A Comment on Dealing with Deep Uncertainty in the Energy Transition

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Cases from the electricity and transportation sectors*

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Abstract

We demonstrate how deep uncertainty (“unknown unknowns”) delays investment in the energy transition. Three cases resembling different characteristics of the energy transition are examined: offshore wind, electric vehicles, and Datteln 4 (a new coal fired power plant). Deep uncertainty typically arises in close connection with – and therefore amplifying – the “usual” statistical risk context. Sources or drivers of deep uncertainty vary with technology or market maturity and may originate from practically all levels, starting with the broader macro-economic environment via the sectoral, firm, project or technology level. There are some approaches to coping with deep uncertainty in the literature, but they appear to be rarely used in practice, particularly with a view to investment decisions. All cases have in common, that long-term credible policy signals would strongly contribute to reducing deep uncertainty, despite all the challenges that come with sending such signals.

Keywords: Deep uncertainty · climate change · decision making · energy transition · investment

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1. Introduction

To avoid dangerous levels of climate change and to achieve what is often called the energy transition a substantial investment volume is required (e.g., Hall et al., 2017; OECD, The World Bank, UN, 2018). Particularly, investment needs to be focused where carbon intense infrastructure is to be substituted by low-carbon alternatives. Two sectors without which an energy transition is impossible are power and transport: The power sector is representing 40 percent, the transport sector 23 percent of global carbon emissions in 2018 (IEA, 2020). The challenge in the power sector is to transform the electricity systems around the globe from rather centrally organized systems relying on fossil fuels to more flexible electricity systems that are not only dominated by renewables-based electricity production but are also able to serve a higher demand for electricity – as electricity is foreseen to substitute fuels also in other – traditionally less electricity dominated – use cases (e.g., Eid et al., 2016; Poudineh and Jamasb, 2014). One important of those use cases is the (upcoming) electrification of the transport sector, the switch to Battery Electric Vehicles (BEVs) and/or Fuel Cell Vehicles (FCV), often called e-mobility.

In this paper we examine the role of so-called deep uncertainty in the energy transition, particularly within the power generation and the transport sector. Deep uncertainty refers to a situation in which a probability distribution across possible outcomes is not known, sometimes not even the set of possible outcomes is known (e.g., Lempert et al., 2003; Marcheau et al. 2019; Walker et al. 2013). The latter sometimes is colloquially also referred to as the "unknown unknowns". We pose the question, to what extent this fundamental uncertainty hinders or delays investment in the context of the energy transition, and what can be done about that. We do so by examining three cases in more detail: First, we look at two examples in the power generation sector, which arguable constitutes the most relevant sector in the context of the energy transition and complement the analysis by one example from the transportation sector.

The first example refers to a decreasing industry within the structural change associated with the energy transition: the construction of a new coal fired power plant, “Datteln 4”, which – in the years before it entered normal operation – was the only coal fired power plant under construction in Europe (Bünder, 2019). The second power market example represents the rapid expansion of electricity generation based on renewables, the offshore wind industry. The third example, located in the transportation sector, is the phase of the introduction of electric vehicles in the German automobile sector.

With electricity production and transport, these three cases cover – as argued above – two sectors particularly important for the energy transition. They are complementary in the sense that investment in a coal fired power plant is something that is expected to disappear as the energy transition moves forward (e.g., Song, 2021). As opposed to that, the scale-up of offshore wind investment is widely recognized as challenging but very much needed to achieve a near 100 percent renewables-based electricity system in Germany (e.g., IEA, 2019; Fernández-Guillamón, 2019). Thirdly, the automobile sector – being aware that the internal combustion engine would likely need to be substituted by alternative drive trains at some point – was challenged by the fact that there are different alternatives (e.g., Agora, 2017; Dijk et al., 2013; Hühlsmann and Fornahl, 2014). The most relevant alternatives probably are the battery electric vehicles (BEVs) on the one hand and fuel-cell electric vehicles (FCV) typically using hydrogen on the other. At least for passenger vehicles, it was (and some may argue that it still is) uncertain which one will turn out to be the dominant technology in passenger vehicles: BEV or FCV or both (e.g., Van de Kaa et al. 2017, for a historic perspective; Agora, 2021, for a more recent view). An established car manufacturer on the market for internal combustion engine (ICE) driven cars will need to decide how to approach the change. Going forward, she may decide to invest in battery related technology, fuel-cell, or both.

