Fictional expectations in energy scenarios and implications for bottom-up planning models

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ARTICLE INFO

Keywords:
Energy scenarios
Bottom-up planning models
Fictional expectations
Energy systems
Energy futures

ABSTRACT

The evolution of renewable energy demonstrates that development of energy systems is not a deterministic process dictated by technology but equally shaped by societal and cultural forces. Key instruments in this process are energy scenarios that describe hypothetical future systems and pathways from the present to this future. Against this background, this paper transfers the sociological concept of fictional expectations to energy scenarios capturing how scenarios, although these are not accurate forecasts, are treated by actors “as-if” and serve as a basis for seemingly rational decisions regarding an unknowable future. As a result, different scenarios compete for credibility to influence decision-making and steer development of the energy system in their favor.

These insights on energy scenarios are applied to draw consequences for developing and applying bottom-up planning models, the quantitative tool energy scenarios generally build on. The paper concludes that bottom-up planning models should be open and accessible, minimize and be transparent about bias, aim for a large scope to be policy relevant, not apply stochastic methods just for the sake of adding complexity, and limit the representation of non-technical factors to input assumptions and the interpretation of results.

1. Introduction

The development of energy systems is not a deterministic process dictated by technology but is equally shaped by societal and cultural forces. How systems develop is closely interrelated with the socially contingent visions of the future that determine how actors direct and coordinate their efforts. A particular illustrative example to demonstrate this is the evolution of renewable energy over the last 200 years.

First visions for renewable energy systems surfaced in utopian literature authored in the early stages of industrialization [3]. In 1865 William Stanley Jevons’ \textit{The Coal Question} warned about the expected depletion of coal reserves sparking one of the first public debates on energy supply [23]. The idea of renewable energy took deeper hold and in the late 19\textsuperscript{th} century advances in solar and wind power attracted academic attention rendering them potential substitutes for steam engines [48]. In his main work \textit{Women and Socialism} August Bebel predicted that after the depletion of coal, a shift to renewable energy was inevitable and would lead to a valuation of land based on renewable potential [5, cited by 1]. Later Émile Zola’s novel \textit{Travail} in 1901 or Archibald Williams’ book \textit{The Romance of Modern Invention} in 1910 introduced the idea of renewable energy to a popular audience [104, cited by 25; 102, cited by 23].

However, in spite of showing promise, renewable energy systems remained science fiction and the industrial shift from steam to electricity was, with the exception of hydro power, mainly fueled by coal and later oil. Insufficient technical maturity as a sole explanation for this falls short of how technical and societal development are intertwined. Building on Thomas Hughes [39] historical studies on electricity supply, Ergen points out that early inventors were too focused on engineering and failed to convey a broader vision for renewable energy systems to governments and private investors. As a result, renewables did not receive long-term investment to achieve learning effects and reach maturity. As an additional reason for little support of renewable energies, Abelshauser [1] cites that Jevons’ expectations regarding the scarcity of fossil fuels turned out to be unfounded, especially due to the increasing exploitation of oil and gas.

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Correspondingly, renewables re-gained momentum in the United States when awareness for the risk of depending on oil imports increased during the 1950s. Solar technology progressed at the same time and the presentation of a first photovoltaic cell in 1954 met great public reception being described by the New York Times as the eventual “realization of one of mankind’s most cherished dreams — the harnessing of the almost limitless energy of the sun for the uses of civilization” [70, cited by 23]. However, photovoltaic (PV) was not ready for the market and lacked government support that rather focused on advancing nuclear power, also due to synergies between its civil and military use [19, 23].

In subsequent years, growing opposition to nuclear power and oil dependency reinforced interest in renewable energy systems. A first study on renewable-based energy systems appeared in Denmark in 1975 [91]. In his article *Energy Strategy: The Road Not Taken?* Amory Lovins [60] contrasted energy systems characterized by fossil and fissile fuels and large-scale infrastructure with an alternative path based on energy efficiency and small-scale renewables tailored to end-use. Krause et al. [53] substantiated these ideas for Germany and in 1980 introduced a comprehensive concept for a renewable energy system. Around the same time, similar studies on technical feasibility and economic implications were also conducted for other countries like the United States, France, or Sweden [63]. The common denominator in all these works is how they take a systematic perspective to propose serious visions and thus mark the point where renewables exited the realm of science fiction and entered public debate.

