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Socio-technical discourses of European electricity decarbonization: Contesting narrative credibility and legitimacy with quantitative story-telling

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ABSTRACT

This paper presents an innovative approach to the responsible use of quantitative analysis when dealing with the governance of sustainability. Rather than using complicated models which try to predict and control the future evolution of complex adaptive systems, quantitative story-telling is proposed to check, first of all, the plausibility of proposed policies. As a case study, we check the plausibility of 'a radical decarbonization of the European economy based on a quick deployment of alternative sources of electrical energy generation'. Although our case study includes a high-level set of quantitative results, it is primarily methodological. The procedure of quantitative story-telling includes: (1) identification of the narratives used to inform policy; (2) identification of the relevant factors determining the feasibility, viability and desirability of expected results; (3) a quantitative analysis which falsifies at least one of these three factors, indicating an implausibility of the expected results; and (4) identification of knowledge gaps in the existing discussions over the issue. The modern European energy system does need an urgent and radical transformation. However, before imposing drastic and ambitious policies, it is essential to check the quality of the diagnosis. Our analysis flags the existence of a few reasons for concern with regard to the current story-telling.

1. Introduction

The European Commission maintains a flagship initiative to transform the European Union into a resource efficient and low-carbon economy [1]. It contends that, within a few decades, economic growth and energy use must be decoupled. Simultaneously, it contends that an improvement of both economic competitiveness and energy security must be realized. Unprecedented societal determination and commitment would be needed to realize such a heroic energy transition [2]. Entire sectors of the economy would necessarily reinvent themselves inside a very short period of time. A reflection on the Commission's narrative choice reveals, however, that their ambitious energy policy package for the European Union is based exclusively on *structural* and *technological* changes. Accordingly, the contextual understanding of 'sectoral reinvention' is both reductionist and incomplete [3–5].

Perhaps more worrisome than this observation is the expectation that the Commission's transition is to be achieved by a series of

technological innovations driven by the invisible hand of the market. The expensive transition experiment done in Germany – the *Energiewende* – is an illustration of this worry. Indeed, according to the German Federal Court of Auditors, the *Energiewende* has thus far been “characterized by inefficiency” [6]. In concluding statement, the Court states that the German Ministry of Economics and Energy has “so far not taken *any* steps to ensure that inefficient programmes which at the same time contribute little to energy transition are phased out” (emphasis added) [6]. At the same time, significant economic investments (nearly €200 bn) in alternative energy sources in Germany has led to the highest electricity prices in Europe [7] without significantly reducing emissions levels [8]. This experience, including societal hesitance to question the decisions of the *Energiewende* policies, flags the existence of a systemic problem with the quality of the scientific evidence used to inform the process of policymaking when dealing with complex issues [9]. Solutions inspired by economics, such as the leveled cost of electricity – based on the assumption that “electricity output is perfectly interchangeable and

Abbreviations: Li-ion, lithium-ion; GDP, gross domestic product; kW, kilowatt; MW, megawatt; GW, gigawatt; TW, terawatt; h, hour; yr, year; Gt, gigatonne; bn, billion; CO₂-eq., carbon dioxide equivalent; bn, billion; MAGIC, Moving Towards Adaptive Governance in Complexity

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homogeneous" [10], have not yet solved the problem [11].

The example of the *Energiewende* illustrates the risk of informing policy with an incomplete hegemonic storyline. In particular, the *Energiewende*'s storyline is dominated by the representation of the performance of an electrical grid based on economic narratives [12]. Alas, when addressing sustainability issues it is unavoidable to face "wicked problems" [13] entailing the coexistence of a virtually infinite set of relevant issues that should be considered simultaneously. When non-equivalent dimensions and scales of analysis and legitimate but divergent expressions of concerns must be considered simultaneously, it becomes difficult to derive an uncontested definition of what should be considered rational and what should be considered fact [14–16]. The Cartesian dream of prediction and control [17,18] clashes against the complexity [13] associated with the sustainability predicament. A situation is created where 'facts are uncertain, values in dispute, stakes high and decisions urgent' and the use of science for policy becomes problematic [19]. In general, when dealing with large doses of uncertainty, a massive generation of expectations translates into a political activity with the goal of mobilizing resources in order to 'colonize' the future of the society [20]. Jasanoff and Kim refer to this generation of societal expectations as the establishment of 'social imaginaries'. Institutional imaginaries, they further say, often come with technological promises [21].

The establishment of a sociotechnical imaginary is an influential act insofar as it creates and manages future expectations [22]. Expectations, through their creation of "dynamism and momentum" [20], play an essential role in "guiding technological innovation and sustainability transitions" [23]. In the context of a sustainability transition, an aggressive mobilization of expectations translates into an ideological endorsement of justification narratives. Once expectations have attained a normative status, they need not be justified nor reflected upon [24]. Any myths that may or may not exist in support of normative expectations are then no longer given space for critical and hesitant reflection [23,25]. In the case of the *Energiewende*, a massive set of expectations has been created. Conflicting those lofty expectations with widespread failures has recently led to substantial disillusionment. To be sure, Kay Scheller, the president of the German Federal Court of Auditors, is currently concerned that "voters could soon lose all faith in the government because of [the *Energiewende*'s] massive failure" [12]. Given their urgent nature, societal disillusionment with a renewable energy transition is quite an unfortunate and undesirable thing.

Janda and Toupizi [26] suggest that learning-type storylines can gainfully problematize hero-type storylines such as those of the European Commission and *Energiewende*. Indeed, learning-type storylines are useful for challenging hegemonic narratives. The intent of problematizing with learning storylines is not, however, to undermine. Rather, the intent of problematizing is to balance and develop the standing discussion. The result of such investigation may be seen to have a positive discursive feedback and lead valuably to the co-creation of increasingly robust transition imaginaries [27,28]. We are convinced that a more informed discussion about problems and potential troubles of energy transitions will benefit all social actors and allow a better policy framing through consideration of different, yet equally legitimate, proposals of sustainability policies.

To deal with this challenge, we propose a new approach to the use of quantitative analysis termed 'quantitative story-telling'. Quantitative story-telling aims towards a more responsible use of quantitative analysis as it informs decision making. In this approach, no solutions to the problem (whose problem?) are proposed. No improvements (for whom?) are suggested. Quantitative story-telling aims simply to check the quality of an elected story-telling and related policy narratives. In this paper, quantitative story-telling is applied to test the plausibility of the claim that 'in two or three decades, it will be possible to scale-up the supply of intermittent sources of electricity (wind- and solar-based) to obtain a significant decarbonization of European economies'. Considering recent attention given to the failures of the *Energiewende*,

the decision to explore the plausibility of that claim is timely and advantageous. Importantly, the fact that we check the plausibility of this story does not mean that we endorse or oppose its problem framing or any of the proposed solutions. We do not necessarily endorse nor oppose a centralized electrical grid based on wind and solar primary energy sources.

The text of the paper is organized as described in the following. Firstly, we introduce the concept of quantitative story-telling and how we conceptualize the problems associated with the scaling-up of the supply of electrical energy generated by intermittent sources into the actual typologies of electrical grids. Secondly, we provide a quantitative analysis of the plausibility of the proposed strategies for a quick transition to a low-carbon economy based on a massive surge in the supply of alternative energy. Thirdly and finally, a quantitative story-telling based on the analysis of the results suggests that there are serious concerns about the claims endorsed by European Union policies. This result is intended as a warning that a political strategy based on the mobilization of expectations about results that are not reachable in the promised time horizon may lead to the choice of unwise and unfair policies.

2. Methods and problem conceptualization

2.1. A new method of quantitative analysis

Any macro-level assessment which involves the scaling-up of electrical energy generation depends largely on its specific expectations of growth in the consumption of electrical energy. Relevant assessments are required to consider determining factors of both demand and supply. On the demand side, the growth of various unique load forms is of primary importance. For example, industrial, transportation, commercial and residential components are frequently individuated. On the supply side, the factors determining the availability of resources are of primary importance. For example, differentiating conventional and renewable resources and consideration of the growth of transmission and distribution infrastructures are both frequent procedures. Even more complex than these primarily engineering aspects, however, is the analysis of how changes in the demand and changes in the supply can be integrated during a sector transition when considering several dimensions of analysis. Crucial dimensions of analysis include the desirability of the specific mix of social practices as well as that mix's resulting economic viability and biophysical feasibility. Such an assessment requires characterizing the pattern of electrical energy end uses on the demand side versus adjustments taking place in conventional sources. In turn, this requires consideration of the economics and financials of fossil and nuclear fuel as well as renewable energy sources, the scaling-up of the generation of renewable sources against the variability of intermittent supply and the consequent problems of transmission and distribution congestion in respective networks.