In the following chapter two we introduce the cases in more detail, show how they generate investment decisions which are subject to deep uncertainty, and how that actually delayed investment. We will look at the approaches that were (explicitly or implicitly) taken when making investments in situations involving deep uncertainty and collect the experience made by several actors involved. Thereafter, chapter three looks at general approaches that are found in the literature suitable to deal with situations of uncertainty. It provides a brief survey reflecting that those methods were and are not commonly applied and discusses to what extent these approaches might be beneficially applied in comparable cases in the future. The final chapter summarizes the findings, first with a focus on relevant aspects for market actors, second also looking at conclusions for policy makers.

2. Deep Uncertainty – Three Examples within the Energy Transition

The context of the energy transition frequently generates investment-decision situations that are – at least partly – involving deep uncertainty (Haas et al. 2021). For our look at real-world cases, we adopted the understanding of deep uncertainty as formulated by Lempert et al. (2003): "Deep uncertainty exists when analysts do not know, or the parties to a decision cannot agree on, (1) the appropriate models to describe the interactions among a system's variables, (2) the probability distributions to represent uncertainty about key variables and parameters in the models, and/or (3) how to value the desirability of alternative outcomes." This notion was developed in the context of long-term policy analysis (LTAP) but appears to be well operationalizable in the investment-decision context. We examine the three cases to identify elements of deep uncertainty and show how this has been reducing the speed of the energy transition.

2.1 Datteln 4 – A New Investment in a Fading Sector

Datteln 4 is the name of a new coal-fired powerplant located in Datteln, Germany. The number 4 refers to three older coal power plants (Datteln 1, 2, and 3) which this new one is supposed to "replace". This wording, however, may be mis-understood: The combined electricity power production capacity of the three old plants (1,2,3) was about 300MW (E.ON, 2009). The capacity of the new plant (4) alone is larger than 1000MW and it also provides district heating on the order of 380MW (Uniper, 2021). The new plant is planned, owned, and operated by Uniper, a firm established to own and run the fossil fuel based power plants of E.ON, a large German utility (Uniper, 2018).

During its construction phase, Datteln 4 faced substantial delays: Construction started in 2007, after Uniper (at the time called E.ON) had officially committed to take the old powerplants off the grid at the end of 2012.[1] Correspondingly, the start of operation was foreseen for 2011. Two years later, in September 2009 the Superior Administrative Court in Münster declared the planning by the city of Datteln invalid, and shortly thereafter the local government ordered the construction to stop. A long legal dispute unfolded. First, the Supreme Administrative Court upheld the ruling in 2013. Years later, after a fully new approval process was initiated by Uniper, the local government allowed to continue the construction in 2016. Despite several related court cases moving on in parallel, construction moved forward as well, until in 2018 the main boiler crashed during a test phase (Uniper, 2018). The reason was a novel type of steel (7CrMoVTiB10-10, often called T24) that was used to increase the efficiency of the power plant, but displayed weaknesses related to connecting the steel parts. Substituting the boiler steel alone caused another delay of about a year and was a main contributor to Uniper's write-offs of about 680 million Euro (Uniper, 2018).

In January 2019, the so-called "Coal Commission" issued its final recommendations as to how to achieve the coal exit, which was suggested to be completed by 2038 (Coal Commission, 2019). One recommendation was to seek a "solution through negotiation" with owners of powerplants which are almost complete, but not in operation yet, to avoid that they would be completed and start to produce (Coal Commission, 2019). This was widely understood to refer to Datteln 4.

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[1] We refer the interested reader to Bund (2020) for an overview of the chronology of the approval procedure of Datteln 4; further information is provided by Deutsche Umwelthilfe (2011) with further references.

Uniper then declared that it would be surprised not to use a very efficient power plant and less efficient ones instead, but nevertheless to be open to negotiations about potential compensations if they are “fair” (Handelsblatt, 2021). Against the recommendation of the “Coal Commission” the German federal government – in the context with its decision around the coal-exit until 2038 – allowed Datteln 4 to start commercial operation, which it did in May 2020, almost a decade after the initial plan. At the time, several related court cases were ongoing, and the period before the commercial start of operation did not happen without activists occupying the power plant area and being evacuated by the police (e.g., Handelsblatt, 2020). After the federal election in 2021, the new coalition treaty suggests moving forward the date of the coal exit by eight years to 2030 (SPD, Bündnis 90/Die Grünen and FDP, 2021). This is widely believed to shorten the commercial lifespan of the plant substantially, making it harder to recover the investment of more than 1 billion Euro (Reuters, 2020).

