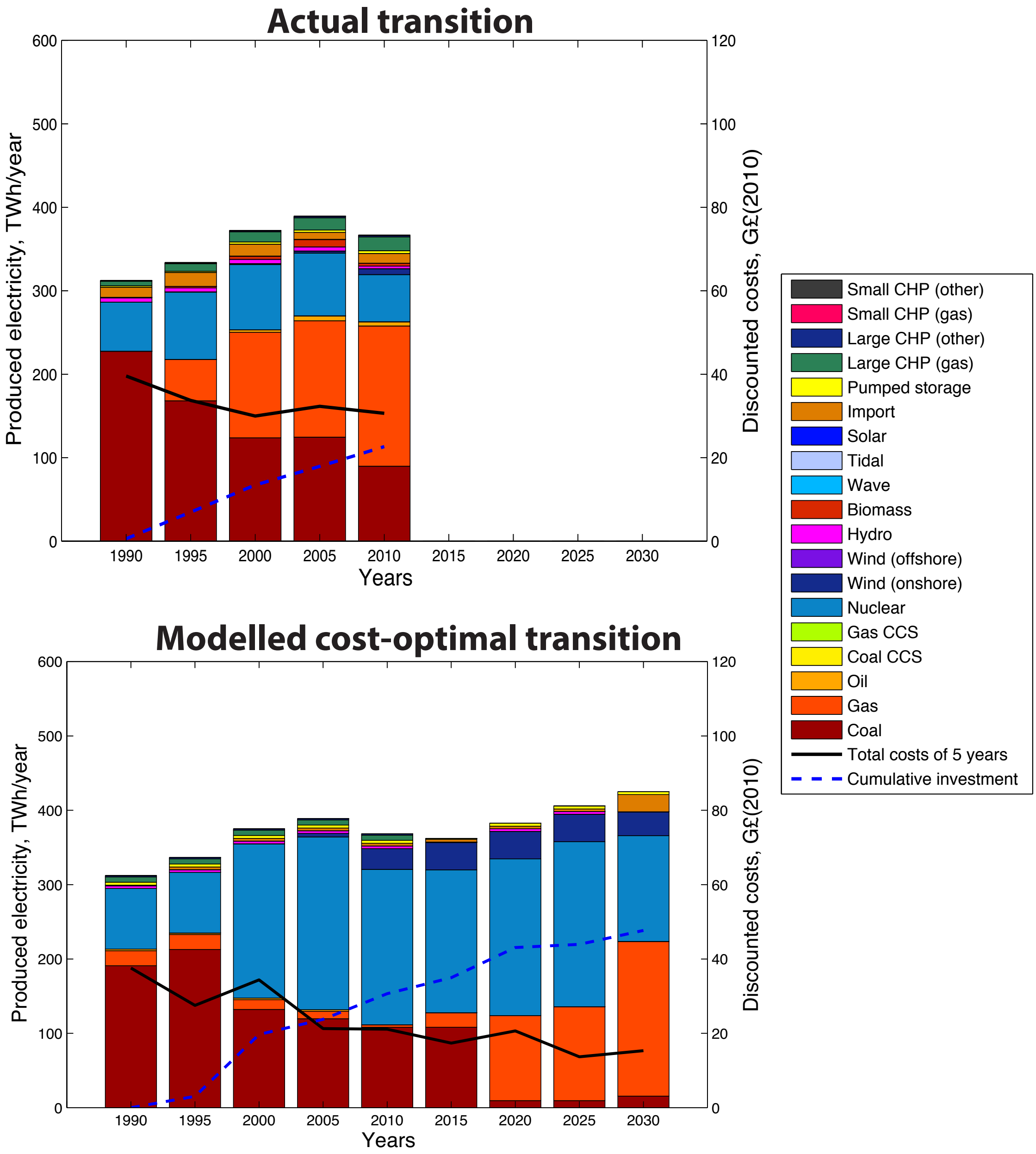


Figure 2. The actual UK power system transition (1990-2010) and the modelled cost-optimal transition in D-EXPANSE in terms of installed capacity

4.2. Results of the future modelling (2010-2050)

Such a high actual deviation of 17% in 20 years from the modelled cost-optimal transition pathway is a thought-provoking result for the bottom-up energy system modelling community. Therefore, this section explores the implications of such a deviation from the cost-optimal solution on the future modelling results. D-EXPANSE is especially suitable for this purpose because it systematically explores large numbers of near-optimal pathways, given a predefined level of deviation.