For all these reasons, an energy sector transition is a very complicated ordeal. Among other aspects, it requires a significant 'rewiring' of the *functional relations* between and within sectors (i.e. a new sector coupling), a re-arrangement of social practices (associated with the patterns of consumption in both paid and non-paid work sectors), a change in existing technologies, a revolution in the economic business models and a re-thinking of institutional regulation. Put differently, the electrical grid will have to go for 'something completely different'. Necessary changes will be determined in an unpredictable way by the effects determined by a series of impredicative relations (chicken-egg causality dilemmas) over drivers of changes only observable across different dimensions and levels of analysis. When trying to predict the evolution of this type of system – a complex adaptive system – and especially when dealing with radical re-adjustments, one must expect the presence of large doses of uncertainty hampering prediction and control [29,30]. While conventional economic analysis does play an important role in determining the viability of changes, it does not

contain a relevant set of methods pertinent to the assessment of the biophysical feasibility of changes. In the words of H.T. Odum, given a technology, a “gallon of gasoline will power a car the same distance no matter what its price” [31]. By implication, within the corpus of learning-type storylines, economic narratives must be complemented with other narrative varieties. A check on the feasibility (compatibility with biophysical constraints), the viability (compatibility with economic and technical constraints) and the desirability (compatibility with institutions, normative values and aspirations of the actors in the society) requires an integrated use of different disciplinary lenses.

Assuming all this to be the situation, a responsible use of quantitative analysis entails a change in the purpose of the analysis. Rather than crunching numbers to identify an ostensibly optimal course of action or to predict future states of the system, it is wiser to use quantification to check the robustness of the story-telling associated with a given policy [9,32]. This approach, proposed and tested in the European project *Moving Towards Adaptive Governance in Complexity* (MAGIC) [33], is called ‘quantitative story-telling’. In addition to complexity science, the process of quantitative story-telling draws philosophically on post-normal science for governance [29,34]. In post-normal science for governance, the quality of analytical outcomes depends on clarifying the choices that have shaped the content of the evidence base and the modes of analysis considered as salient and credible. Quantitative story-telling is not, therefore, concerned with refinement of the minutiae of existing dynamical models. Instead, it is used to explore counterfactuals of hegemonic hero stories and question whether existing science-policy consensuses are ignoring crucial problems by taking too narrow a view of the challenges to be faced. Quantitative story-telling is used in this paper to check the plausibility of the proposed set of strategies anticipating a quick transition to a low-carbon economy based on intermittent sources of electrical energy.

In the rest of this section, we illustrate the pre-analytical choices that have shaped our quantitative analysis. We do this in order to make transparent our framing of the issue and the consequent identification of the relations to be considered when checking the plausibility of the chosen story-telling [35].

2.2. “The” peculiar, policy relevant characteristic of electrical energy

2.2.1. Accounting for electrical energy

Different forms of energy present different challenges and require different accounting techniques. The form of energy known as electrical energy happens to be convenient, versatile, reliable and precise. Technologies which convert electrical energy to other useful forms of energy – mechanical, chemical and thermal, to name a few – are, moreover, highly efficient. All these characteristics are of course highly desirable for society. Electrical energy does, however, have a fundamental drawback in that it is a flow of energy. Flow resources are not directly useful unless they are either put to immediate use or stored. One could claim that electrical energy is “better” than thermal energy in the same way one could claim that ice cream is “better” than a cookie. While ice cream may be more delicious at the point of consumption, if not eaten on the spot, ice cream will melt down and become useless. The ice cream metaphor illustrates how electrical energy can be considered, at the point of consumption, more user friendly than chemical energy (e.g. in the case of fossil fuel energy carriers) and

nuclear energy (e.g. in the case of fissile material energy carriers). In contrast to electrical energy, however, fossil and nuclear fuels are stocks of energy and therefore allow the generation of flows of energy whenever a consumer desires. The chemical energy in the tank of a car, for example, can be used whenever the owner decides to use the car. On the contrary, electrical energy requires the simultaneous operation of a device generating it and a device utilizing it.

Due to this difference, electrical energy’s flow aspect implies the need for a high-resolution spatial and temporal balance between its supply and demand. Meaningful energy accounting measures must, therefore, individuate the specific link to be established in space and time between power capacity supplying electrical energy and power capacity demanding electrical energy. The consumption of a kWh of electrical energy is an event that must be defined after adopting local scales of space and time. Indeed, the long-term averaged value of a quantity of electricity loses the relevant information needed to characterize the social desirability, economic viability and biophysical feasibility of electrical energy. GWh per year, a common metric in energy accounting, has this drawback. To make an analogy between GWh per year and the ice cream metaphor, for a person selling ice-cream cones, information about the availability of one tonne of ice cream per year does not guarantee that this quantity of ice cream will be accessible in the right quantity, at the right moment and in the right place. In contrast, meaningful energy accounting for stocks of energy (cookies in the ice cream metaphor), may appropriately be made at a relatively coarse spatial-temporal scale. GJ of gasoline stocks per year at the national scale, for example. In summary, successfully accounting for stocks of energy (e.g. fossil fuels) generally requires significantly less spatial-temporal precision than successfully accounting for flows of energy (e.g. electrical energy).

The need for a high-resolution spatial and temporal balance between the supply and demand of electrical energy additionally allows for the definition of a metric of quality of any given watt-hours. In relation to regulatory aspects, three types of power capacity for producing electrical energy may be identified: (i) base-load (predictable, but supply is difficult to regulate); (ii) peak-load (predictable and easy to regulate); and (iii) intermittent (not predictable and supply cannot be regulated, only curtailed). The characteristics of these three forms of power capacity determine the quality of the watt-hours produced. By implication, from an engineering point of view and contrary to what is assumed by business-as-usual economic analyses based on price, different types of kWh can and should be distinguished due to implications in their possible use in the grid. When considering existing electrical grids, predictable and regulatable watt-hours are of the highest usefulness in matching supply and demand. It is, therefore, reasonable to expect that the cost of production of peak-load watt-hours is higher than that of base-load watt-hours. For the same reason, it is reasonable to expect that the cost of production of base-load watt-hours is higher than that of intermittent watt-hours. From this realization we can deduce that the fact that watt-hours produced by intermittent power capacity (e.g. wind turbines, solar photovoltaic panels) may be cheaper in terms of fixed and operating costs than watt-hours produced by other forms of power capacity is not by itself a particularly relevant piece of information for the design of a national electrical grid. These points may be summarized in the crucial, yet in the case of contemporary energy accounting for social systems frequently overlooked, realization that not all watt-hours of energy are the same. Table 1 summarizes key

Table 1

Characterization of performance factors for different types of electric power plants. Usage rates based off [36], capacity factors calculated from the datasets used in Section 3 of this article (annual-national averages). Section 2.3 provides additional theoretical background to the content of this table.

| Type | Power capacity | Gross usage | Capacity factor | Grid demand | Utilization factor | Energy-to-power ratio |
|---------------|----------------|----------------|-----------------|--------------|--------------------|-----------------------|
| Baseloaders | 1 MW | 6000 + h/yr | 0.7 + | Approx. 100% | 0.7 + | 6+ GWh/MW |
| Peakable | 1 MW | 1000–4000 h/yr | 0.1–0.5 | Approx. 100% | 0.1–0.5 | 1–4 GWh/MW |
| Intermittents | 1 MW | 400–3000 h/yr | 0.05–0.3 | 0–100% | 0–0.3 | 0–3 GWh/MW |

classificatory differences between the three types of power capacity mentioned. The *Capacity factor* scales *Gross usage* based off an 8760-hour year. *Grid demand*, in particular for intermittents, defines curtailment. The *Utilization factor* is directly related to both the *Capacity factor* and *Grid demand*.

2.2.2. Storage

It follows from the flow nature of electrical energy that, within the existing pattern of production and consumption of electrical energy based on a centralized system of production and distribution, supplied electrical energy that is not immediately put to use must be either stored or 'wasted'. Utility-scale storage is problematic. By using capacitors, electrical energy can in fact be directly stored without conversion. Using capacitors (or better, supercapacitors) as a means of utility-scale energy storage in electrical grids, however, is not feasible neither currently nor in the foreseeable future. Supercapacitors self-discharge completely in just 3-4 days, a self-discharge rate two orders of magnitude higher than that of, for example, lithium-ion (Li-ion) batteries. The energy density of supercapacitors is furthermore relatively low, at least an order of magnitude less than that of Li-ion batteries [37,38]. To overcome these practical incompatibilities, electrical energy must instead be converted to another form of energy in order to be effectively stored. To name a few of the more common forms, energy might be stored at the utility-scale in the form of mechanical energy (e.g. flywheels), gravitational energy (e.g. pumped hydro), thermal energy or chemical energy (batteries, e.g. flow, lead-acid, Li-ion, sodium or zinc batteries).