In the year 2006, around the time when the investment decision in favour of Datteln 4 must have been taken, even the start of the “Coal Commission” planning the coal exit was more than a decade away. But there was already a strong and well-known political movement against coal-based electricity production. Even from the perspective of E.ON it appeared acceptable not long after the construction started that this powerplant might be “the last of its kind” in Germany (Sorge, 2011). It was therefore clear at the time that the investment decision runs against a general long-term trend (e.g., Hake et al., 2015). However, it appears reasonable to assume that it was hard to predict or to develop any sound idea of probabilities how fast and how exactly that trend away from coal-based power plants would materialize. The strategy of E.ON appeared to be to seek agreement with the local authorities fast and then complete the construction early in order to be one of the more efficient coal power plants which would then expect a high demand and with a view to remain one of the most efficient coal power plants as new plants would not be built anymore. In parallel, contracts were struck early on in 2007 with Deutsche Bahn to power a significant part of the train grid and with RWE to sell the electricity (Flauger and Fockenbrock, 2015). These measures were essentially reducing the uncertainty from the electricity market.

The increasing trend away from fossil fuels, however, was not only driving legal steps to massively delay the construction process. It also made every delay more harmful for the overall business model of Datteln 4. Even in the context of innovation – using a novel steel type to increase efficiency – an unexpected event (bursting boiler) had drastic consequences as this reduced the time window available for commercial operation which was – by that time – already reduced through the coal exit foreseen until 2038 at the time. At first sight it may appear surprising that initially E.ON, later Uniper more or less constantly decided to stay with their initial investment decision from 2006, namely to build the power plant and enter into commercial operation as fast as possible even though the construction took 13 years instead of the expected 4 years. And all this constantly moved against a comparatively stable long-term political trend.

The observation of one asymmetry may be helpful for an explanation in this context: The political trend induced uncertainty from the perspective of the power plant investor. The policymaker, however, was not able (or not willing) to signal in a reliable way that the long-term profitability of coal fired power plants can be expected to significantly fall soon. In other words, policy was not able to credibly commit to a coal exit path sufficiently fast to avoid long-term investment in that technology. This may be particularly relevant facing the completely different situation on the side of E.ON or Uniper: they had a credible way to commit to their plan, namely initially investing significantly in the illiquid asset dedicated to their plan, in other words a fast start and substantial investment in the initial construction site (which then was forced to pause in 2009).

The legal environment related to property protection may also make it more realistic to pursue this strategy – particularly as everything happens in accordance with the local authorities. To what extent that strategy was successful from the perspective of Uniper can only be evaluated once the compensation payments are fully negotiated. From the perspective of the society, the powerplant has delayed the energy transition, and it is very likely that this asymmetry regarding the commitment in an environment of deep uncertainty has been welfare-reducing.

2.2 Offshore Wind – A known Technology in a New Environment

Investment in offshore wind in Germany will need to increase to reach the goal of net zero emissions by the year 2045 while at the same time serving a strong shift of overall energy consumption towards electricity (e.g., IEA, 2021). One challenge related to offshore wind investment is related to this being a comparatively young technology. It is well understood – and investors are experienced with that – to build and run on-shore wind farms for power production for over 30 years (e.g., Ackermann and Söder, 2002; Gipe, 1995). The use of windmills as such actually go back to 200 BC, and the earliest windmills to generate electricity to the late 19th century (Kaldellis and Zafirakis, 2011). The volatility of wind resource provision and also the physical presence of wind farms near human settlements created challenges to proper integration into stable electricity systems or a strong scale-up, respectively (e.g., Felber and Stoeglehner, 2014; Solli, 2010; Warren et al. 2005). Offshore wind farms can in principle overcome both issues as they are a less volatile and more steady source of renewables based electricity (see Buck et al., 2019) and as they are typically far away from the coastline, they do not generate negative externalities from disturbing human settlements or changing landscape views.

On the other hand, it is exactly this location-related innovation which produces fundamental challenges to project developers, implementers and therefore also the investors: Market actors were not experienced with constructing, operating, and maintaining windmills in the high sea (e.g., Perveen et al., 2014). Many unexpected problems occurred which had to be resolved within the ongoing project and which also informed investors in potential future projects that there is still a lot of uncertainty related to offshore wind investment. Sun (2021) has undertaken an extensive study identifying elements of deep uncertainty in the context of offshore wind by combining the analysis of applied academic and industry publications with interviewing market actors of the initial phase of offshore wind financing.[2]

The study demonstrates explicitly where situations of deep uncertainty appear and that they have delayed investment. Situations of deep uncertainty were identified and characterized based on the discussion with market participants involved in the respective transactions. The sources of deep uncertainty that were identified were clustered by the project phase (exploration & planning, development and construction, operation) and the sphere or level (overall market environment, technology, project, industry/sector-level).

Figure 1: Frequency of deep-uncertainty incidents along the project cycle. Source: Sun (2021).