Actual transition

Modelled cost-optimal transition

Figure 3. The actual UK power system transition (1990-2010) and the modelled cost-optimal transition in D-EXPANSE in terms of annual electricity generation

Figure 4 shows the cost-optimal transition pathway, modelled with D-EXPANSE, for the period of 2010-2050. Due to the stringent emission targets after 2030, the cost-optimal pathway relies on nuclear power with increasing levels of renewable energy, such as onshore wind power, biomass and, toward 2050, wave power. There is still a significant capacity of gas CCGT that is mostly serving as a back-up capacity. This power supply mix is comparable with the runs of the existing energy system models [3, 20].

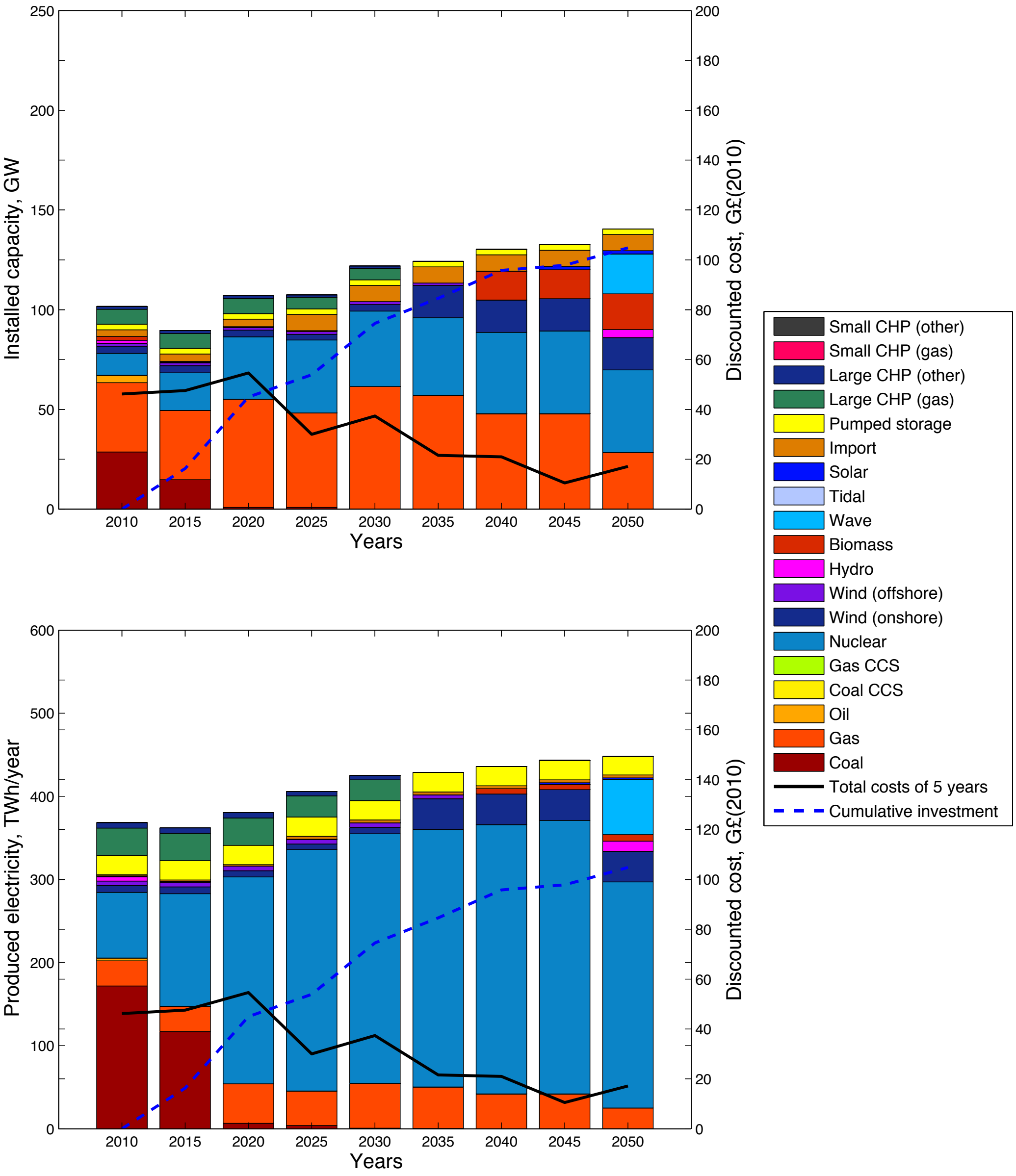


Figure 4. Cost-optimal transition pathway, modelled with D-EXPANSE, for the period 2010-2050

The D-EXPANSE model was run in its efficient random generation mode for three levels of deviations from the cost-optimal pathway in terms of the total system costs by 2050: 1%, 5% and 17%. These levels were chosen in order to illustrate the effects of the cost-optimality assumption on the technology deployment levels. Based on the retrospective modelling results, such deviation levels may even be conservative. Retrospectively, 17% deviation was observed in 20 years, while it may be significantly higher in 40 years.

One thousand pathways were generated for the three deviation levels and the descriptives of the technology deployment across the pathways are shown in Figures 5, 6 and 7. Not all the combinations of these technology deployment levels are possible in the pathways [6]; a set of maximally different pathways is shown in [7].