By far the most prevalent utility-scale energy storage technology to date is pumped hydro, covering roughly 96% of storage capacity globally [39]. In the developed world, however, relatively limited expansion potential exists in terms of new pumped hydro sites. Most of the low-hanging fruit locations have already been developed. Other energy storage technologies are also rapidly becoming cost competitive. In particular, the battery family of storage technology has been gaining momentum in high-level policy [39]. Many outlook analyses also focus on batteries. Lazard's annual *Levelized Cost of Storage Analysis*, for example, goes so far as to omit entirely mechanical, gravitational and thermal energy storage technologies. This omission is a decision based on their identification of "limited current or future commercial deployment expectations [for those technologies]" [40]. Bloomberg's *New Energy Outlook* similarly maintains a substantial focus on batteries for storage, although not entirely exclusively like Lazard [41].

2.3. The role of alternative sources in the existing electrical grid

After establishing a baseline understanding of electrical energy, including its beneficial and problematic aspects as well as its storage potential, it is meaningful to provide a baseline understanding of alternatives in the electrical grid. The following symbolic equations (Eqs. (1) and (2)) form a trivial comparison between a conventional fossil fuel-based electrical grid (Eq. (1)) and an electrical grid with a relatively large quantity of its electrical energy generated from intermittents power capacity (Eq. (2)). In practice, intermittents power capacity is power capacity converting solar and wind primary energy sources into electrical energy. Key technologies include solar photovoltaic panels and wind turbines. It's also worth noting that the introduction of intermittents power capacity in the electrical grid is by and large fueling the contemporary renewables energy transition. Following Table 1, Eqs. (1) and (2) represent a symbolic, macro-characterization critical to the issue of scaling-up alternatives in the electrical grid.

$$PC \times GU = GE_{el} \quad (1)$$

$$PC \times GU \times GD = TE_{el} + WE_{el} \quad (2)$$

In Eqs. (1) and (2), *PC* stands for *power capacity* (generally nameplate

e.g. measured in megawatts), *GU* stands for *gross usage* (the total time of use over given a period e.g. measured in hours/year), and *GE_{el}* stands for *gross electrical energy* (gross generated e.g. measured in gigawatt-hours/year). In Eq. (2), *GD* stands for *grid demand* (the demand, placed by the grid, on physically identifiable power capacity represented as a percentage of generated electrical energy), *TE_{el}* stands for *transmitted electrical energy* and *WE_{el}* stands for *wasted electrical energy*. *GE_{el}* is equivalent to the sum of *TE_{el}* and *WE_{el}*. Lastly, in relation to the previous Table 1, Eq. (1) is analogous to an extensive representation of *utilization factor* in the case of 100% *grid demand*. Eq. (2) is analogous to an extensive representation of *utilization factor* in the case *grid demand* is less than 100%.

The predicament of an electrical grid with high intermittents penetration is that intermittents power capacity is constrained by both *GU* and *GD* when not given grid priority. In this situation, curtailment typically occurs when curtailment is economical. As a result, *GU* is lower than it would be if determined only by natural constraints and *WE_{el}* increases. In other words, observed utilization factors decrease in relation to corresponding capacity factors. On the other hand, when intermittents power capacity is given grid priority, only *GU* constrains the equation. In that circumstance, however, intermittents power capacity will have either: (i) forced the curtailment of base-load power capacity (leading to an increase in losses at the system level similar to the previous case); (ii) created an additional requirement for peak-load power capacity capable of compensating low-quality supply of electrical energy from intermittents with high-quality supply of electrical energy; or (iii) created a situation of unfulfilled demand (major power outages). In Section 3 a story-telling following a major scaling-up of intermittents power capacity will be explored, the *GD* estimated, and the option space around *WE_{el}* and *GU* discussed.

In summary, mitigating the unwelcome effects which result from the injection of large quantities of a 'low-quality' supply of electrical energy in the electrical grid (the effect of intermittents integration) is an exceptionally delicate task. Subjective decisions must be made by electrical grid operators. In general, increasing the temporal ability for a base-load system subcomponent to dispatch (increasing its ability to ramp power output) causes that subcomponent to suffer in terms of thermodynamic efficiency, capital investment and operational investment. The solution of peak-load power capacity, the classic example of which is open-cycle gas turbines, is both relatively expensive in financial terms and relatively inefficient in thermodynamic terms.

2.4. The importance of adopting a relational framework

Up until this point, Section 2 has described how the large-scale accommodation of alternatives in a national-scale, centralized electrical grid implies the need for any or all of: (i) a considerable non-intermittent operating reserve; (ii) a considerable energy storage ability; or (iii) a considerable change in the social practices creating the demand for electrical energy. Whereas options (i) and (ii) are structural changes, option (iii) includes an important component of functional change. In order to anticipate, in a holistic manner, the large-scale accommodation of alternatives in a national-scale electrical grid, a methodology capable of coordinating both structural and functional analyses is, therefore, a prerequisite. By extension, reductionist approaches (which, by definition, ignore function) miss part of the picture.

By shifting the analytical focus from epiphenomena (a non-causal byproduct – a simple recombination of the same structural elements) to phenomena, the adoption of a relational analytical framework proves a radical departure from reductionist science. Relational analysis is central to the methodology of this contribution's analysis [42]. In the relational mindset, and indeed in quantitative story-telling, structural elements are considered instances (specific realizations) of a system's functional relations. According to Rosen, conventional dynamical modeling does not adhere to these methods. Instead, dynamical modeling makes a dangerous claim that "a sufficiently elaborate

characterization of [a system's] structural detail will automatically lead to a functional understanding of [that system's] behaviors" [43].

To illustrate the point, no level of material description of structures used to generate peak-load electrical energy (e.g. open-cycle gas turbines vs. the use of hydropower) and structures used to consume peak-load electrical energy (e.g. certain consumer appliances) is sufficient to create a robust understanding of the inherently functional, social demand for peak-load electrical energy in the first place [44]. Similarly, no understanding of the functional, social demand for peak-load electrical energy suffices to create a robust understanding of the instantiating structures. Both descriptions are inextricably needed and together they form an impredicative relation. In summary, social energy systems are characterized by the existence of inherently irreducible, impredicative definitions. They are, by extension, non-simulable (no largest model) and not purely synthetic. Effectively, they are complex adaptive systems [45]. The recognition of this point formats the results generated in Section 3 and frames the discussion made in Section 4.

3. Our quantitative analysis

3.1. Goal of the analysis

Our exercise in quantitative story-telling investigates additional factors which could be used to inform policies such as the *Energiewende*. We try to put ourselves in the shoes of a grid planner with the goal of integrating intermittent sources of electricity into the existing German (and Spanish) electrical grid. We then use quantitative analysis to ask whether grid problems, such as those experienced in the *Energiewende*, could have been anticipated. In order to investigate these concerns, we anticipate a scaling-up of annual wind and solar generation in Germany and Spain to what would be 100% of the current annual electrical grid demand for each country. While the case study is primarily illustrative in purpose, it does reflect current policies. In Spain, the most recent legal proposals make plans for 100% of the nation's electrical energy to be sourced from renewable primary energy sources by 2050 [46]. In Germany, the Renewable Energy Act states that renewable primary energy sources should fulfill "at least 80% of gross electricity consumption" by 2050 [47]. In order to fulfill their part of the Paris Agreement, however, Germany will likely need to have 100% renewables in the electrical grid by just 2040 [48].

Admittedly, intermittent solar and wind primary energy sources do not fully encompass 'renewable energy'. Indeed, hydro and biomass currently account for 10–12% of the net electrical energy generation in Germany and Spain [49]. As previously noted, however, both hydro and biomass have markedly limited expansion potential [48,50]. While neglecting hydro and biomass expansion potential introduces error to the results, the margin of error introduced by their omission is insubstantial in comparison with other analysis uncertainties. For example, electric vehicle uptake is widely predicted to force a major increase in electrical grid demand over both the medium- and long-terms (2030 and 2050, respectively). However, uncertainties surrounding the exact degree of electric vehicle uptake prohibit the precise characterization of changes in overall grid demand [51]. As a result, anticipations of grid demand in the medium- and long-term in e.g. the United Kingdom have fluctuated no less than 100% in just the past two years precisely due to changing estimates of electric vehicle uptake [52,53]. The future of our electrical grids is a highly uncertain ordeal.

An additional, final remark is that the enclosed analysis embarks from a perspective of national security. From the perspective of national security, in the occasion of a failure event either an increasing amount of contingency power capacity (e.g. backup power plants or storage) must be provided within national boundaries or the national social demand profile must accommodate. As before, these assumptions represent just one possible, pessimistic future. Still, they are not entirely far-fetched. Indeed, the issue of security of supply in the electrical grid

has encouraged many European states (including both Germany and Spain) to implement substantial capacity mechanisms in recent years [54,55]. Such mechanisms stand chiefly in contrast to alternative visions of a highly cooperative European super-grid.