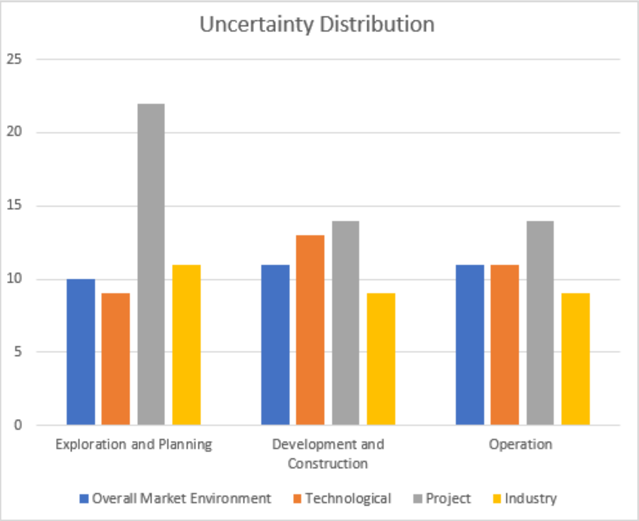

Figure 2 demonstrates that deep uncertainty in offshore wind projects appears during all project phases. The graph distinguishes between the overall economic environment, the industry level, the technology level, or the specific project (or implementation) level. It appears to be some change as to the level where the source of deep uncertainty is located. Naturally, in the exploration and

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[2] The discussion of offshore wind in this paper is mainly based on Sun (2021).

planning phase there is a higher frequency of project-specific sources of deep uncertainty, while technology related deep uncertainty tends to be higher during the development and construction phase.

The identified situations also show that deep uncertainty often appears in a close combination with other (somehow standard) uncertainty, which often makes it difficult to clearly identify the element of deep uncertainty. Also, different situations and decisions are interlinked in a way that events may amplify each other's consequences. Sometimes, it is the interaction itself between different situations or events that gives rise to an element of deep uncertainty.

This may be illustrated by an example: Borkum West II is an offshore Wind Park in the North Sea about 50km off the coast of northern Germany.[3] It was planned and constructed under the leadership of Trianel, a European multinational utility company as the second phase (203 MW capacity, total expected investment volume of 800 million Euro) of an already existing offshore Wind Park. Main shareholder was the fifth largest German utility company called EWE. Construction started in 2018, the start of commercial operation was planned about one and a half years later, latest at the end of 2019.

The turbine manufacturer that was selected for the project was Senvion. It was a mid-sized company known as a driver for innovation and responsible to deliver and erect the turbines. After bringing 15 turbines to the construction site, Senvion had to file for bankruptcy, to many unexpected as the order books were full at the time. This further delayed the construction process which was already behind schedule. The main problem caused by a delay was not only the loss of revenues, but the feed-in-tariff that was offered would be reduced by 1ct/kWh in case operation would start after first of January 2020, then causing double digit million losses for the shareholders of the

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[3] The case in more detail and additional examples around situations involving deep uncertainty in the offshore wind context are provided by Sun (2021).

park. So new decisions had to be taken how to continue the project on which several hundred million Euro had already been spent.

Senvion and the wind park project company then entered a new contract to deliver the second half of the turbines and some direct contracts with Senvion's subcontractors were added to increase the reliability of the installation. When the park started commercial operation, it had to accept a decrease in the feed-in-tariff causing a loss of about 61 million Euro. When the leader Trianel entered discussions with the German Ministry to ex post extend the deadline for such special cases, the government actually responded with a corresponding regulation to extend implementation deadlines in cases where the turbine manufacturer becomes insolvent. This new regulation, however, did only apply from 2021 on and was therefore not relevant for Borkum West II.

Although each individual event is not necessarily carrying a lot of characteristics of deep uncertainty, the combination of the events where the negative consequences seem to pile up almost as consequences of each other makes it a situation in which it is plausible to assume that the situation can hardly be modelled, probabilities for the overall possible outcomes are not plausible and if one event may trigger different others it may even become hard to "rank" different outcomes. The project developer and main shareholder of this project EWE declared in the light of this development that it would discontinue its engagement in offshore wind (Flauger, 2020).

