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How modelers construct energy costs: Discursive elements in Energy System and Integrated Assessment Models

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ABSTRACT

Energy system and integrated assessment models (IAMs) are widely used techniques for knowledge production to assess costs of future energy pathways and economic effects of energy/climate policies. With their increased use for policy assessment and increasing dominance in energy policy science, such models attract increasing criticism. In the last years, such models – especially the highly complex IAMs, have been accused of being *arbitrary*. We challenge this view and argue that the models and their assumptions are not arbitrary, but they are normative and reflect the modelers' understanding of the functioning of the society, the environment-societal relations and respective appropriate scientific tools and theories – in short: models are shaped by discursive structures, reproducing and reinforcing particular societal discourses. We identify 9 distinct paths, all relating to crucial model decisions, via which discourses enter models: for each of these decisions, there are multiple "correct" answers, in the sense that they can be justified within a particular discourse. We conclude that decisions of modelers about the structure and about assumptions in energy modeling are not arbitrary but contingent to the discursive context the modeler is related to. This has two implications. First, modelers and consumers of model output must reflect on what a model and its assumptions *represent*, and not only whether are they *correct*. Second, models hardly need to add more (mathematical) complexity, but rather be reduced and simplified so that they can continue to fulfill their main function as formalized and powerful instruments for thought experiments about future energy pathways.

1. Introduction

How much does decarbonization of the energy system cost? Hundreds of researchers have tried to answer this fundamental question in the last decades. With the rise in computing power, a whole new scientific branch of energy system models and integrated assessment models (IAMs) has arisen, and today scientific energy system and policy analysis without models is unthinkable [1–4]. Such models are used for energy and climate policy advice on all political levels, be it global [5], European [6,7] or national [8,9]. The central output of these models are costs, technology mixes and impacts of different possible future energy pathways, examining the effect of changes in a wide range of parameters, such as input costs; different global, regional or national climate change mitigation policies; or specific national or regional energy policies [4,10,11]. Their results are widely used in politics and public debates as they are often presented as an *objective* basis for decision-making [12].

However, energy system models and especially IAMs have also been criticized of being "inescapably subjective" [13], as being neither theory-driven nor empirically sound [14,15] and of creating their own worlds in which basic scientific standards such as falsification is impossible [16,17], especially since both the models and the used data are often intransparent [18]. Modelers have started to counter this criticism by explicitly framing their research as exploring an unknown future to avoid misinterpretation of models as projection tools. Model evaluation and intercomparison projects [2,3,19] are other ways modelers take to improve the "appropriateness, interpretability, verifiability, credibility, and usefulness" of models [20] and "reduce model uncertainty" [21]. Still, models – especially IAMs – are criticized for creating "a perception of knowledge and precision that is illusory and can fool policymakers into thinking that the forecasts the models generate have some kind of scientific legitimacy" [14] (see also [22,23]). Pindyck further accuses modelers of *arbitrarily* deciding both the functions of the system and the single parameters, including decisive ones like discount rates, damage

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functions or technology cost, making the entire model and its output arbitrary [14].

In this article, we scrutinize this statement. By applying a social constructivist notion of knowledge, going beyond the positivist fact-value dichotomy, we challenge the view that assumptions and parameters in energy models and IAMs are "arbitrary" and seek the discursive determinants of modelers' decisions for how their models are built and the input data is generated. Specifically, we investigate what kind of discursive elements can be found in the models and where these elements enter the models.

We do not investigate whether particular assumptions of model structure or input data are – in a positivist sense – *correct* or *realistic*; further, we do not explain which specific discourses are present in specific modeling teams – we identify whether and where entry points for discourses in energy models and IAMs exist.

2. Literature review and theoretical foundation

Research about possible energy futures is a hot topic in climate and environmental studies. Especially the social and societal implications of different energy futures, the stories and narratives behind energy policies and visions and the social context of energy related behavior has gotten further attention [24,25]. However, regarding the process of energy modeling the vast amount of research has been related to the development of *better*, more *coherent* and even more *complex* – and hence seemingly more *accurate* – modeling techniques. In recent years, researchers have started to reflect on modeling techniques and some criticized them as being arbitrary and non-falsifiable [14,26]. The modeling community responded to this by increasing the complexity of modeling techniques, involving stakeholders for data input or scenario evaluation, or run modeling intercomparison projects to determine "best practices" and to compare the specific features of the models and their effects on the results [2,3,19,27,28]. Also researchers from non-modeling communities have started to investigate specific non-technical aspects of modeling such as the epistemic modes of modeling [29], the objectives [1], the archeology of models [30], the effects on policy recommendations of different modeling narratives [31], the theoretical perspectives on knowledge generation of IAMs [32] or the impact of models on policy advise [12]. Further, there are nascent attempts to better integrate modeling with socio-technical transitions analysis [33]. A discourse-analytical understanding of energy models and IAMs is however still lacking.