In summary, three main objectives of the entailed analysis are: (i) to explore scale issues of intermittent renewable primary energy sources in the electrical grid; (ii) to illustrate how a relational analysis approach may be used to inform electrical grid futures; and (iii) to provide an example of how electrical grid option spaces may be established. To achieve these objectives, the extent of the anticipated worst annual failure event is detailed at various consumer guarantee and confidence levels. Related to the worst annual failure event, the maximal instantaneous power gap and integrated energy gap – both critical aspects of contingency planning – are calculated. These numerical results are then discussed from a structural-functional perspective.

3.2. Datasets

Spain and Germany were selected as exploratory cases due to their status as countries undergoing rapid renewable energy transitions. In the global context, and in both absolute and relative terms, both countries are leaders in the use of intermittent primary renewable energy sources (wind and solar). Table 2 introduces the datasets used in this case study to detail electrical energy production. In general, the data is characterized by a high degree of completeness in the sense very few data points were missing or contestably outliers. A more detailed explanation of data fidelity may be found in Appendix A. While the data actually reflects electrical grid demand, it proxies total feasible renewable electrical energy generation remarkably well. To date, for Germany and Spain, for the current analytical purposes and in large part because of legal priority granted to it, a negligible amount of electrical energy from renewable energy sources was curtailed (within the range of 0–2%) [56,57]. Following Table 2, Fig. 1 describes the changes in the power capacity used to generate electrical energy by detailing the power capacity profile at the start and end points of the datasets detailed in Table 2.

Perhaps the most striking aspect of Fig. 1 is the significant increase in total power capacity following a relative increase in electrical energy sourced from intermittent primary energy sources. Specifically, Spain observed a 17% increase in total system power capacity over 12 years and Germany observed a 27% increase in 8 years, 14.5 GW and 47.5 GW respectively. This increase was a result of a respective 11% and 17% increase in intermittently sourced electrical energy generation. While prodigious amounts of wind and solar power capacity were added in both countries, conventional fossil-fuel and nuclear power capacity only marginally decreased *regardless of a negligible change in demand*. This remarkable long-term trend is depicted in a more transparent manner in Fig. 2.

3.3. Results

Following the discussion in Section 3.1, within existing electrical grids decision makers operate in a high-dimensional option space. The apparent historical decision to retain a majority of conventional power

Table 2

Summary of datasets used in the case study. Intermittents penetration reflects the percentage of electrical energy generated by wind and solar primary energy sources in the respective country (annual average). Spain refers to Peninsular Spain only. Sources as follows. Spain: [58]. Germany: collated from the four German transmission system operators [59–62].

| Region | Start date | Length | Resolution | Intermittents penetration | |
|---------|------------|--------|------------|---------------------------|-------|
| | | | | End | Start |
| Spain | 1/1/2007 | 144 mo | 10 min | 20.1% | 9.4% |
| Germany | 1/1/2011 | 96 mo | 60 min | 30.0% | 13.3% |

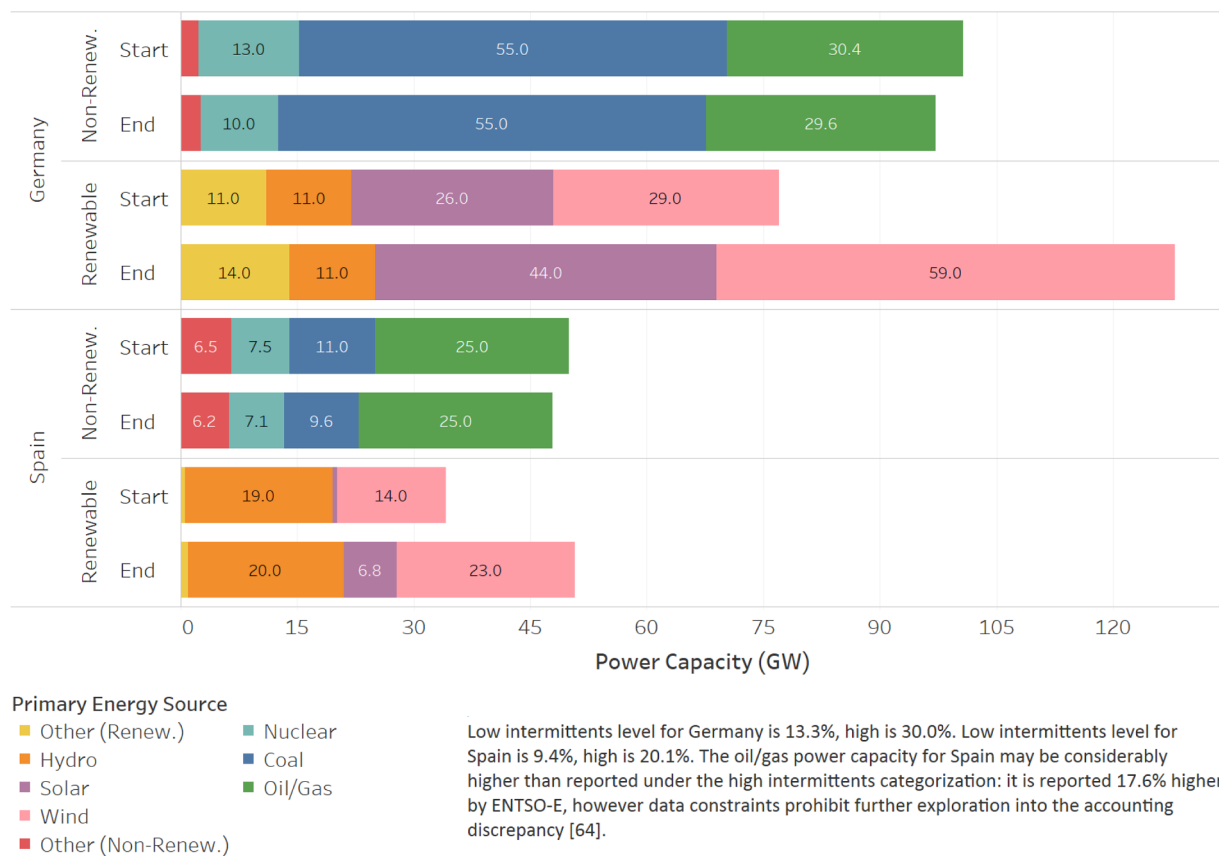


Fig. 1. Structural reading of the electrical grid power capacity composition. Refer to Table 2 for the points in time associated with the differing intermittents penetration levels (i.e. the Start and End points). Sources as follow. Spain: [58,63,64]. Germany: [59–62,65].

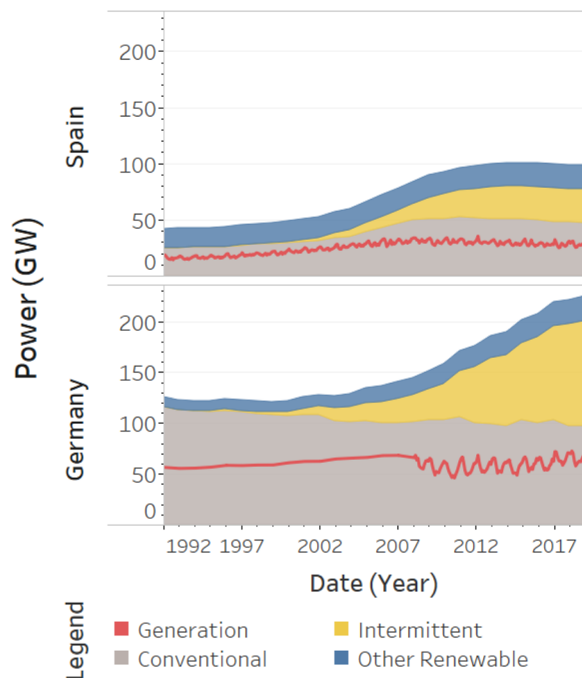


Fig. 2. Electrical energy generation and growth in power capacities over time during the Spanish and German renewable energy transitions. Additional characteristic data available in Fig. 1. The generation data overlay is presented at a monthly resolution for Spain and yearly until 2008 for Germany, monthly thereafter. Sources as follow. Spain: [63,66]. Germany: [49,64,67].

capacity regardless of a significant increase in renewables power capacity (depicted in Figs. 1 and 2) represented just one of the many possible options decision makers had available to them. The original option space contained many alternative transition pathways. In the exploration of future grid possibilities, it is of primary importance to describe the option space in a manner capable of informing a plurality of decision makers each with different but equally relevant considerations and concerns. Table 3 provides a set of statistical information reflecting challenges which would need to be overcome by decision makers. Specifically, it describes energy and power dimensions of the predicted worst annual failure event. This event represents the crux of what would need to be overcome in an electrical grid with high intermittents penetration. In reality, each point of data in Table 3 is the basis of a unique scenario characterized by different functional assumptions about social demand. Each of these functional assumptions entails different structural implications. To restate the assumptive basis, the ensemble of anticipations described imagines future electrical grids where intermittent renewable primary energy sources are used to generate electrical energy at a scale equal to 100% of the present-year electrical grid demand.