In its initial phase, offshore wind experienced several such unexpected events. Other examples are a very concentrated and shrinking cable industry, which was surprised by the exploding transmission cable demand from the emerging offshore wind industry. This led to delivery times for cable of up to 50 months (Wirtschaftswoche, 2012a). Another example may be BARD Offshore I, which came into operation three years after the plan, more than 90% above the planned budget at an overall investment of about 3 billion Euro (Wirtschaftswoche, 2012b). Among the events delaying the start of commercial operation were technical defaults, work accidents, withdrawals of investors, a smouldering fire, an unexpected grid disconnection, and a severe reconstruction of the turbines that became necessary after almost half of them were already in place in the North Sea. On the other hand, the costs incurred also generated innovation and contributed to the technological advancement in the offshore wind industry: A lot of effort was devoted to establishing an own production of 5MW wind turbines which were better than what was available on the market at the time (DeVries, 2008; 4COffshore, 2021). Those turbines were also placed on tripile-foundations (designed and patented by BARD) which are lighter, smaller, more stable, and faster to install – once the technology is established. Some of the additional investment (about 60 million Euro) went into design of a novel ship to install the turbines, as installing-vessels were often a bottleneck and the requirements of the offshore context are special: The new jack-up vessel included a self-elevating crane which – when at the construction site – is able to stand on the bottom of the sea and lift parts more than 100m above the sea level relatively independent of the harsh conditions in the open sea (Offshore Wind Solution, 2013).

Despite the long-term contribution to innovation in offshore, the cost overrun and the delay, perhaps increased by political uncertainty[4] resulted in BARD's bankruptcy in 2013, the same year it started commercial operation.

The existing offshore wind park was bought by a subsidiary of HypoVereinsbank. In 2017 it became the most productive offshore wind park in Germany. In 2019 it was bought by Macquarie, a global financial services group. Still, at the time of its planning and construction, the many obstacles did likely not only delay the construction of the respective wind parks themselves, but probably also made other market actors hesitate. It is, however, not possible to identify one particular source of deep uncertainty. It is rather the interplay of the different sources with a strong role of the natural uncertainty surrounding a new technology, complex projects involving the cooperation

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[4] The coalition government at the time discussed about reducing the offshore wind target for 2020 from 10 to 6.5 GW.

of many actors within a context of sometimes varying political signals, that drive the element of deep uncertainty.

2.3 E-Mobility – Battery versus Fuel Cell

The automobile sector is also going through a substantial structural change in the context of the energy transition. While it has been known to the industry for a while that alternative drive systems are needed to reduce net emissions to practically zero, the transformation in the automobile or transportation sector carries different characteristics as compared to the transition from fossil-based coal fired power plants to renewables-base such as offshore wind. One prominent difference is that at the time when the transition picked up speed, none of the alternative drive trains was really competitive with the internal combustion engine (ICE) (e.g., Nykvist and Nilsson, 2015; Santini, 2011, for further references). The relevance of this is leveraged by two aspects: firstly, there were (at least) two alternatives that are considered candidates to be the dominant technology in the decades to come: battery electric vehicles (BEV) and fuel-cell electric vehicles (FCV), typically run with hydrogen. Secondly, both alternatives need not only massive investments on the side of the car manufacturers, but also require substantial (sometimes publicly, some privately funded) infrastructure investment to set up a network of charging stations (for BEVs) or hydrogen fuelling stations (for FCV).

As European regulators discussed how to accelerate the energy transition in the automobile sector, the industry was not in favour of additional regulation and committed in 1998 – in a voluntary agreement between the EU and the Association of European Automobile manufacturers – to reduce the average CO2 emissions from new cars to 140g per kilometre by 2008 (Hooftman et al., 2018). Technically, this would have been possible with both new technologies (BEV and FCV), but also with a highly innovative ICE technology.

So, the investment decision of an established car manufacturer in 1998 would be subject to quite some uncertainty with respect to which path to follow. How much to focus on innovating the traditional technology versus a new one, and whether to invest in research in hydrogen rather than battery or both. It was quite clear that emissions would have to go down drastically in the medium to long-term. It appeared also unreasonable to assume that this would be achievable with the traditional internal combustion engine technology. While it is plausible that this was a decision situation without a proper probability distribution available, it is less plausible that there are particularly many potential outcomes or that it would be impossible to rank the outcomes – given a particular investment decision. Therefore, in the light of our criteria above there are only mild elements of deep uncertainty, but rather a situation that may be best described by ambiguity. This is still challenging from an investor's perspective. Some reasons are (i) the strong path dependency, since "taking the hydrogen path" requires substantial investment and has an unclear payoff in case BEVs turn out to be the dominating technology – and vice versa; (ii) the unavailability of a financial hedge; (iii) the strong infrastructure dependence which clearly ties the challenge to government support that will be needed to secure the infrastructure.

Another challenge making a potential fundamental innovation (e.g., to electric mobility) even more disruptive lies in the established complex supply chains in the German automobile industry (e.g., Krpata, 2021). The latter is something that distinguishes established car manufacturers from new market entrants (like Tesla) which must build car-design, technology, and supply chains more or less from scratch, but do not need to worry about changing well established practices.