To identify the social embeddedness of modelers' decisions regarding assumptions and structures in modeling processes, we will first refer to more general concepts how to analyze economic phenomena and will later apply this to the case of energy system models and, especially, IAMs. Berger and Luckmann further developed the view that reality is socially constructed and not detached from societal institutions, experiences, signs and roles [34]. This has been applied to the economic domain, looking at economic knowledge generation and the implications for the perception and interpretation of economic action in different societal fields. Relating to this basic assumption, a large amount of research has been done to analyze the calculative characteristics of economic transactions, economic knowledge generation and risk management [35–38], yet an analysis of energy modeling is lacking. Smelser and Swedberg [39] founded a new strand of economic sociology, based on the assumption that the economy is an integral part of society and must be analyzed with the same methods and assumptions as other societal phenomena, including the examination of social structures, conventions, institutions, identities and the perception of different actors of these categories. Furthermore, special interest has been given to power aspects of economic knowledge generation e.g. the social construction of accounting methods and their influence on perceptions of economic categories and institutions like the "firm", "credit rating", "risks" or "responsibilities" of different agents. Miller for example discusses the permeable and historically contingent character of cost conceptions in accounting by analyzing accounting standards as tools for decision-making, finding that these "different functions of cost accounting called for different concepts of costs." [40]. Common to all these studies is their finding that calculative tools to measure economic phenomena and correlations produce their objects by measuring them. Particularly in the study of finance the reciprocal role of economists and their objects have been analyzed, revealing that results of calculative actions cannot be understood as representations of an objective reality but as determining and constituting the subject to be examined [37,41]. "Reality" is thus not something that can be *measured* – as a positivist researcher would claim – but in a social constructivist sense it can be at best be *understood* by looking at the social construction process and its determinants.

This social constructivist perspective on reality relates to the *archeology of knowledge* concept of Foucault, viewing practices/behavior not as "arbitrary" but "contingent" on discursive structures [42]. Here, we follow this school of thought understanding the act of building complex mathematical-computational models, such as IAMs, as a process that is closely connected to and influenced by societal discourses and institutions, but also as one that can shape reality by reproducing a discourse by calculating it (power effect). Looking at models and their outputs thus means looking at "artefacts" [29] but with power effects: discursive structures are main determinants for behavior – but actors can and do influence these structures, e.g. through discursive battles about dominating narratives.

3. Method

In this article, we analyze how energy model results such as cost statements *are made* by modeling practices – specifically, how and where discursive elements are channeled into the models. For this, we use and extend the SKAD framework, which was designed "to analyze ongoing and heterogeneous processes of the social construction—production, circulation, transformation—of knowledge" [43]. The SKAD links the process orientation of the sociology of knowledge to epistemic assumptions from Foucauldian discourse analysis [38]. To identify the context in which modelers decide for specific parameters and functions, we use this research concept to relate the modes of knowledge production in energy models and IAMs to wider societal discourses.

Discourses are here defined as sense-making units that produce a certain set of practices and assign meaning to objects and social phenomena [43], including norms, worldviews and specific system beliefs. Economic discourses are thus "*collective practices processing economic institutions such as markets and firms*" [43,44]. Discourses are (re)produced and carried by "*epistemic communities"*, understood as networks of "*professionals with recognized expertise and competence*" and an "*authoritative claim to policy-relevant knowledge*" [45]. Actors within an epistemic community share a set of normative beliefs and notions of validity, and perceive that they share a common policy enterprise [45]. Following the SKAD, we do not consider the individual modelers and why they make a particular decision, but focus on the structure in which modelers' assumptions are embedded. We view modelers as carriers of worldviews (consciously or unconsciously), and these worldviews depend on the discourses to which they adhere.