In a closed, national and centralized electrical grid where electrical energy is sourced predominantly from intermittent primary energy sources, three categories of options are available to decision makers planning to accommodate the expected worst annual failure event (detailed in Table 3). Firstly, reserve conventional power capacity may be retained. Secondly, social demands for electrical energy may, either forcibly or willingly, undergo major change. Thirdly, a major addition of storage capacity may be made. Figs. 1 and 2 in Section 3.2 indicated that the first option – retention of reserve conventional power capacity – was apparently the one historically taken both in Germany and Spain. From Table 3 we could say that a majority of conventional power

Table 3

Statistical description of annual ‘worst events’ in two imagined electrical grids where 100% of the electrical energy is generated from intermittent sources (an annual average of combined wind and solar). The insight presented is helpful for informing subjective decisions within the option space. The power gap is characterized as both an absolute level (in GW) and a relative level (percentage of the total electrical energy demanded but unfulfilled). The energy gap described refers to a singular, continuous period where less than the guaranteed level of total electrical energy was fulfilled by intermittent energy sources. See [Appendix A](#) for extended discussion on the underlying statistical methods.

| | | Guarantee | Confidence Level | | | |
|--------------------|------------|-----------|------------------|-------------|-------------|--------------|
| | | | 50% | 75% | 99% | |
| Variable / Country | Power Gap | Spain | 95% | 31 GW (73%) | 34 GW (78%) | 39 GW (91%) |
| | | | 90% | 32 GW (74%) | 34 GW (78%) | 38 GW (88%) |
| | | | 75% | 31 GW (71%) | 33 GW (75%) | 37 GW (86%) |
| | | | 50% | 29 GW (67%) | 31 GW (73%) | 38 GW (87%) |
| | | Germany | 95% | 65 GW (81%) | 71 GW (88%) | 84 GW (100%) |
| | | | 90% | 65 GW (81%) | 70 GW (87%) | 84 GW (100%) |
| | | | 75% | 63 GW (79%) | 69 GW (86%) | 84 GW (100%) |
| | | | 50% | 60 GW (74%) | 67 GW (83%) | 83 GW (100%) |
| | Energy Gap | Spain | 95% | 4.2 TWh | 4.7 TWh | 5.8 TWh |
| | | | 90% | 3.7 TWh | 4.2 TWh | 5.4 TWh |
| | | | 75% | 2.8 TWh | 3.2 TWh | 4.3 TWh |
| | | | 50% | 1.5 TWh | 1.8 TWh | 2.5 TWh |
| | | Germany | 95% | 14 TWh | 17 TWh | 22 TWh |
| | | | 90% | 13 TWh | 15 TWh | 21 TWh |
| | | | 75% | 10 TWh | 12 TWh | 17 TWh |
| | | | 50% | 6.6 TWh | 7.3 TWh | 9.1 TWh |

capacity would need to be retained if the first option is to be taken in isolation (i.e. we expect failure events at a power magnitude equal to that of the entire electrical grid). It's also worth noting, however, that the first option largely defeats the decoupling purpose of a renewables transition. The second option – changes in social demand profiles – is inevitable. That said, the nature of the changes and the degree policy guidance will play is unclear. Following the previous discussion of socio-technological imaginaries and technological promise, the second option typically but unfortunately takes a backstage position in contemporary energy transition efforts [68,69]. This is due to the fact that contemporary energy transition efforts are primarily concerned with quantified change of the structural composition of the electrical grid [70]. In contrast to the first and second options, the third option – storage – has gained significant traction in recent years [39].

Following the generation gaps presented in [Table 3](#), estimations of the monetary costs and greenhouse gas externalities associated with the use of Li-ion batteries as utility-scale electrical grid storage are provided in [Table 4](#). (The decision to explore the utility-scale use of Li-ion batteries is justified in [Section 2.1](#) and in [Section 4](#).) Working as a peak electricity provider, the unsubsidized and levelized cost of Li-ion batteries is currently estimated to be between \$285 and \$581/MWh [71]. The greenhouse gas emissions resulting from manufacturing of just the lithium batteries (i.e. none of the other required infrastructure) is estimated to be between 33 and 172 tons CO₂-eq/MWh [72]. An example of interpreting [Table 4](#) follows. If a Germany highly concerned with national security aimed to guarantee 95% of their annual average 100% intermittents electrical energy generation at a 99% confidence level, they should expect to prepare contingency storage capable of providing 22 TWh with an 84 GW peak output. [Table 4](#) contextualizes the structural costs of that storage related to the use of utility-scale Li-ion batteries to be between \$6.4 bn and \$13 bn. In terms of greenhouse gas emissions, the structural costs of storage are expected to be between 0.74 Gt and 3.9 Gt CO₂-eq.

For context, the greenhouse gas emissions embodied in just the manufacturing of the Li-ion batteries used as peakers and described in

[Table 4](#) are on the order of the entirety of greenhouse gas emissions for their respective countries (in 2016, 0.9 Gt and 0.3 Gt CO₂-eq. for all sectors including indirect emissions¹ for Germany and Spain, respectively) [73]. While the financial costs are substantial, they are rather minor in relation to the cost of replacing existing conventional power capacity with renewable alternatives assuming current price points [74]. It should lastly be noted that [Table 4](#) is a naïve interpretation of [Table 3](#). The [Table 4](#) estimates do not take into account additional storage capacity required to avoid damaging depths of discharge, additional additive factors such as imperfect round-trip efficiency, self-discharge rates, climate control of the storage facilities and compensation for transmission losses and subtractive factors such as time-of-use tariffs (– 15 to 25%) and other grid flexibility measures [75]. Though many of these factors are functional decisions of confidence and guarantee, decisions that electrical grid operators make as they align themselves in the option space described by [Tables 3](#) and [4](#), these factors serve to compound the quantitative estimates provided in this section and are beyond the scope of this work.

4. The plausibility of a quick scaling-up of intermittents

In recent years in Germany and Spain there have been fleeting moments where nearly all electrical energy consumed was derived from renewable primary energy sources. Clearly the combination of weather patterns and energy demand was remarkably favorable at these moments. Indeed, over the course of the past year, the average generation from intermittents for Germany and Spain was between 20% and 30% for both countries. This figure is a far cry less than totality. Considering these facts, it is important to then realize that the continued policy mandate to increase renewables power capacity results from largely unquestioned assumptions of social practice and inflexible functional

¹ Indirect emissions do not, in this case, include land-use, land-use change and forestry (LULUCFs).

Table 4

Interpreted impacts for Table 3, where electrical energy discrepancies (unfulfilled guarantees) are fulfilled by Li-ion batteries. Monetary figures refer to the unsubsidized levelized cost of storage from Lazard [71], which includes capital, operation and maintenance, charging, taxes and extended warranty costs. Monetary figures in USD. Greenhouse gas figures refer only to the manufacturing of the battery, using range estimates from a review of the literature [72].

| | | | Confidence Level | | |
|--------------------|----------------------------------|-----------|-------------------|------------------|------------------|
| | | | 50% | 75% | 99% |
| Variable / Country | Energy Gap (\$[USD]) | Guarantee | | | |
| | | 95% | \$1.2bn-\$2.4bn | \$1.3bn-\$2.7bn | \$1.7bn-\$3.4bn |
| | | 90% | \$1.1bn-\$2.2bn | \$1.2bn-\$2.4bn | \$1.5bn-\$3.1bn |
| | | 75% | \$0.79bn-\$1.6bn | \$0.92bn-\$1.9bn | \$1.2bn-\$2.5bn |
| | | 50% | \$0.44bn-\$0.89bn | \$0.52bn-\$1.1bn | \$0.71bn-\$1.5bn |
| | Germany | 95% | \$4.1bn-\$8.3bn | \$4.7bn-\$9.6bn | \$6.4bn-\$13bn |
| | | 90% | \$3.7bn-\$7.5bn | \$4.4bn-\$8.9bn | \$6.0bn-\$12bn |
| | | 75% | \$3.0bn-\$6.1bn | \$3.5bn-\$7.2bn | \$4.9bn-\$10bn |
| | | 50% | \$1.9bn-\$3.8bn | \$2.1bn-\$4.2bn | \$2.6bn-\$5.3bn |
| | Energy Gap (CO ₂ -eq) | Guarantee | | | |
| | | 95% | 0.14 Gt-0.72 Gt | 0.15 Gt-0.80 Gt | 0.19 Gt-1.0 Gt |
| | | 90% | 0.12 Gt-0.64 Gt | 0.14 Gt-0.72 Gt | 0.18 Gt-0.92 Gt |
| | | 75% | 0.091 Gt-0.47 Gt | 0.11 Gt-0.55 Gt | 0.14 Gt-0.74 Gt |
| | | 50% | 0.050 Gt-0.26 Gt | 0.060 Gt-0.31 Gt | 0.082 Gt-0.43 Gt |
| | Spain | 95% | 0.47 Gt-2.4 Gt | 0.55 Gt-2.9 Gt | 0.74 Gt-3.9 Gt |
| | | 90% | 0.43 Gt-2.2 Gt | 0.50 Gt-2.6 Gt | 0.69 Gt-3.6 Gt |
| | | 75% | 0.34 Gt-1.8 Gt | 0.41 Gt-2.1 Gt | 0.56 Gt-2.9 Gt |
| | | 50% | 0.22 Gt-1.1 Gt | 0.24 Gt-1.3 Gt | 0.30 Gt-1.6 Gt |