Since the 1980s, these visions were partly put into practice. With scientific consensus about climate change as an additional driver, renewable energy made significant progress, quadrupling its global consumption of primary energy from 1980 to 2019. Due to rising consumption in emerging economies, global shares only rose from 6.7% to 11.4% but in industrialized countries the increase was more pronounced, for example from 1.4% to 17% in Germany [81]. Reinforced investments induced learning effects that diminished levelized costs of electricity from PV and wind in the last ten years by 89% and 70%, respectively [82].

The trend towards renewables is reflected again by the visions that are projected into the future today. Studies on renewable energy systems are growing in number and detail [35, 42, 37, 74]. While in the 1980s many scholars expressed their skepticism or blunt rejection of the idea, consensus emerged that renewable energy will make a significant contribution to energy supply and controversy shifted to whether renewables can fully replace nuclear and fossil fuels [34, 84, 13]. Outside of academia, new visions for renewable futures, like the Green New Deal, are put forward and many stimulus packages in response to the COVID-19 pandemic are committed to a green recovery, eventually moving renewable energy into the center of public policy [27, 15].

This outlined (and non-exhaustive) history of renewables demonstrates how visions of the future impact the energy system. Striving for a clearer understanding of this impact, this paper transfers the sociological concept of fictional expectations to energy scenarios and derives implications for bottom-up planning models—the common quantitative tool for creating energy scenarios, see Section 3. First, the following section introduces Jens Beckert’s concept of fictional expectations driving economic development [6] and applies it to how planning of energy systems builds on scenarios. The next section give a brief introduction on bottom-up planning models as a key method for creating scenarios. Section 4 links the two previous sections and applies the insights on energy scenarios to derive implications for developing and applying bottom-up planning models. The last section concludes.

### 2. Fictional expectations in energy scenarios

According to Beckert, economic behavior regarding the future is limited by unknowability. Unlike uncertainty, unknowability is not only non-deterministic, it also cannot be captured probabilistically to enable rational decisions. To remain capable of taking decisions, intentionally rational actors develop fictional expectations of the future in place of perfect information. These expectations extend empirical facts with assumptions that are narratively convincing and formed by calculation and imagination. As a result, fictional expectations are socially contingent and rest on conceptions “influenced by culture, history and power relations” [7, cited by 41]. Although not inevitably accurate, fictional expectations are treated by actors "as-if” and, thus, decisively shape their actions [6]. Beckert’s work contributes to a line of research that takes a narrative and performative perspective on the economy and economics. For instance, in *Narrative Economics* Robert Shiller [87] describes how narratives are an overlooked factor driving markets and investment decisions; in *An Engine, Not a Camera* Donald MacKenzie [62] argues that modern economic theory rather shapes than describes financial markets.

In application of his concept, Beckert revisits microeconomics to explain how fictional expectations open a creative moment for innovation and, more importantly, considers forecasts of economic or technological development as
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Fictional expectations whose purpose is not to predict the future, but to coordinate economic activity [7].

In the energy sector, the equivalent to forecasts are scenarios. Originating from military planning, scenarios are strategic tools describing a hypothetical future and pathways from the present to this future [71]. Scenarios are often categorized as either predictive describing the most probable future, explorative investigating an imaginable future or normative outlining a desirable future [71]. Correspondingly, Beckert describes forecasts as "coordinating, performative, inventive, and political" [7, p. 217]. Different energy scenarios reflect these properties to a varying degree, depending on the author: Scenarios issued by governmental agencies are mostly predictive aiming to coordinate public policy and private investment, but to build credibility and acceptance they refrain from innovation and reflect political consensus. Scenarios from non-governmental organizations (NGOs), consulting firms, or industrial companies seek to influence public policy and opinion in their respective favor. Therefore, they are more political, often normative, and sometimes, when it is inevitable to achieve their objective, innovative. Scientific scenarios exhibit the greatest level of innovation and exploration, especially when addressed to an academic audience and not the general public. In addition, energy scenarios can greatly differ in scope and can range from comprehensive pathways for the entire world, like the IPCC report [22], to explorative concepts for energy supply of single buildings [51].

To examine how scenarios shape decisions and drive the development of energy systems, the following sections successively transfer the characteristics of forecasts identified by Beckert to energy scenarios. As a result, the section’s structure loosely mirrors the chapter on forecasts in Beckert [7].