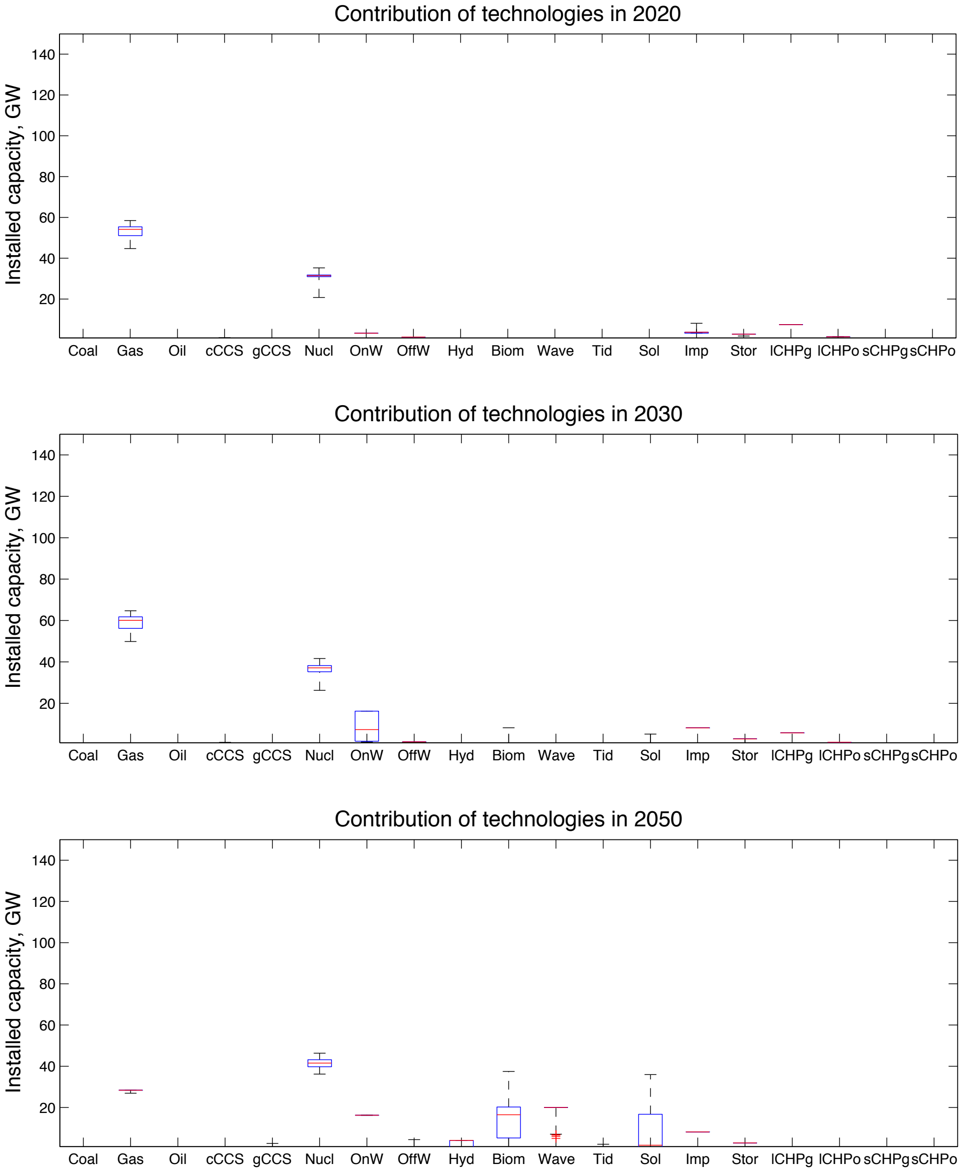


Figure 5. Technology deployment patterns in 2020, 2030 and 2050 in 1000 transition pathways that deviate by 1% from the cost-optimal pathway

Figures 5 and 6 show that 1% or 5% deviations have an effect on the technology deployment levels, but this effect is not large. It includes the technologies that are roughly substitutable and have similar levels of costs, like nuclear and gas (2020 and 2030) or solar and biomass (2050). However, from the perspective of the individual technologies, their deployment levels can be as low as zero or as significant as 40-50GW by 2050. As seen in Figure 7, the deviation of 17%, that is the retrospectively measured deviation, can have significant impacts on the technology deployment levels, modelled in D-EXPANSE. This illustrates the need for systematically addressing the near-optimal pathways, as done in D-EXPANSE.