demand. From a historical perspective, modern society demands a flow of electrical energy at a remarkably high confidence level. An ideological assumption has been made that, rather than change our social practices of consumption, the supply of electrical energy derived from renewable primary energy sources should increase.

Relatively few analyses attempt to estimate potential storage requirements in a fully renewable electrical grid. This is a major oversight in the discourse since solving that problem is given the highest priority by many supranational interest groups [i.a. 39,41,76]. Those analyses that do attempt to estimate general storage requirements are, however, compatible with the average results presented in Table 3. For example, assuming that grid expansions are limited to the national scale and that no backup generation is provided, [77] estimate that the European Union would require between 7 and 30 days of storage to accommodate shares of 90% or more of intermittent renewable energy. The results are also comparable with the specific analysis for Germany by Kuhn [78], which predicts a requirement of storage power output on the order of 53 GW by 2050.

Following the results in Table 4 and using the United Nation's [79] population estimates, while planning for the expected annual worst event in the most extreme scenario (99% confidence interval, 95% guaranteed) the anticipated levelized costs of Li-ion battery storage backup supply are on the order of 37–73 USD per capita for Spain and 77–157 USD per capita for Germany. These costs are relatively minor in relation to other expenses in the renewable energy transition. On the other hand, annual greenhouse gas emissions from lithium battery manufacturing are on the order of 4–21 tons CO₂-eq per capita for Spain and 9–47 tons CO₂-eq per capita for Germany. These figures are majorly concerning. Putting these emissions into context, the figures are between 0.5x and 3x of the 2015 per capita greenhouse gas emissions (Kyoto basket) for both Spain and Germany [80]. The biophysical implications of the considered transition, even when considering coarse assessments, include substantial reason for concern.

More concerning than the emissions figures, however, is the magnitude of lithium that would be required. When considering the conservative functional options in Table 3 (99% confidence interval, 95% guaranteed), the use of Li-ion storage that would be required in the

anticipated 100% intermittent electricity system already represents some 7% (Spain) and 13.5% (Germany) of the world's proven lithium reserves and 4x (Spain) and 15x (Germany) the current annual production volume of lithium, or 12x (Spain) and 43x (Germany) the current annual production volume of lithium used in the production of batteries [72,81–83]. Considering that the effective lifespan of a Li-ion battery is on the order of 5–10 years [76,84], one can conclude that utility scale Li-ion battery electricity storage is not currently a large-scale environmentally feasible or economically viable option for developed nations. While the use of utility scale Li-ion battery electricity storage may possibly be desirable domestically, given the anticipated levels of extraction it is highly doubtful to be desirable from a global perspective. Indeed, contemporary levels of lithium extraction alone are already highly contentious [85]. From the anticipated levels of lithium extraction, major desirability concerns over social and environmental justice would be anticipated [86]. These are all concerning points given the reliance on Li-ion by major supranational energy outlooks. Bloomberg New Energy Finance, for example, estimates that an eye-popping 1291 GW of new battery capacity (primarily but not exclusively Li-ion) will be added by 2050. 30% of that capacity is assumed to be driven by Europe where a 77% portion is expected to go to utility-scale batteries [41].

Naturally, as intermittent electricity generation penetrates the electrical grid, system administrators have structural options alternative to Li-ion. One could import energy via Pan-European interconnectors i.e. increase the range of effective spatial smoothing. Alternatively, one could build or maintain dispatchable backup conventional power plants (the current solution). One could also majorly overbuild intermittent renewables power capacity. Even spatial smoothing within a country's borders, however, will prove difficult. Kies et al. [57] estimate that, in Germany, even with considerably improved spatial smoothing and relatively available high voltage transmission lines, curtailment in a 100% renewables scenario may be forced into the realm of 60–80%. In their simulations Kies et al. [57] estimate that utilization factors for wind farms in Northern Germany (where a majority of the wind power capacity is currently located in Germany) would be on the order of 2%. This future is drastically different from the

present reality – current curtailment is negligible. It presents an additional complication with respect to the major scaling-up of alternatives in the electrical grid.

Lastly, there will always exist special circumstances which allow some entities to pursue transition pathways alternative to the ones described for Germany and Spain. Denmark, for example, has received widespread critical acclaim in recent years and in response to its renewable energy transition successes. However, while Denmark itself has no significant hydropower potential, it sits on the doorstep of a cooperative Norway and a cooperative Sweden which together have nearly 70% of Europe's hydropower (maximum storage capacity) [87]. Every year there are multiple weeks where Denmark imports on average 60–80% of the electrical energy it consumes [88]. The Denmark model is not easily reproducible. There will always be special cases and outliers. Successes aside – and there have been many – there remain major functional hurdles between our present society and a future one powered on renewable electrical energy.

Despite major functional hurdles, physical-technical and economic models continue to dominate the energy analysis discourse and related decision-making processes. Notwithstanding, there exists widespread acknowledgement that such models are poor predictors of the future [89–92]. Assessments of systemic factors affecting the adoption of transformative energy technologies find many reasons for their poor predictive power. One such reason is that technology adopters are not *homo economicus* and are motivated by much more than financial considerations [89,93]. Concerning these points, quantitative story-telling suggests moving away from a discussion based on ‘matters of fact’ and towards a discussion about ‘matters of concern’.

This shift in analytical focus from fact to concern is non-trivial, however. In contrast to the assessment of a matter of fact, an analysis of a matter of concern is necessarily based on multiple, non-equivalent and non-reducible quality checks. One major issue with socio-technological imaginaries is that they are often shaped more by narratives and endorsed storylines than biophysical reality [94,95]. In this sense, an analysis of a matter of concern relevant for decision makers should include a quality check on its feasibility. In the example of quantitative story-telling proposed in this paper, we illustrated that analysts should be able to assess how much electrical energy can be produced by the different functional categories of production (base-load, peak-load, intermittents) when matching demand across space and time. This analysis of biophysical congruence is independent from the price of a kWh. We also made a call for analysts to discuss how to define a relation between power capacity and gross supply (i.e. utilization factor, power load, or, the characterization based on production factors per typology). Depending on the level of centralization of the proposed electrical grid, analysts should explore how much energy must be stored in order to integrate a given quantity of intermittents in the grid in order to balancing demand and supply. They should address storage loss profiles and the spatial/temporal distribution of dispatched, stored energy. They should also consider degradation rates of storage infrastructure and embodied inputs in the manufacturing and installation of that storage infrastructure.

In addition to a feasibility check, the analysis of a matter of concern should be based on quality checks on desirability and viability. Exploring that point, a desirability check requires establishing a bridge between a technical analysis and the implications of proposed changes on the patterns of consumption in the society. This type of analysis has not been presented in this paper, though it is developed in the activities of the MAGIC project. How will the proposed changes affect the expression of the current mix of social practices? How will they affect the quality of life in terms of material standard of living and social activities? The establishment of this bridge is essential. Technical information will remain useless if the technical analysis of feasibility is not coupled to an analysis of its policy relevance, i.e. the implications of choices in terms of desirability for society. Lastly, an economic viability check implies that those solutions that have been identified as feasible

and desirable by the society (using non-economic narratives and story-tellings) are verified in relation to their reasonable chances of economic success, in order to be able to identify effective policies.

In this paper we attempted to show the importance of considering more than one lens at a time in order to obtain a better framing of sustainability issues. We used the discussion on alternative sources of electrical energy as a case study and learning-type story. For reasons of length, we focused primarily on one lens (biophysical feasibility). This choice does not imply that the other lenses are less important. The message of quantitative story-telling is that we need to learn how to integrate the great diversity of available knowledge claims relevant to the understanding of a wicked problem. To achieve this result we should avoid as much as possible the hegemonization of narratives and hero-type story-tellings [19,26]. Instead, a diversity of framings of a given issue is essential in order to reduce the unavoidable generation of ‘hypocognition’ [96] associated with any representation of a problem or solution. As a consequence, more informed and equitable choices may be made.