2.1. Power of persuasion

To convince recipients and guide their decisions, forecasts must be convincing. Beckert identifies two instruments to achieve this, which are typically combined: quantitative model results and narrative elements. For example, economic forecasts consist of a computed growth rate and a story about economic development to support the rate. The purpose of quantitative results and the underlying mathematical method is to evoke precision and objectivity [7, p. 220]. To reinforce this perception, method complexity is even increased if it does not benefit accuracy [7, p. 226]. Narrative elements convince by suggesting causal relationships and tying forecasts to existing knowledge and convictions of the recipients [7, pp. 91, 221, 245].

Energy scenarios combine quantitative methods and narrative elements in a very similar way [71]. Elaboration of quantitative and narrative parts varies and scenarios targeting a professional audience typically emphasize quantitative elements; targeting a general audience emphasizes narratives.

Similar to economic forecasts, the purpose of complex methods in energy scenarios is to create legitimacy and credibility [83]. Aykut [4] attributes the authority of energy models not only to their academic reputation and seemingly quantitative nature, but also their intransparency to non-experts. This is for example reflected by critique of the IIASA energy scenarios in Keepin and Wynne [49]. This critique, only possible because Keepin worked at IIASA, finds that the applied model is needlessly complex and simple calculations using a few key assumptions are sufficient to largely reproduce its results [49, 32]. In addition, results are not robust to minor changes of these key assumptions. Based on this analysis, Wynne [103] even goes as far as stating that energy models are "symbolic vehicles for gaining authority" only used to create an appearance of scientific objectivity.

The role of narrative elements in energy scenarios is equally acknowledged in the literature [98, 67]. In contrast to purely technical descriptions, stories get people engaged and create awareness for the societal significance of energy scenarios, which is particular relevant for public policies [66, 43].

Analogously to forecasts, energy scenarios are deemed plausible, if narratives correspond to the knowledge and convictions of the recipient [83]. For instance, Aykut [4] identifies energy scenarios that are based on official economic forecasts and thus avoid controversial assumptions on economic development to be decisive for the success of the German anti-nuclear movement. Conversely, rejection of similar efforts in France is ascribed to putting forward scenarios with rigid assumptions on energy consumption.

To appear plausible and desirable, narratives for transformative scenarios often draw on similar events in the past like the industrial revolution or disruptions in other industries [44, 18]. For the same reason, energy scenarios are often associated with various political ideals. Although there are several studies questioning the objectivity and authority evoked by quantitative methods in energy scenarios, there is no research critically examining the association of normative ideals. This seems particularly intriguing, because associations are often conflicting and range from a broad political spectrum. For example, sovereignty is a reoccurring argument in favor of national resources, both conventional and renewable, and was first cited by Jevon regarding Britain’s dependence on coal [45, 88]. Economic growth and the creation of jobs is also equally used as an argument in favor of conventional and renewable energy [96].
At the same time, the idea of degrowth serves as an argument for renewables as well. Conventional energy is often promoted arguing it will induce economic growth to lift a significant share of the world’s population out of poverty. On the other hand, ambitious mitigation scenarios are often motivated by pointing out how climate change has the most severe impact on people in poverty. Finally, it is argued that renewable energy increases democratic participation through decentralization of energy supply [53, 36, 92].

Beyond methods and storylines, persuasiveness of a scenario also depends on the authority of its author [83]. Braunreiter and Blumer [11] for instance observe that researchers refrained from citing a scenario by an environmental organization, not because its quality was questioned, but because it would not “look serious”.

2.2. Coordinating actors

Beckert points out that despite becoming increasingly sophisticated, economic forecasts are rarely accurate and have a long record of not foreseeing recessions [7, pp. 223, 241]. He ascribes this to flaws of the forecasting process itself, like incomplete data, inaccurate models, the inability to foresee major changes but also to unpredictable exogenous shocks to the economy, like political events or natural disasters [7, pp. 228-231]. Today, we must add global pandemics to the list, demonstrating how unpredictable exogenous shocks are. Nevertheless, considerable effort is dedicated to forecasting and forecasts receive great interest, because their true purpose, according to Beckert, is to coordinate economic activity. Facing an unknown future, relying on forecasts enables actors to be seemingly rational and partly relieves them from responsibility, if decisions turn out to be poor [7, p. 236]. Consequently, government, businesses, and consumers adapt their decisions to the same forecasts and as a result forecasts achieve consistent behavior across the whole economy. This implies that forecasts are performative meaning they do not just predict, but also shape economic activity [7, p. 237].