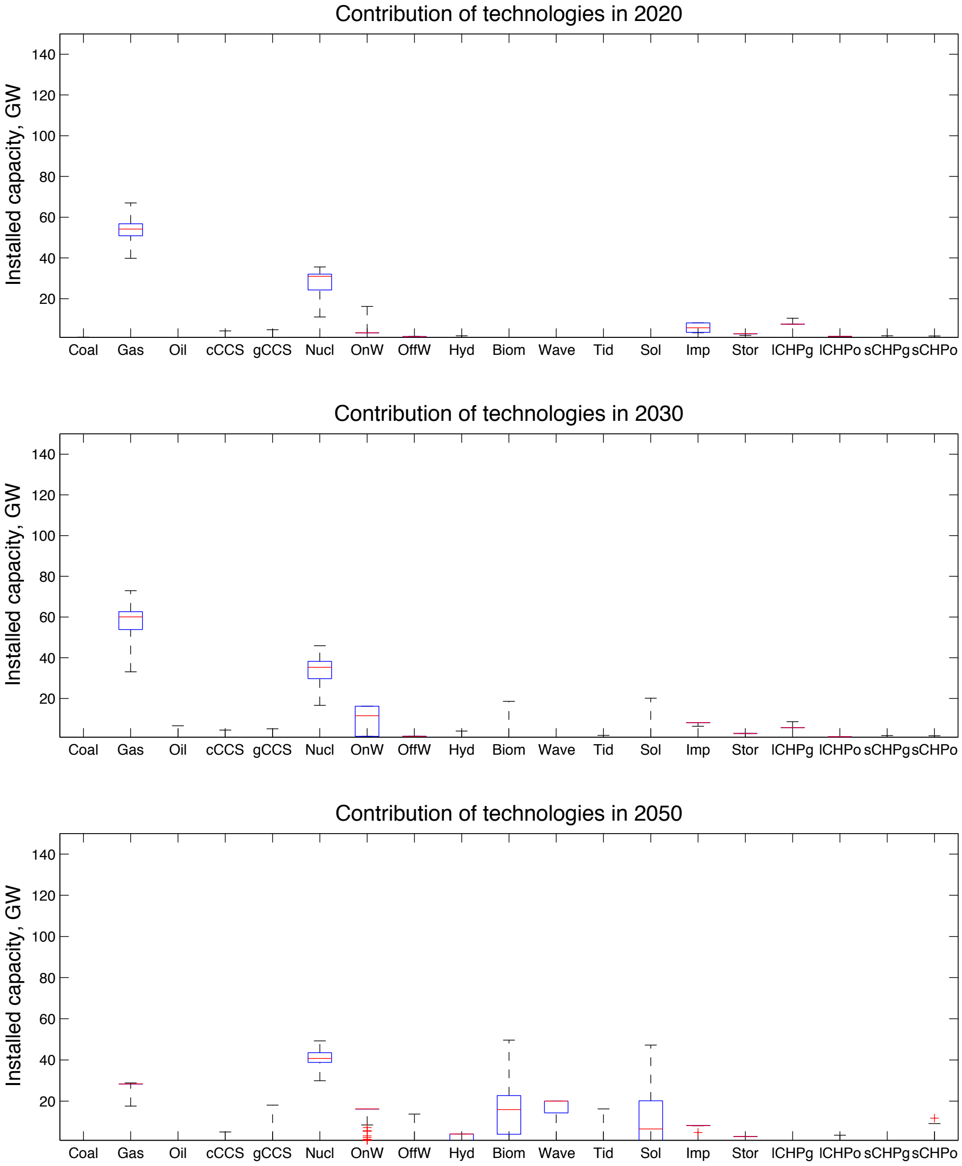