5. Conclusions

The analysis provided in this manuscript points at an excessive reliance on economic narratives as one of the possible causes leading to the underestimation of the technical and biophysical hurdles in the implementation of renewable energy transition policies. This manuscript proposes that discussions about a future, completely distinct energy system should be complemented by other types of narratives. We suggest moving away from a ‘Yes, we can!’ mode of discussion in which the solution is to set a business models with the goal of achieving a certain set of normalized expectations. We also suggest moving away from a mode of discussion which assumes that ‘no matter the problem’ human ingenuity and the invisible hands of the market will be capable of solving it. Instead, it may be advantageous to start exploring a mode of discussion based on ‘Houston, we’ve had a problem.’

In this sense, the quantitative story-telling method proposal does not claim to provide uncontested ‘facts’ to the process of deliberation over sustainability policies. As a matter of fact, during the activities of the MAGIC project, we have been consistently confronted by strong believers of a quick decarbonization through a massive and rapid deployment of intermittent electricity sources – supporters of the ‘economics of techno-scientific promises’ [97]. This disagreement is perfectly legitimate. Any analysis of the possible evolution of a complex adaptive system can always be contested by challenging specific technical assumptions. However, critiques of this nature should not be used to avoid the discussion of the proposed concerns. In fact, a discussion about the plausibility of policies should not be focused on ‘what may happen’ but rather on reaching an agreement on ‘what cannot happen’. Numerous learning-type stories should be included to balance hero-type stories [26]. In our stakeholder experience in the MAGIC project, those convinced that technological innovation represents a panacea in the modern sustainable energy crisis tend to avoid discussing concerns about the plausibility of policies currently proposed. The usefulness of the quantitative story-telling methodology does not depend on whether the analysis presented should be considered as a fact. Rather, its usefulness depends on whether the concerns raised provide a sobering reminder about the risks of bad planning. Quantitative story-telling is about learning how to handle ‘uncomfortable knowledge’ that is disturbing our visions and aspirations for the future. As stated by Rayner, the systemic refusal to handle uncomfortable knowledge is the main mechanism of the social construction of ignorance in science and environmental policy discourses [15].

In view of the analysis presented here, the descriptive and prescriptive discourse surrounding the contemporary European renewable energy transition seems to be characterized by a critical lack of holistic (structural and functional) analyses. Indeed the term ‘energy transition’ is nearly always used in reference to a change in the structural

composition of primary energy supply [2]. Unfortunately, over the past century, our economies have become so intertwined with oil and gas that substituting fossil fuels will take an Olympic effort. This does not entail that a transition away from fossil energy cannot be done. We, as a society, will have to do it either willing or not. However, it is essential to acknowledge that when dealing with a complex pattern of production and consumption (i.e. the metabolic pattern of social-ecological systems) it is unthinkable to imagine a transition based on the maintenance of the same pattern of consumption (required for the stabilization of existing institutions and social practices) coupled to the introduction of a new pattern of production [98]. That is, in order to be capable of using alternative sources of electrical energy we must change the existing institutions and social practices. Society as a whole must move to a different integrated pattern of production and consumption. This is not an easy task and above all this is not a task that can be achieved by technological change alone. Any change in the existing pattern of production and consumption of energy will require adjustments in both the existing power structure and existing social relations. In relation to this point, the natural inertia of social systems may explain why, globally, fossil fuel subsidies still outpace renewables subsidies 4:1 [99]. The massive replacement of fossil fuel as an energy carrier in modern economy is a task so complex that it will require an exercise of extreme humility by those attempting to analyze it. This transition cannot be predicted and controlled by simple technocratic planning nor left to the invisible hands of the market in accordance with neo-liberal ideologies. In a situation where the characterization of the future is highly uncertain and highly contested, it is not advisable to operate under command and control or put blind faith in the market forces. Otherwise, we risk propelling ourselves headlong and blindfold into a situation of structural-functional mismatch.

The general consideration of the factors discussed in this paper suggests that the scale and scope of the modern world's energy power systems has become so huge that there is no *primarily* technological or engineering fix to the problem of a renewable energy transition on a timescale relevant to the forces that mandate that transition. Society must re-define itself in order to be able to produce and consume energy within a different metabolic pattern. This discussion must be based on the simultaneous consideration of several non-equivalent narratives. Tables 3 and 4 presented just one of many ways of introducing a relational analysis approach with functional and structural considerations made together. This approach may provide a more holistic vision by informing the discussion over potential consequences of proposed

solutions.

The experience created by a quick deployment of intermittents electrical energy supply in Germany and Spain suggests that a primarily structural analysis does not adequately speak towards the feasibility, viability or desirability of decisions. When considering the implications of a massive and rapid build-up of an electrical energy generation system built around wind and solar primary energy sources there are several concerns be addressed. For the building of a dependable backup generation or storage, society would need a huge supply of material for the batteries, panels, infrastructures and transmission lines. When considering the costs of this transition, it is not even sure that this task is feasible. It is also not clear that the task would represent a low-carbon solution, especially if it must be implemented in just two or three decades. Of course, these statements do not mean that we do not have to fight for alternatives. They do mean, however, that in our search for a more sustainable energy system we must be careful to not filter out uncomfortable knowledge claims about the existence of potential problems. This point is important because of the hegemonic role played by economic narratives in the definition of policies. Indeed, the uncontested endorsement of economic story-telling represents a formidable filter against uncomfortable knowledge about the sustainability predicament [100].

Declaration of Competing Interest

None.

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Appendix A

A.1. Quantitative analysis

In this appendix the methods for the creation of all non-trivial figures and tables are elaborated.

A.1.1. Fig. 1

Data directly from sources listed except for Germany where final power capacities for 2018 are forecasted using ENTSOE-E growth ratios applied to the 2015 Eurostat values. Furthermore, the following aggregations were made:

Spain. ‘Oil/Gas’ represents ‘fuel’, ‘gas’ and ‘combined cycle’ categories. ‘Hydro’ includes ‘Hydro: Mixed Conventional’, ‘Hydro’, and ‘Other Hydro’. ‘Solar’ includes ‘Solar: Photovoltaic’ and ‘Solar: Thermal’.

Germany. ‘Coal’ includes ‘Hard Coal (Anthracite)’ and ‘Brown Coal (Lignite)’. ‘Wind’ includes ‘Wind: Onshore’ and ‘Wind: Offshore’.

A.1.2. Fig. 2

‘Intermittent Renewables’ includes all forms of wind and solar power capacity. ‘Other Renewables’ includes all other renewables save intermittents (hydro, biofuel, waste, geothermal etc.). ‘Conventional’ includes all non-renewable energy sources (oil, gas, coal, nuclear etc.). Generation data is net production measured at the power plant (i.e. before e.g. distribution losses). For Germany, generation data is at a yearly resolution until 2008, thereafter it is at a monthly resolution, due to data availability constraints. For Spain, generation data is at a monthly resolution for the complete timeframe.

A.1.3. Tables 3 and 4

Data curation. For several reasons, portions of the Spain and Germany electricity production datasets were interpolated. Overall, interpolated values represent only a minor portion not expected to significantly impact the results. In summary, 5.3% of the timestamps in the Spain dataset and 0.2% of the values in the Germany dataset contain interpolated values. The first pane of Fig. 3 and the first pane of Fig. 4 describe the frequency of the interpolated values in time. A piecewise cubic hermite interpolating polynomial (PCHIP) was selected for interpolation due to its preservation of monotonicity – it is not prone to exaggerating oscillations as e.g. a standard cubic spline interpolation may. The following list provides statistics for