So how did the established car manufacturers react to the challenge? Figure 3 provides a perspective towards what some German car manufacturers at least discussed over the years: it displays for three firms, VW, Daimler, and BMW word counts in their annual reports from 1995 to 2019.[5] The orange line shows how often "hydrogen" or "fuel cell" was used, the blue line represents the

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[5] This analysis was performed by Ehmann (2020).

corresponding frequency of the term “battery”. The figure suggests that around the time of the voluntary commitment by the European car industry alternative drive trains were not discussed a lot. The graphs show that at that time and in the following years – if anything – those car manufacturers were discussing hydrogen as an alternative to the internal combustion engine. As the target date of the voluntary agreement (2008) approached and as it became obvious that the goals would be substantially missed, the discussion about battery electric vehicles seemed to start and then overtook the discussion about hydrogen and fuel cells in the annual reports.

Figure 2: Frequency of the different phrases in the annual reports of three German car manufacturers. Source: Ehmann (2020).

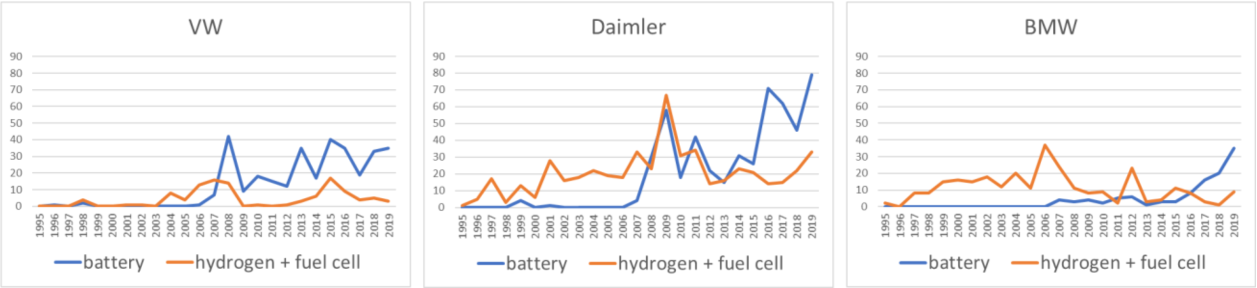

Figure 3 is not a proof, but it is at least consistent with the view that the ambiguity (between hydrogen / fuel cell and battery-driven passenger vehicles) delayed investment in battery electric vehicles. This might have slowed down the energy transition in the passenger vehicle sector – under the assumption that the battery electric drive train will turn out to dominate ex post.

One may argue that it would have been beneficial if the policy maker would have made a (credible) commitment to one of the two alternatives early on, to avoid losing time and money on the “other” alternative. However, this ignores the many lessons learnt about the problems with the role of the government in innovation, as to avoid to “pick the winning technology” as this has been going wrong numerous times in the past (e.g., David, 1985 and Liebowitz and Margolis, 1995). The literature in this context rather seems to suggest “technology-open innovation support” (a recent example is provided by the effective public financing of a broad range of Covid-19 vaccine R&D activities, see e.g. Agarwal and Gaule, 2021). While it is plausible to argue for this from an economic perspective (as the innovation in the technology that is – ex post – not dominating may drive innovation somewhere else or at a later point in time), this is less straight forward from the perspective of an investor – as she might not be the beneficiary of the "other" innovation. Fuelling infrastructure requirements make that problem more difficult.

3. Using Decision Approaches facing Deep Uncertainty

We now discuss some approaches dealing with deep uncertainty from the perspective of the investor. The discussion will be illustrated at hand of our cases which involve deep uncertainty in different ways and to a different degree.

As to the potential decision approaches we will follow the overview that is provided and explained in more detail in Haas et al. (2021). We therefore start with probabilistic approaches (such as cost benefit analysis or the net present value approach) and then move to approaches which do not – or only partially – refer to probabilistic concepts. Those include *robust decision making*, *real options*, *hedging* and *diversification*, *info-gap decision theory* as well as so-called *dynamic adaptive planning*.

It is well known that probabilistic concepts such as the cost benefit approach (CBA) or standard net present value (NPV) display severe weaknesses in the context of deep uncertainty – not least because probabilities are not available. As the approaches are essentially based on a prediction for the different decision alternatives, either sufficient information to make the prediction is required or assumptions need to be made. However, the NPV approach is a well-established standard approach in decision making and is implemented by investors based on a lot of procedural experience.

For the decision to build Datteln 4, the NPV (or CBA) would hardly reflect the important uncertainty about the political environment delaying or potentially cancelling the completion of the power plant. One may argue, however, that the probability of the scenario of either incomplete construction or early shutdown is less relevant for the investment decision than one might think: Relying on a fairly safe system of proprietary rights in Germany may make it substantially less likely that the construction (or the operation) of a power plant (once it has been approved) will be stopped without a substantial compensation either through negotiation or through litigation. So, while the evolvement around Datteln 4 might look dramatic from the perspective of a policy maker or society, the degree of deep uncertainty from the perspective of the investor might be lower as the investor can benefit to some extent from the established and credible long-term commitment by the German government to enforce proprietary rights.