Again, Beckert’s characterization of forecasts can be transferred to energy scenarios. Overall, projections of energy scenarios are as inaccurate as economic forecasts, partly because they must build on economic forecasts [76, 93, 97]. To stay abreast, even long-term scenarios 30 years into the future, like the World Energy Outlook (WEO), are outdated so quickly that they require substantial revision every year. Similar to forecasts, energy scenarios struggle to incorporate exogenous shocks affecting demand or fuel prices [29, 20]. In addition, scenarios often neglect major changes and assume an overly conservative continuation of present trends. A prominent example of this bias is displayed in Figure 1. It shows how the WEO continuously underestimated solar installations in the last ten years although estimates were continuously revised upwards [64].

Irrespective of accuracy, scenarios impact the development of the energy system, because they affect decisions of governments and investors [85]. This applies in particular to predictive scenarios by established institutions like the International Energy Agency (IEA), large companies, or governments. For example, higher solar projections in the WEO could have encouraged additional investments and further driven up renewable expansion [17]. Similarly, Midttun and Baumgartner [65] argue that expansion of French nuclear capacities in the 1970s anticipated increasing electricity demand based on prominent scenarios. Although their underlying assumption on the relationship of economic growth and electricity demand proved wrong, these scenarios became true in a self-fulfilling way, since the state-owned power company instead promoted electric heating to induce the anticipated increase in demand [4].

The importance of credible scenarios for decision making conversely implies that diverging scenarios hinder planning and can stall the development of the energy system [31]. For example, the official governmental objective in Germany is to achieve a renewable share of 65% in power consumption by 2030, but currently implemented policies will only achieve around 55% [2, 75]. In addition, very heterogeneous actors advocate for much higher shares up to 100% and projections for consumption that determine how shares translate into absolute values diverge as well [28, 50]. Overall, the emerging uncertainty not only discourages investment into renewables, but into complementary technologies like storage, electric mobility, or electric heating as well.

Explorative scenarios, often from academia or NGOs, rarely have a direct impact on investments, but constitute an avant-garde and drive long-term innovation. If they become sufficiently convincing, their ideas are eventually established and included into predictive scenarios. For instance, first scenarios for renewable energy systems referenced in Section 1 were rejected by the established experts at the time and did not encourage great investments [84, 33]. Also, they appear outdated from today’s perspective including no PV, no electrification of heating, and an exclusive use of synthetic fuels in the transport sector. Nevertheless, these scenarios sparked public discussion and further academic research on renewables finally resulting in significant progress and recognition of renewables by established scenarios.

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1This does not necessarily imply that forecasts are self-fulfilling. For example, an optimistic forecast on the eve of an unexpected recession might in fact have the opposite effect and deepen the recession.
A similar case can be made for the use of hydrogen as an energy carrier, which was already described by Jules Vernes in his 1876 novel The Mysterious Island and debated among experts since the 1970s, but only included in governmental scenarios recently [99, 8, 30, 96].

Finally, scenarios do not only influence governments and investors, but other scenarios as well. To increase the legitimacy of their own work, researchers frequently use assumptions or results from established scenarios as inputs to their own scenarios [11]. As a result, potential bias transfers to academic scenarios, which is especially critical in case of sensitive assumptions like final demand.

In notable difference to economic forecasts, energy scenarios have become more reflective about their epistemic value [90]. According to Beckert, economic forecasts purport to predict the future, despite their long record of inaccuracy. The IEA, publisher of the WEO, on the other hand, acknowledges that "there is no single story about the future of global energy and no long-term IEA forecast for the energy sector" [40] and similarly many academic publications stress the fictionality of energy scenarios. However, this clarification is of no difference, because actors nonetheless treat them as predictions when making decisions. So, when the IEA states "the course of the energy system might be affected by changing some of the key variables" [40] to underline the limitations of their work, they are modestly omitting that one variable are energy scenarios like the WEO itself.

2.3. Competition for influence

Since convincing forecasts affect decision-making, their authors hold considerable influence over the future. Therefore, the competition for credibility between forecasters is also a competition for political influence and forecasting methods are assets in this competition [7, p. 80].

In energy, scenarios are key contributions to the debate about the system’s future since they shape economic and political decision-making. To influence expectations according to their interests, different actors publish competing scenarios and create a "battlefield" of energy system planning [73, cited by 71].