We chose the case of energy modeling and IAMs, as the transformation of the energy system is a field where decisions are urgent and contested, and where they will have far-reaching impacts both on the energy system and its actors and on society. Furthermore, the complexity of the system requires the extensive use of models as policy-advice instruments. Energy is thus a case with a strong model-policy interface, and it is one with a well networked research community and wide range of different models to look at. Hence, we apply our analytical framework to energy, but it would be equally applicable to modeling of other (contested) policy areas, e.g. mobility or tax policy, and we would greatly appreciate seeing such studies in the future.

The SKAD framework proposes four different analytical units to analyze knowledge production in discursive settings: *frames, classifications, phenomenal structures* and *narratives* [38]. As SKAD is explicitly built as a research program, rather than a fixed framework, it can be adjusted to specific research questions. Here, we use it as a conceptual starting point to determine how discursive elements enter energy models, using three of Keller's four analytical units. We integrate the unit *frames* into the unit *narratives*, as we analyze a scientific device – energy models – in which modelers themselves *frame* their analysis, typically in the storyline or narrative of their model. Furthermore, we add the category *conventions* here as – due to the broad scope and complexity of models – modelers often refer to others within their (epistemic) community to justify decisions. In this way, they themselves refer to and produce specific *discourse coalitions* in economics.

3.1. Narratives

Narratives act as a sense-making processes by providing the interpretation context to a single event or information [31,38]. These narratives are important features of modeling as they (may help to) make the results meaningful to the reader by providing context to the scenario. Typically, the narrative is found in the "prose" of the model, such as model descriptions or within introductory or concluding texts where the problem is framed or the results are explained. Narratives are also important for the modeler to derive or justify data assumptions for an unknown future: the narrative is the base for defining or selecting appropriate input data and to ensure that a scenario is internally and externally consistent [46–48].

Thus, narratives help the modeler deal with uncertainty regarding specific parameter values or probability distributions for values or modeled events [49–52]. How modelers deal with uncertainty differs strongly: the typical approach is to apply a sensitivity analysis for key variables [53], but some model uncertainty itself [54] and others suggest to view uncertainty not as the result of a fundamental unknowability about the future but as a result of yet unknown decisions of decision-makers [50]. Also here, narratives are used to justify decisions by giving context and making if-then aspects of scenarios explicit.

3.2. Conventions

Conventions are practices that have been established as "correct" within a scientific community and are thus not questioned among peers. Conventions can be used in two ways in modeling. First, they are an answer to the sheer mass of variables: identifying and citing values for uncontested (within one's own community) variables helps reduce the workload. Second, they are a way to handle uncertainty, by referring to the findings and/or assumptions of others, especially if their results have been peer-reviewed. By basing a model on a shared and accepted stock of knowledge and aligning their modeling decisions with convention, modelers position their model in the respective research community and increase its credibility [55]. Thus, conventions are not only implicit routines and simplifications of complex processes, but are part of the self-assurance and identity of the scientific sense-making/explaining process and in that way reproducing a discursive structure.

3.3. The phenomenal structure

The phenomenal structure relates to all relationships that the model entails, and thus includes all equations, fixed boundary conditions and global assumptions of the model: they describe "what the model models". The basic structure can thus be analyzed as a formalized representation of the modeler's understanding of *how the world (or the target system) works in relation to his/her research interest*. Looking at the phenomenal structure of the model can therefore inform us about the modeler's general *beliefs* or *worldviews*, that are parts of wider discourses.

3.4. Classifications

Classifications are social ordering processes inherent in all forms of formalized knowledge that use categories, denominations, steps or other organizational structures. Energy models, just like any mathematical model, are good objects for analyzing classifications, as models are systems of algorithms – and all classifications are explicit and formalized. Energy models work with several classifications, including which parameters are exogenous or endogenous, or what cost unit to use (e.g. nominal or relative).

Some elements fit into more than one analytical unit, depending on the specific research interest. For example, some conventions can also be part of a narrative of the model, or classifications of structure and data could also be analyzed as determining the phenomenal structure. However, we use the analytical approach of the SKAD framework to differentiate between different forms of how discourses come into models and relate it to empirically observed implications in real energy system models and IAMs.

To identify which are the crucial aspects in energy system modeling practices, we first did a literature review looking at major meta-studies [2], and critical self-reflections of modelers [13,21,56] in order to collect specific modeling elements that are either contested or vary strongly between models. From an initially extensive list of energy modeling elements we selected 9 elements that have strong effects on the outcomes of models – the "costs" of decarbonizing the energy system – and are illustrative and representative when relating them to the four discourse analytical units. Hence, our analysis does not hold all important modeling parameters, and it does not discuss all possible discursive elements; rather, we identify common structures in energy modeling, affecting the modelers' decisions so as to illustrate that such discursive elements exist and that these decisions are not arbitrary, but contingent to specific discourses.