In the young offshore wind industry and from the perspective of a car manufacturer, the main drivers of deep uncertainty are rooted in complexity or technology (or less credible policy commitment). Here, the weaknesses of the classical NPV approach as a decision support instrument are more substantial. Comparing the NPV of a hydrogen- with the one of a “battery-path” seem unrealistic, and the young offshore wind industry is systematically faced with “first of its kind” problems which also can hardly be integrated in an NPV analysis (see Sun, 2021).

The approaches that need less probability related assumptions are quite diverse: they have different starting points, require different degrees of modelling, and may also have adaptive elements over time.

The framework of robust decision making typically starts by performing multiple simulations to derive multiple plausible futures. Different strategies (in other words: decision alternatives) are evaluated for each scenario, and finally a set of so-called robust strategies is identified, basically: which decisions lead to acceptable results across a broader set of scenarios. This approach requires a lot of data and modelling efforts (Hallegatte at al., 2012) and has so far been applied in the context of policy making (e.g., Jones at al., 2014).

The data and modelling requirements suggest that it is suitable only in a limited number of investment cases, where the efforts seem realistic and worthwhile. The general approach might also be applicable if scenarios in connection with the decisions (or strategies) can be determined with a limited amount of effort. The application in the Datteln 4 case would seem realistic: Once the construction is approved the power plant will either be generating a substantial profit as hoped by the investors at the time, or it may be delayed – potentially still offering cost coverage or it would be limited for political reasons, then expecting compensation payments. Note, that this is taking the perspective of the investor, not the policy maker. For the case of offshore wind, the unforeseeable nature of the upcoming problems seems to make the application more challenging as scenarios can hardly be determined. This could be different again for certain decisions in the transformation to zero emission passenger vehicles since some of the uncertainty can be characterised by an “either or”. Robust decision making therefore seems less appropriate in cases of deep uncertainty, which are strongly characterised by a large set of hardly known possible outcomes which differ strongly with respect to the acceptability to the investor.

The real options approach is already applied in the investment context, particularly also in the context of investment decision in power plants. One example is Fortin et al. (2007), who apply a combination of a real options framework with a portfolio optimization to power plant investments. Similarly, the approach has been applied in the automobile sector: Avadikyan and Llerena (2010) have looked at the example of a hybridization strategy also taking the flexibilities and irreversibility of investment decisions during the transition into account. Although their example is looking at the transition from ICE to hybrid, rather than the transition to either of two new technologies. In the context of real options, it is relevant to point to the strengths of the approach: to identify the “value of waiting” for additional information. This value may be quite different from the perspective of an investor as compared to the society under time pressure to avoid serious climate damage.

Hedging or diversification is part of modern portfolio theory which aims at identifying efficient strategies and requires assumptions about a probability distribution at least as a starting point. It can then unfold its strengths if a lot is known about correlations in the underlying system. These assumptions (possible outcomes known, initial assumptions about probabilities needed and sufficient knowledge about the underlying system to derive information about the correlation) suggest where this framework may be used. In the context of the energy transition this has not been applied very frequently. A review of the use in energy planning is provided by DelLano-Paz et al. (2017), where planning seeks to minimize either the risk or the costs of a (power generation) portfolio. For our cases, however, using a portfolio theory as a decision support tool for individual investment decisions which are typically not part of a portfolio appears not the first choice.

An approach that does not need assumptions on probabilities is the info-gap decision theory (Ben-Haim, 2017). The approach focuses on the information that is missing to make a decision. It identifies the decision alternative that – given a range of desired outcomes – can stand the highest level of uncertainty. It needs to compare outcomes and is therefore not suitable for completely unexpected outcomes.