In this debate, the state holds a central role, because planning concerns infrastructure and the environment—both public goods [65]. Through research funding, subsidies, market design, and building permissions the government decisively shapes the energy system and examples like nuclear power or renewable energy demonstrate that government support is a necessary (but not sufficient) condition for new technologies to emerge [23]. Therefore, scenarios by the
government possess authority because they are likely to reflect the future course of public policy.

Other actors present in the debate and publishing energy scenarios include industry organizations, environmental NGOs, and academia [47]. It is commonly acknowledged that scenarios often reflect their publishers’ interests: for example, scenarios by industry organizations tend towards higher consumption, and scenarios by environmental NGOs towards lower consumption [71]. Drawing up scenarios must carefully balance between diverging from the consensus to promote own interests on the one hand, but comply with the consensus to remain credible on the other. In addition to these professional organizations, the general public, too, increasingly engages in the debate, but unlike other groups, members of the general public do not typically study energy scenarios directly and instead learn about their content from media [12].

The role of professional organizations and the authority of complex models restrict influence on the debate and consequently on the development of the energy system. In extreme cases, professional networks between universities, industry, and government form a “cognitive monopoly” characterized by a common perspective on the energy system [65]. Outsiders pointing out deficiencies of that perspective can be denounced as uninformed by pointing out their lack of recognized expertise or sophisticated methodology [103]. Illustrating this, Midttun and Baumgartner [65] describe how environmentalists in several European countries had to establish expertise and forecasting methods of their own to influence public policy according to their interests. At the time, established models and scenarios expected a strong growth in demand that suggested the expansion of nuclear power. In opposition to nuclear power, environmentalists rejected these scenarios and developed methods forecasting constant demand. After gaining recognition, these scenarios were included into planning of future polices and eventually proved much more accurate. Overall, the process added new perspectives to the debate about energy and created awareness of bias in models.

Concluding from the previous description of how political debate shapes the energy system, a popular but illusive concept of scientific policy advice can be rejected: Decision-makers do not simply derive their actions from the scenarios presented by research, but decisions emerge out of the current state of debate instead [31]. Only scenarios contributing to this debate can have an actual, although indirect impact.

3. Bottom-up planning models

Bottom-up planning is the most frequently deployed quantitative method in the development of energy scenarios [55]. In the past, scenarios from models like MARKAL/TIMES or PRIMES had a considerable impact on energy policy [95]. Bottom-up modeling refers to representing physical flows in the energy system and is therefore also termed the "engineering approach” [80]. It is opposed to a top-down approach pursued by integrated assessment or computable general equilibrium models that build on economic and social abstraction. Planning implies investigating the optimal design of the system. Planning models are opposed to simulations performed by agent-based or mixed-complementarity models, that account for the individual objectives of different actors. Bottom-up planning models decide on the expansion and operation of technologies to satisfy demand and maximize social welfare. In case of perfectly inelastic demand, a common assumption, maximizing social welfare is equivalent to minimizing system costs. To solve large and detailed models within reasonable time, bottom-up planning models are usually formulated as linear optimization problems. Historically, bottom-up models came up as an alternative to econometric and macro-economic models for investigating energy efficiency and alternative energy sources [4].

Bottom-up planning models are also referred to as partial equilibrium or market models, since markets achieve a welfare maximum if perfect competition is assumed. However, these terms can be misleading, because several conditions of perfect competition do not apply to the energy system. First, unknowability of the future, illustrated by the inaccuracy of scenarios documented in the previous section, violates the assumption of perfect information. Second, the energy system is subject to significant externalities, like environmental damage or government intervention. Finally, perfect competition requires a long-term equilibrium, but the transformation of the energy system is a dynamic process. Note that violations of perfect competition apply particularly to the expansion of technologies, viz the planning part of models. For bottom-up models limited to the operation of predefined capacities the term market model can be considered more appropriate.

Thanks to their engineering focus, bottom-up planning models can identify technically feasible solutions to satisfy demand under certain constraints, for example an upper limit on carbon emissions. By attributing costs to each decision on expansion and operation, models can also estimate the economic costs of solutions. These characteristics render bottom-up planning models suitable for techno-economic analyses of energy scenarios. Typical research includes: to investigate the trade-offs between different technologies, for example, heating with electricity or hydrogen;
Figure 2: Graph representing exemplary bottom-up planning model

to quantify the benefits of potential innovations, like further decreasing costs of renewables; and to foster a systematic understanding of how technologies interact, for example, PV and batteries are typically complements, but power grids and batteries substitute each other. To analyze specific policies, like a political limit on wind power in certain areas, the effect of the policy must be translated into an appropriate boundary condition of the model, for instance, a corresponding capacity limit.