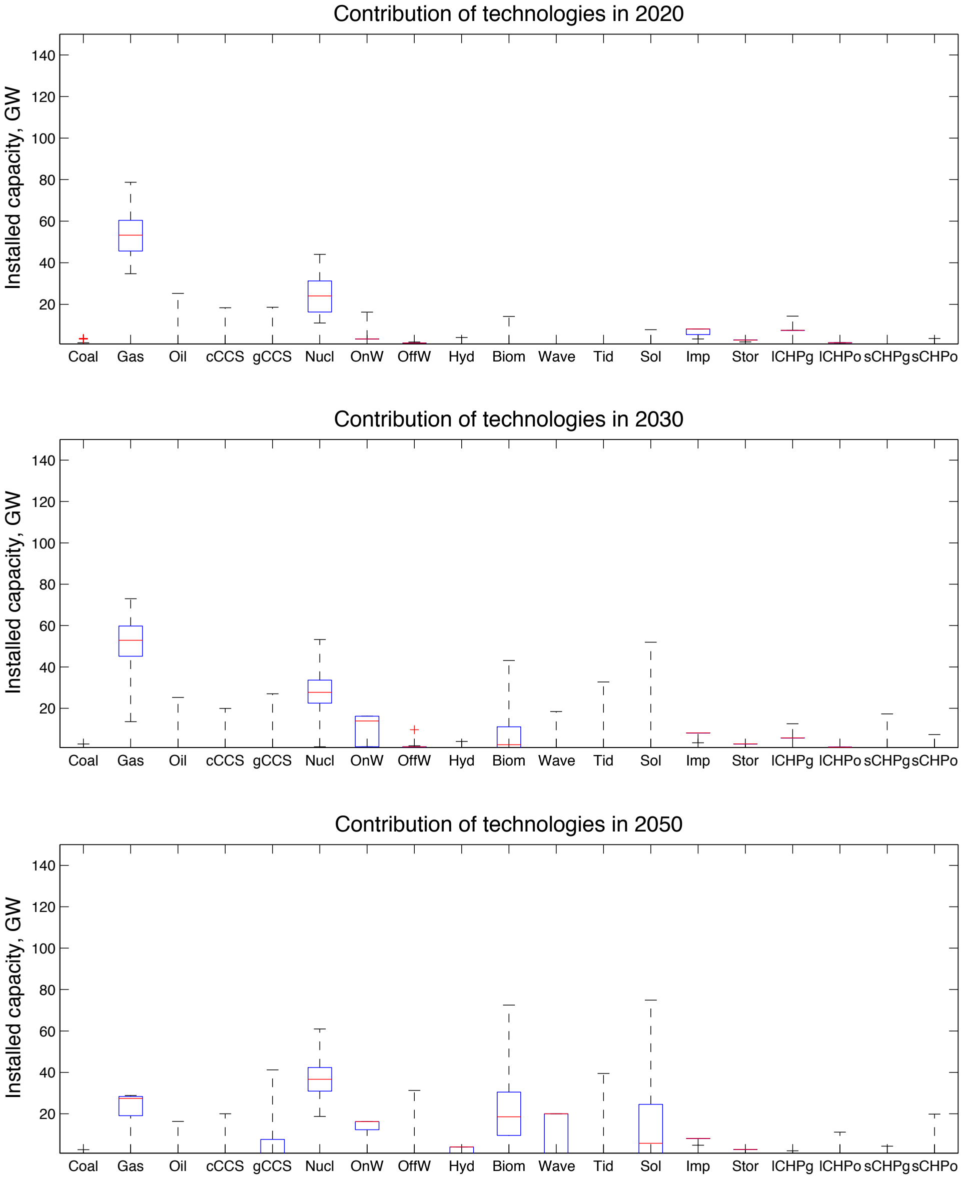