Perhaps less a decision support instrument but rather a process-oriented approach is called Dynamic Adaptive Planning (Walker et al., 2019). This process it not geared towards a static one-time decision but includes a timing for sub-decisions. The process starts with the definition of objectives as well as constraints. The decisions to reach the objectives are then divided into sub-decisions which include time frames after which pre-defined decisions are made based on the information becoming available. In parallel, areas are defined where the plan is “vulnerable”, and a monitoring is installed to show if a vulnerability is triggered and requires action. Should the initial objectives get out of reach, then the initial loop would be started over again. Among the approaches that we discuss here, this one hast the highest flexibility. Based on that it is applicable to all levels of deep uncertainty, including the unknown unknowns. Further, it can be applied in combination with other, perhaps more technical, approaches. This seems necessary, as the sub-decisions need to be determined. If we take the first of our cases: the initial investment by E.ON in Datteln 4. This dynamic approach would not seem helpful, but as the situation evolves, the approach would imply a regular check if the objectives can still be reached, e.g., based on the expected future cash-flow and expected return, the political dynamics of the energy transition or the legal situation or the expected project lifetime. The added value of using this approach which allows for completely unexpected events in the context of offshore wind financing may be larger as it provides this frame for reflecting about the objectives at the level where they are endangered by new information becoming available (or risks materializing). Also, in the context of the car manufacturer who must decide whether to invest in BEV or in FCV innovation, this planning approach will make the objectives and particularly the “mission-critical” risks and potential reactions explicit if unexpected events materialize. While this clearly does not solve the decision problem, an established dynamic adaptive planning procedure in place may emphasize the possibilities to adapt and thereby reduce the value of waiting for more information.

4. Lessons learnt from the three cases

All three cases in the context of the energy transition have demonstrated that elements of deep uncertainty are present in the respective context and that this uncertainty decreases the speed of the energy transition since it makes it difficult to invest in the infrastructure or technology that is needed to drive the structural change.

Achieving an ambitious directed structural change such as it is required for the transition and at the same time avoiding excessive societal costs caused by inefficiencies requires an efficient interplay between investors (private and public) and the policy sphere. Further it requires the policy maker to be able to set a frame in which the transition can happen, without over-restricting the creativity of the market to identify efficient solutions – given the objective of the transformation. The cases display challenges and lessons learnt on both sides, the investor as well as the policy maker.

4.1 Investor related aspects

Looking across all the approaches above dealing with deep uncertainty, it becomes clear that they are very diverse regarding what type of information is needed to apply them, what level or depth of modelling is required or even where the approach is able to contribute to decision making, optimization, or planning. However, robust decision making, and dynamic adaptive planning appear to be applicable in a broader context and to provide additional information which might be helpful in the decision context and looking forward.

From the analysis of the cases, we cannot exclude that some of the approaches were applied from the firms' perspective. However, it appeared that often standard instruments were applied, and elements of deep uncertainty were often not treated different from risk-type uncertainty. The established real-option approach is a notable exception. However, having established that the energy transition does systematically more often lead to situations involving deep uncertainty, it seems promising to consider adding decision making approaches to the toolbox that do explicitly allow for elements of such deep uncertainty as the changing – sometimes disruptive – investment environment in the context of the energy transition or on the path towards a long-term sustainable economy will likely remain for some time to come.

4.2 Policy related aspects

The construction of a new coal-fired power plant (Datteln 4) starting commercial operation in 2020 appears to be against all trends and general policy announcements related to the energy transition. At the same time new technologies in the automobile sector in Germany suffer from reluctant investment and adoption. Again, this is against public policy messages talking about the long-term goal of zero-emission vehicles. These examples illustrate how challenging it is for a policy maker to send long-term credible policy signals to the markets to induce change. In fact, investors strongly prefer a reliable investment environment. By nature, a stable investment environment is easier to achieve in a rather static context, than within a changing context. Part of the stable investment environment is the reliability of the public administration including the approval of local authorities. This de-facto stability appeared to dominate the signals for change that were sent from the policy makers including the coal commission. A minister made this almost explicit by stating: “Whether the power plant will be finished and used is not an issue of political will but a legal question.”[6]

In a similar way, the policy signals which were sent to the car manufacturers were not sufficient to overcome the numerous challenges, which is arguably demanding: uncertainty about the choice of the technology plus a strong network-infrastructure required at least initially made it difficult for a commercial investor or a car manufacturer to act. But long-term policy signals which are credible are needed in this case as well. The uncertainty in the offshore wind industry was in a way less challenging for the policy maker as it did not involve two such distinct technology alternatives, and it was a much more focused or concentrated industry. A high initial feed-in-tariff guaranteed for more than a decade together with the government mandating the KfW to set up a dedicated fund of 5 billion Euro to co-invest in off-shore wind parks might have constituted a credible commitment that offshore wind has a role in the German electricity system.

The government needs to send a credible long-term signal that the transformational change will happen. There may be concerns about this inducing costs and risks to the competitiveness, but that could at least partly be compensated by a strong and broad government support of research and innovation. While an individual firm investing in research needs to focus on the value of R&D for the firm, from a government perspective it is also a success if an innovation within a firm is

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[6] "Ob das Kraftwerk kommt, ist keine Frage des politischen Wollens sondern des rechtlichen Könnens." See Sorge, 2011.

recognized and used somewhere else. And a stronger innovation orientation will be helpful along the structural change – not limited to the energy transition.

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