Since bottom-up planning models take a system perspective, they do not consider the different agents in the system, like generators, consumers, or regulators and monetary flows between these agents, like subsidies, taxes, or market prices. Accordingly, computed costs are system costs, not the costs of individual agents, and computed prices are opportunity costs of meeting demand, not the market price of transactions between agents. Consequently, planning models are not suited to address strictly economic questions regarding individual profits, market design, or subsidy schemes, which are better addressed by simulative tools. In fact, this is not so much a shortcoming of optimization models, but rather reflects how identifying an optimal system precedes research on implementing the system practically. For example, if bottom-up planning models robustly find great benefits from expanding electricity storage, but investments are not profitable under current regulations, this is not a flaw of planning, but of the current policy framework.

The scope of bottom-up planning models ranges from single buildings to countries or continents to the entire world. Since comprehensive decarbonization scenarios have to consider more than one building, the term macro-energy systems has been coined to refer to larger systems [58]. In addition, also the sectoral scope of models varies ranging from only one sector, like the power sector, to coverage of several sectors, like the power, heating, and transport sector, plus their interaction. The graph in Figure 2 shows the structure of a stylized bottom-up planning model. In the graph, carriers are symbolized by colored and technologies by gray vertices. Entering edges of technologies refer to input carriers; outgoing edges refer to outputs. Accordingly, this model is focused on the power sector and additionally includes hydrogen and synthetic gas to represent technologies for long-term storage of electricity.

4. Implications for bottom-up planning

This section applies insights on energy scenarios from Section 2 to derive implications for the development and application of bottom-up planning models introduced in Section 3.

4.1. Openness and accessibility

Since scenarios are important communication tools in the debate about energy futures, equal opportunity to participate in the debate implies equal access to the scenarios underlying modeling knowledge. The consequences here
are twofold: First, methods and inputs of scenarios must be transparent, so everybody in the debate has the knowledge
to critically assess them. Second, modeling tools must be openly available and accessible, so everybody in the debate
can contribute scenarios. In the academic literature the need for both transparent scenarios and open models has been
widely acknowledged [78, 100, 68, 46]. Since Keepin’s critique of the IIASA model that was only possible because
he worked at IIASA himself, influential models like TIMES have been made publicly available and open-source has
become the standard for new models [103, 21].

An essential but often overlooked factor in this context, especially beyond the scientific community, is accessi-
bility. Many actors outside of academia do not have the resources in terms of working time or technical knowledge
to familiarize themselves with complex data documentations or programming tools. Open modeling tools requiring
substantial programming skills, scenario data provided in a rare data format, or extensive documentations that are hard
to understand all formally comply with openness but do little to open up the debate.

4.2. Bias minimization

Analysis in Section 2 revealed that quantitative models are not objective tools and inevitably biased, either by the
pursued method, or the assumed parameters. Nevertheless, there are strategies to be transparent about potential bias
and minimize it.

Methodologically, the engineering approach of bottom-up planning models leaves less room for bias than models
based on economics or other social sciences. In contrast to economic laws, which can be highly ambiguous—Beckert
describes for example how different macroeconomic models either assume a positive, a negative, or no effect of public
spending on economic growth—natural laws are unambiguous [7, p. 229]. However, bottom-up models are not exact
representations of the physical energy system but must approximate certain laws and heavily aggregate the system to
keep complexity reasonable. For instance, models usually approximate the physical power grid by neglecting distribu-
tion grids, aggregating the transmission grid into larger nodes, and applying some linear approximation of power flow
equations [57]. On the upside, research frequently questions such simplifications and tests them against more accurate
representations for validation [69, 26, 24]. In addition, an increasing number of studies compares different models to
investigate differences and identify bias [61, 56]. To increase transparency about methodological bias, this research
should be pursued further and in addition, scenario studies should openly discuss how their methods might bias results,
especially if they diverge from standards.