Figure 6. Technology deployment patterns in 2020, 2030 and 2050 in 1000 transition pathways that deviate by 5% from the cost-optimal pathway

5. Discussion

This conference paper questioned the widely used practice of optimising the total energy system costs in order to foresee the future energy system transition. The D-EXPANSE model, that has the structure of the conventional bottom-up energy system model, but also systematically explores near-optimal transition pathways, was used retrospectively to model the UK power system transition between 1990 and 2010. When the modelled cost-optimal pathway from D-EXPANSE was compared to the actual transition, the deviation of 17% in total cumulative system costs for 1990-2010 from the cost-optimal solution was measured. Such a high deviation is a novel and thought-provoking finding for the energy systems modelling community, whose models are completely dependent on the cost-optimality assumption. Even more, a radical energy system transition is aspired for the future due to environmental reasons [42]. Thus, it could be expected that costs may play an even smaller role in shaping the future transition than in the past. The future deviation from the modelled cost-optimal pathway may thus be even higher.


Contribution of technologies in 2020

Contribution of technologies in 2030

Contribution of technologies in 2050

Figure 7. Technology deployment patterns in 2020, 2030 and 2050 in 1000 transition pathways that deviate by 17% from the cost-optimal pathway

As the D-EXPANSE results for the future UK power system transition between 2010 and 2050 show, a deviation of 17% can lead to significantly different pathways of technology deployment. Thus, the current practice of considering solely the cost-optimal pathway in the bottom-up models glosses over the range of other pathways that can be in reality as likely as the optimal one. More caution is thus needed when interpreting the results of the existing bottom-up models. Furthermore, while a substantial body of research goes into the analysis of parametric uncertainty in energy system models, this conference paper shows that further research is essential for addressing the structural assumption of cost-optimality.

The presented work, however, has limitations and could be improved in two directions: the retrospective analysis and the general procedure of modelling the near-optimal pathways in D-EXPANSE. The retrospective analysis is at its early stage and can be strengthened by improving the precision of the historic data on the technology and fuel costs as well as on the actual phase-out of the capacity that existed in 1990. The retrospective analysis was done on the basis of the actual cost data (i.e. their reconstruction as precisely as possible). However, the real-world energy-related decisions are made in terms of expectations about the future costs, because the actual costs in the future cannot be known. A retrospective analysis could thus be done using the estimates of expected costs at a certain time period as it may better represent the case of today's modelling for the future, where the cost expectations rather than actual costs are used.

With respect to the practice of modelling the near-optimal pathways in D-EXPANSE, additional work is needed to analyse how the deviation from cost-optimality could be best defined. Currently, the deviation is measured in terms of cumulative total system costs at the end of the modelling period. Yet, alternative metrics could be used too, e.g. deviations in annual total costs. Further research is also needed to extract the patterns from large numbers of near-optimal pathways in order to understand the interdependencies between certain technology choices and deviations from cost-optimality. After all, this research illuminated a significant weakness of the widely used bottom-up energy system models. Although the D-EXPANSE model aims to forego this weakness, it still remains to be seen how these insights on the near-optimality could be integrated into the large conventional models, such as TIMES or MARKAL [1, 2]. Using the maximally-different near-optimal pathways from the D-EXPANSE model to inform the scenario construction in the conventional bottom-up models is a possibility.

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