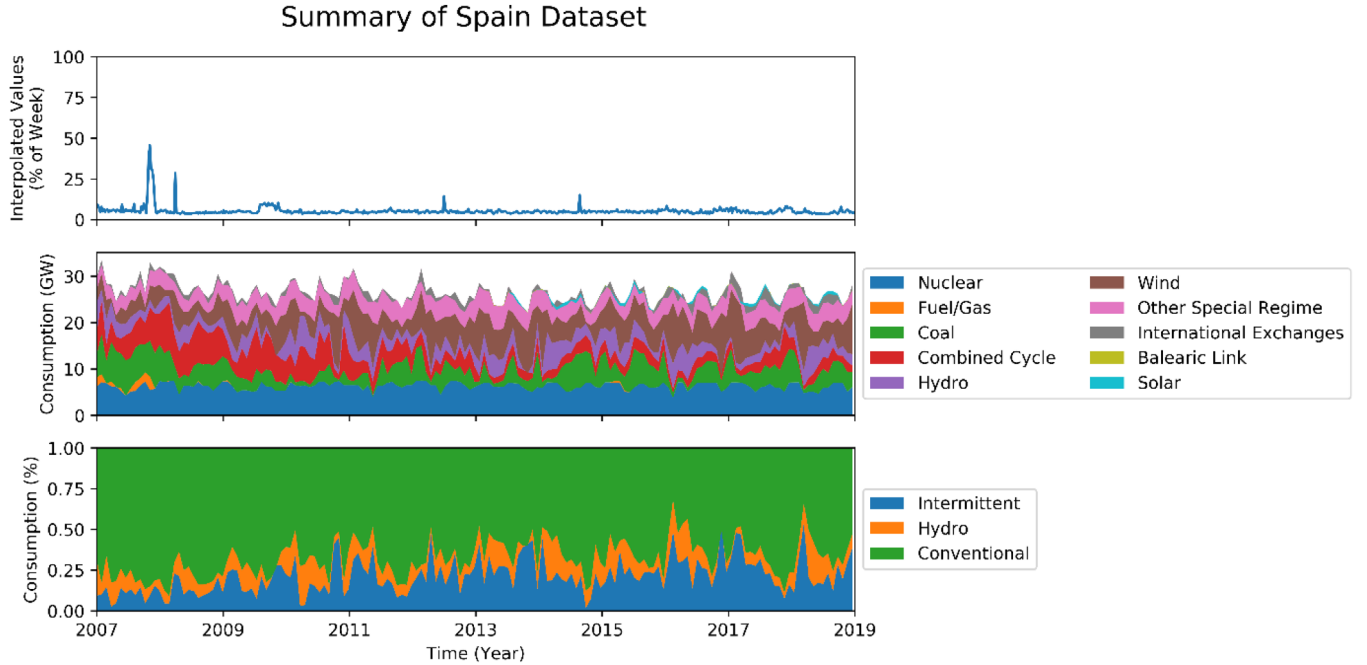


Fig. 3. Summary of Spain dataset describing: (i) temporal location of interpolated values representing 5.3% of the total; (ii) full break-down of electricity consumption 2007–2018 inclusive; (iii) relative generation mix between the three functional categories described in Section 2.3. Data for the second two panes is reported at a monthly resolution where the underlying data is at a 10-min resolution.

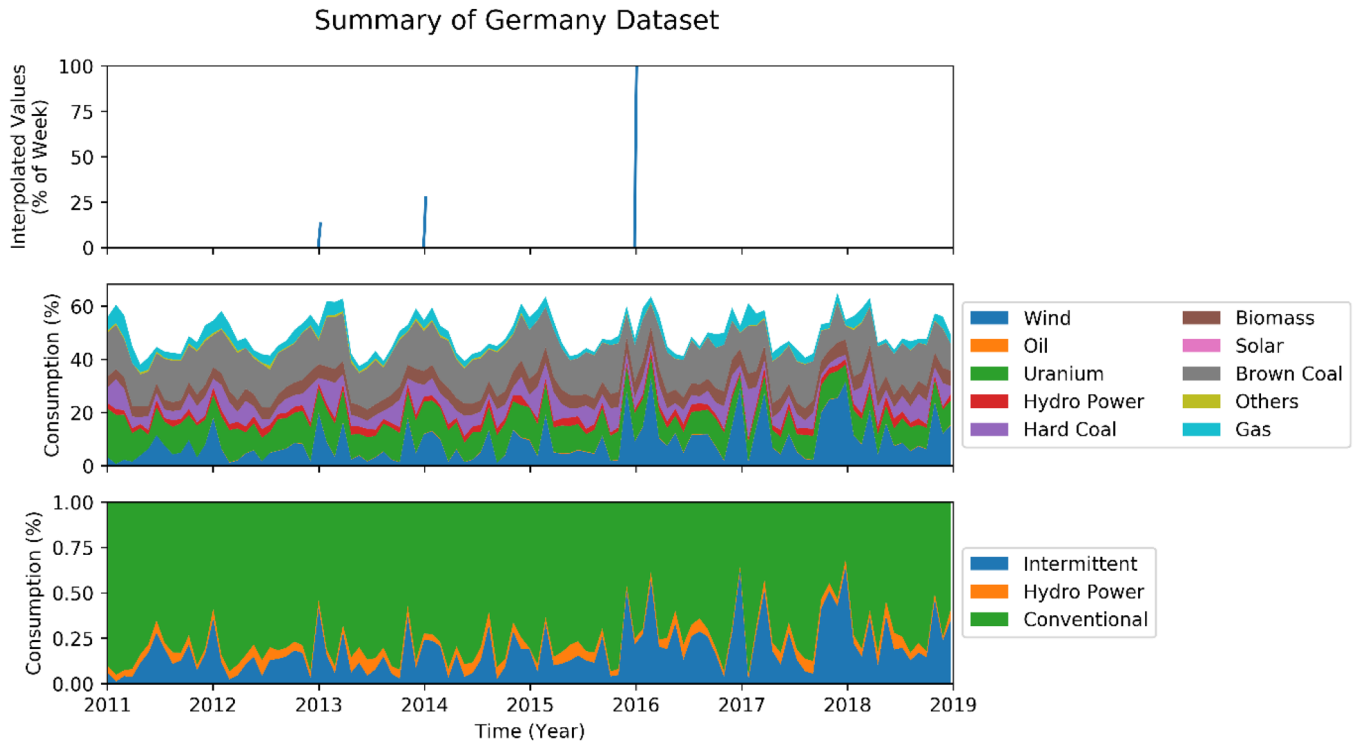


Fig. 4. Summary of Germany dataset describing: (i) temporal location of interpolated values representing 0.2% of the total; (ii) full break-down of electricity consumption 2011–2018 inclusive; (iii) relative generation mix between the three functional categories described in Section 2.3. Data for the second two panes is reported at a monthly resolution where the underlying data is hourly.

the relative breakdown of missing or discarded values:

- 1 The following comment amending instances where not all accounting categories are reported (incomplete data). Spain: 3.6% (22,713; minor concentration bias between 3 h and 4 h); Germany: 0.2% (155).
- 2 Amending the unlikely autocorrelation between at least one of the individuated generation time series (set of windows ranging from 1 to 6 timestamps; allowance of 10% maximum delta between windows excepting in comparisons between windows where at least one of the windows averages less than 10 MW). For example, for Spain on 11 November 2007 between 12h20 and 12h40 hydroelectric generation trembles nearly 1500% and all other sources of generation are zeroed – this is unrealistic, the data is incorrect. Spain: 1.3% (8478); Germany: 0.0% (0).
- 3 High standard error between reported total demand and calculated total demand (sum of individuated generation sources). Errors more than 1 ± 0.25 discarded. The vast majority lie within 1 ± 0.01 . Spain: 0.3% (2151); Germany: 0.0% (0).

Lastly, in the circumstance multiple, distinct values were reported for the same time period, the first reported value was kept. This issue only presented itself with the Spain dataset.

Statistical procedure. The following list details the general statistical procedure used to calculate the confidence levels and guarantees in Tables 3 and 4.

- 1 Calculate the percentage of the total generation sourced from intermittents (wind or solar) for each observation.
- 2 Find the yearly mean percentage generated for each point in time by taking the centered rolling mean with a one-year window for each year.
- 3 For each observation, calculate the guaranteed percentage for each of the guarantee levels (0.5, 0.75, 0.9 and 0.95) by multiplying the mean generation by each of the guarantee levels.
- 4 Calculate the discrepancy between the intermittents generation and the guaranteed percentage by multiplying the total production (power) by the intermittents generation percentage less the guaranteed percentage.
- 5 Locate all time intervals of the discrepancy values with an average under the guaranteed percentage (i.e. using a rolling sum method).
- 6 Calculate, in hours, the length of all located time intervals.
- 7 Calculate the maximum subarray (the contiguous subarray of the time series with the largest sum) of the hourly discrepancies. Calculate the additive inverse of the sum of that number, which represents the energy gap of the ‘most significant’ located time interval. Report this value in the table.
- 8 For each year, calculate the mean, max, min, standard deviation ($n - 1$ method i.e. sample not population) and standard error of the located time interval lengths.
- 9 Report the 50% confidence level in the table.
- 10 Calculate and report the 75% and 99% confidence levels using 1-tailed normal z-scores of 0.68 and 2.33, respectively.

Nota bene. It should be noted that the standard error and standard deviation methods were run over low population sizes (the number of complete years in the dataset). For Spain $n = 12$, for Germany $n = 8$. With regard to the relatively low n value, readers are reminded that the nature of this work's analysis is to illustrate the methodology described previously and highlight plausible concerns involved.

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