The second source of bias in bottom-up planning models are quantitative assumptions. Similar to methods, the
reasonable range for technical parameters is much more narrow than for parameters that are related to economic or
social questions. Calorific values of energy carriers are exactly defined, full-load hours of renewables are limited by
empirical data, and Carnot’s rule gives maximum efficiencies. On the other hand, estimates of capital costs, investment
costs, or the socially feasible potential of renewables can vary greatly. As described in the previous sections, some
assumptions also depend on results of the scenario itself, for example heavy expansion of a technology can induce
learning effects and reduce investment costs. Here, one approach can be to include this mechanism, in this case
learning rates, into the model, although this always comes at the risk of obscuring bias instead of reducing it, for
instance, because a subjective cost estimate is just replaced with a subjective learning rate [59]. A similar example is
to replace an exogenously fixed demand with an assumed demand elasticity.

In general, modelers should try to assess parameters critically and refrain from unquestioned adoption of parameters
used in other scenarios, even if they hold high authority. All parameters should be documented transparently and key
parameters with strong impact on results, like demand or renewable potential, should be compared to the range from
other scenarios and ideally subjected to sensitivity analysis [103, 78].

4.3. Unknowability and probabilistic methods

Based on the concept of fictional expectations, Beckert draws conclusions about probabilistic methods in eco-
nomics, which can be transferred to bottom-up planning models. He states that if future events are unknowable—and
not uncertain—probabilistic methods are as inaccurate as deterministic methods [7, p. 43]. But, since probabilistic
methods add sophistication and probabilistic statements about the future are harder to refute, they are still being used.

Various studies recommend the implementation of probabilistic methods into bottom-up planning models to ac-
count for uncertainty and increase their accuracy [79, 80, 101]. Given the limitations of probabilistic methods, this can
only be recommended for parameters that are actually uncertain, not unknowable. In other words: Probabilistic imple-
mentation of a parameter requires a well-founded estimate of its distribution to add accuracy and not just complexity to
a model. For example, historic weather data can quantify the distribution of renewable generation very well rendering
its probabilistic implementation sensible. On the other hand, deriving a robust stochastic distribution for economic parameters, like capital or investment costs, appears much more difficult, so a probabilistic implementation should be considered carefully and only be pursued to make scenarios more robust—not just for the sake of complexity.

4.4. Influence on decision making

Beyond methods and parameters, the ability of scenarios to advance the debate on energy futures decisively depends on how they are deployed. The influence scenarios have on current debates and decisions—often referred to as policy relevance—can be used to draw two implications for modeling.

First, scenario scope, and therefore model scope must coincide with the decisions and questions under consideration. Accordingly, Hughes and Lipsy [38] describe how long-term scenarios for decarbonization rarely have an effect on short-term decisions, because actors find their insights difficult to apply. Overall, scope in bottom-up planning models can be divided into temporal, regional, and sectoral scope, each having its significance. A temporal scope of multiple years is important to model the dynamics of decarbonization, a large regional scope to consider how energy carriers are exchanged between different regions, and a broad sectoral scope to reflect the utilization of electricity outside of the power sector. For example, analysis of the additional renewable capacity to achieve a certain renewable share by 2030 has to consider how much of the existing capacity is decommissioned by 2030, net exchange of electricity with neighboring countries, and the amount of added demand from the heat and transport sector. To cover a large scope while maintaining a sufficient technical detail is challenging for bottom-up planning models. Even if methods reduce computational complexity are deployed, models cannot have all-encompassing scope or detail and must flexibly adapt to questions investigated in a specific scenario.

Second, energy scenarios should carefully consider technical feasibility to prevent severe path dependencies. To demonstrate the disruption, if widely shared expectations, or scenarios, are realized to be infeasible too late, Beckert points to the financial crisis of 2008 caused by expectations regarding housing prices and home ownership that suddenly proved false [7, p. 120]. In energy scenarios, speculative assumptions on the availability of technologies, for example the maturity of technologies like carbon capture and nuclear fusion or the effective potential of specific renewables, could create similar effects [10]. If their availability is widely expected and anticipated by decisions, sudden unavailability will cause failure to achieve mitigation goals. Therefore, scenarios should focus on a risk-averse approach and deviating, more explorative, scenarios should be labelled as such and be aware of imposed path dependencies.

4.5. Socio-scientific questions

Bottom-up planning takes a technical perspective on energy systems, although Section 2 shows how system development is equally a social process. Against this background, a growing number of studies suggests that bottom-up planning models increasingly address socio-scientific questions, too [72, 86, 54]. Specific questions to be addressed include: adoption of consumer technologies, acceptance of industry-scale technologies, opportunities for the public to engage, and, similar to past debates described in Midttun and Baumgartner [65], behavioral change of end-users. Literature discusses two ways for bottom-up planning models to address these questions, either endogenously by integrating them into models or exogenously, either by adjusting inputs or interpreting outputs accordingly [86, 54].