The modeling elements are conceptualized as dependent variables that can be understood in their social context, namely specific discursive structures. These discursive structures can be found in specific modeling communities but also in wider societal institutions and processes. We understand specific modeler choices as the practice of a discursive structure. Thus, we can observe decisions about assumptions and their explanation or reference, compare it with other assumptions, make the implications explicit and relate it to specific belief system about the functioning of the society where possible. However, we do not apply a discourse analysis of specific debates in society and do not explain which discourse underlies a particular decision. Instead, we define the four analytical units as discursive structures that are themselves part of wider societal discourses. We use the term social context synonymously with discursive embeddedness or being "related to discourses" in general. The data we use are the written documentation of the models provided by the modelers themselves and accompanying texts. Thus, the analysis is limited to an analysis of modeling parameters and structures, using the SKAD approach. However, we do not provide a discourse analysis about societal climate-energy debates and do not explain individual modeler choices.

4. Discursive elements in energy system and integrated assessment modeling

4.1. Narratives

4.1.1. Scenarios

The most commonly acknowledged position for narratives in modeling are the scenarios, which are generally seen as a set of quantified variables corresponding to a qualitative narrative. Modelers have described the process of building a scenario as quantifying a narrative, or storytelling with numbers [57,58]. Thus, a model narrative represents a particular view of the problem to solve, who or what caused the problem, who is to solve the problem in which technical environment and policy setting [31,47,48] (see also Section 4.3.1 *Problem definition*). Narratives are central in scenario creation, as they frame the problem, help modelers justify quantitative assumptions in a consistent way, and help reduce the number of scenarios from an infinite number of possible to a manageable set of feasible and consistent scenarios [46,48,59,60].

As modelers are part of a specific epistemic community, the decisions about which scenarios to create and which are the relevant dynamic drivers, parameters and policy settings that define a scenario depends on narratives about political-economic pathways and related trade-offs. A central narrative in most IAMs and energy models is to seek ways for the *most cost-efficient* decarbonization, which generally means keeping global warming below 2 °C above pre-industrial times. Further, modelers often depict and reproduce the narrative that energy efficiency provides “nega-watts”, which are cheaper than the regular megawatts but equal and interchangeable [61].

Models also hold more specific narratives. In the IAM *REMIND*, for example, modelers decided to include “the development of fossil fuel subsidies and taxes over REMIND’s time horizon [and let this be] prescribed by scenario assumptions. In the default case, subsidies phase out by 2050” [62]. They refer to two specific narratives: fossil fuel subsidies as one of the main “uncertainties” to be addressed by using scenarios, and secondly that 2050 is an appropriate year for a subsidy phase-out. This 2050 timeframe can be found in several national and international targets and climate mitigation plans [63,64]. By using 2050 as the default date for target achievement, the 2050 target *narrative* is reproduced and strengthened while targets set for other dates become deviant options.

Most energy models and IAMs assess overall (often global) costs of climate protection (for models with high time-resolution with system stability boundary conditions), but ignore distributive effects [56] and the institutional reforms needed for a socio-technical transition [65]; they also ignore that cost can be a boundary constraint but it is rarely a driver of energy transitions [66]. Furthermore, energy models usually do not represent the centralization-decentralization question which is highly present in national energy debates, with challengers often propagating decentralization while incumbents are advocating for a non-radical shift to a new, but still centralized system [67,68]. Hence, the narrative of cost-optimal decarbonization is powerful, but does not depict further narratives shaping the transition used by others: this choice of narrative greatly affects the result and policy recommendations, but it is rarely made explicit. Yet, it is not an arbitrary choice, but one rooted in the neoclassical economics belief of economic efficiency being the main (or only legitimate) aim of policy interference with the “free market”.

4.1.2. Boundary conditions: the climate target narratives

The selection of a target, the definition what is the “default” or an “ambitious” one, has great impact on the results. The IPCC assessment report [5] is often read as requiring the world to decarbonize by some 70–80% by 2050 to stay below 2 °C global warming, and that the 2 °C target will suffice to avoid “dangerous climate change” [69] (for a discussion of the 2 °C narrative see [70]). However, when looking beyond 2050 in the IPCC report, the two pathways staying below 2 °C foresee zero and then negative emissions: one can thus refer to the same report (and graph) to justify 80% or 100% or > 100% decarbonization by mid-century. Which target to model is in part a function of what solution one prefers: whereas an 80% target is a reduction target, for which there is much flexibility and room for trade-off between sectors (making carbon trading a potentially efficient instrument, appealing to neoclassical economists), a 100% target is an elimination target, without any flexibility as all sectors must completely stop emissions (rendering carbon trading meaningless, as there is no carbon to be traded, which is appealing to advocates of a carbon ban) [15,65,71].