The capability to integrate socio-scientific questions of individual preferences and convictions into the mathematical formulation of engineering-focused bottom-up models is limited. Behavioral change or attitude towards technology call for simulative or qualitative methods, but since bottom-up planning models are based on optimization, any representation of social aspects within them is restricted to optimization, too. To address socio-scientific questions anyway, external costs that reflect social aspects can be added to the model and incorporated into the optimization problem, analogously to other cost components. For example, the perceived discomfort from wind turbines can be translated into monetary values and added to the objective function to account for social acceptance of technologies. But the choice of considered externalities and the quantification of their social costs is highly subjective. Estimates for specific technologies often vary by a factor of 100, while estimates for other uncertain parameters, like capital costs, investment costs, or renewable potential rarely vary by more than a factor of two [94, 52, 9]. Therefore, models considering external costs will carry a large potential bias imposed by the selection of external costs. Overall, the optimization-based approach of bottom-up planning models is not well suited for socio-scientific questions and, if used anyway, the great range of conceivable social costs is likely to introduce a bias.

Nevertheless, bottom-up planning models can sensibly address socio-scientific questions if their focus remains techno-economic and input assumptions reflect social aspects instead. For example, behavioral change of end-users can be simulated using independent models and then reflected by the exogenous inputs on demand to quantify its potential
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for climate mitigation. Similarly, the adoption of consumer technologies can be analyzed separately and translated into corresponding boundary constraints for optimization. Questions of public acceptance are already addressed in various studies using bottom-up planning models. Typically, these studies apply modeling for alternatives and quantify the additional cost arising if deployment of certain technologies is limited according to social preferences [14, 69, 77].

In conclusion, striving for holistic planning models to address socio-scientific questions is elusive [90]. The strictly techno-economic perspective of bottom-up planning models is not a weakness but a strength, because it allows for robust results and small bias. Non-technical questions are best addressed by interdisciplinary research connecting different disciplines, their respective methods and models.

5. Discussion and conclusion

Energy scenarios are a driving force in the development of energy systems and build on bottom-up planning models for quantitative insights. Against this background, this paper analyzed the role of energy scenarios from an economic sociology perspective applying the concept of fictional expectations. The concept describes how collectively formed expectations about an unknowable future enable seemingly rational behavior, for example in case of economic and technological forecasts. The paper finds that energy scenarios exhibit characteristics of fictional expectations as well: To be persuasive energy scenarios combine narrative elements that get actors engaged and quantitative models that evoke precision and objectivity; the purpose of scenarios is not forecasting the future but to navigate decisions of a diverse range of actors into a common direction, and as a result different scenarios are competing for influence over the development of the energy system.

Generally, energy scenarios build on bottom-up planning models representing physical flows and investigating the optimal design of the system. Thanks to their engineering perspective, bottom-up planning models are comparatively robust, but their capability to address certain policy questions, like market design, is limited.

Insights on energy scenarios are applied to draw consequences for developing and applying bottom-up planning models: The impact scenarios have on the development of the energy system implies that their underlying tools, bottom-up planning models, should be open and accessible to enable a diverse range of actors to contribute scenarios and to allow for their critical review. In addition, impact on system development and public opinion suggests that modelers should minimize and be transparent about the bias imposed by choice of modeling methods and parameter data. To be relevant for public policy, the spatial, temporal, and sectoral scope of models must coincide with the decisions and questions under consideration. The inability of scenarios to forecast the future suggests limiting stochastic modelling methods to well quantified uncertainties, like weather-dependent renewable generation, instead of entirely unknowable factors, like interest rates. Finally, applying bottom-up planning models should account for the social dimension of system development captured by the reflections on energy scenarios in this paper. To achieve this without introducing major bias, it is advised to vary input assumptions and interpret results accordingly but retain the model’s optimization approach and engineering perspective.

In this paper, an economic sociology perspective on energy scenarios was developed and used to derive implications for a specific type of engineering focused energy models. Future research should adopt a similar approach to reflect on other type of models as well, for instance simulative economic models capable to address questions of market design. A starting point for such an analysis provides the review of socio-scientific literature on markets and its application to the energy sector in Silvast [89].

Acknowledgements

The research leading to these results has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 773406. Also, we want to thank participants of the internal research seminar for their constructive feedback on earlier drafts of this paper.

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