After the Paris Agreement, a new narrative challenges the *2 °C world,* as policy-makers referred to 1.5 °C being the threshold below which humanity almost certainly remains safe, whereas 2 °C may have regionally disastrous consequences, or even trigger tipping elements in the Earth system [72]. Within the 1.5 °C set of futures, two are dominant: the elimination narrative, prescribing rapid and complete decarbonization like in the 2 °C outlook, just faster [61,65], and the *overshoot narrative*. Because the carbon budget for 1.5 °C has been largely consumed, the second narrative introduces the concept of temperature overshoot, allowing the temperature increase to temporarily exceed 2 °C, assuming that solar radiation management and/or negative emission technology can bring temperatures down towards the end of the century [73,74]. The concept of an overshoot is a result of the physics of climate change (the carbon budget size), but it also gives room for flexibility and hence carbon trading. The negative emissions can also be brought about by carbon trading through a market for carbon offsets, making the overshoot narrative much more attractive to neoclassical economists than the elimination narrative. In any case, the modeler must include a specific climate narrative into the model and in that way refers to and reproduces specific societal discourses about climate, technology and sustainability.

4.1.3. Learning rates

One of the key parameters in energy models and IAMs is the learning rate, which describes the technological progress as a function of the cumulated capacity of a technology over time. The learning rate is pivotal for any intertemporal optimization model, as it leads to tipping points: as soon as a technology becomes the cheapest, all investment will go into this technology, massively skewing the model result towards this option (as the optimization model searches for the cheapest energy mix). Hence, modelers impose additional constraints “*to control the penetration of learning technologies*” and limit penetration to “*what is deemed realistic*” [75]. Often, this means relying on historical, technology-specific learning rates and extrapolating these several decades into the future, coupled with the modelers expectation of a “realistic” maximum expansion pace and/or “realistic” minimum costs in the future. REMIND, for example, uses constant technology-specific learning rates and limit the possible cost reduction to exogenously prescribed floor costs beyond which costs cannot decrease [62].

In other cases, the decision for a specific learning rate for the future and accompanying restrictions is based on the modeler’s technological scenario. MESSAGE, for example, assumes variable learning rates, depending on the storyline of each scenario: scenarios with stronger technological change also have higher learning rates, reflecting the higher rate of innovation required for this scenario to materialize. In this model, the learning is exogenous, and hence assumed by the modelers, outside the MESSAGE model itself. MESSAGE also uses floor costs of “learned out” technologies, which depend on the storyline: scenarios with more change have lower floor costs [76,77].

A further example of how narratives affect the representation of technological learning is the case of the concentrating solar power (CSP). In Europe, the German Aerospace Center (DLR) championed the vision of the Club of Rome that for secure decarbonization of the European power system based on renewables, “*centrally regulated, large-scale imports of controllable concentrating solar power from the desert are necessary*” [68]. This narrative was reproduced and strengthened through numerous scientific reports [78,79]. In this narrative, CSP has high learning rates, rapidly making it cheaper so as to facilitate its market breakthrough – without that, CSP would not appear in the scenario output. Whereas some modeling teams picked up on that narrative (e.g. MESSAGE) leading to high shares of CSP in their scenarios, others ignore CSP as an option at all (e.g. IMAGE) [53], whereas yet others include CSP as an option but assume low learning rates leading to a negligible expansion (e.g. REMIND [80]).

The technology narrative of each model and scenario run thus determines the energy mix of each scenario. Whether a technology is strong or if does not exist at all in a scenario depends on whether it is included in the classification (see Section 4.4.1) or whether it is outcompeted by other, cheaper or faster learning technologies. This is not a matter of techno-economics but of expectations about which technologies are good or necessary, and which are channeled into the model through the discourse-dependent choice of learning rates.

4.2. Conventions

Conventions are a specific form of social institutions that are widely accepted as the "appropriate" or "normal" state or behavior in a specific community. As Keller puts it "*conventions form the basis of discourse practices as a set of more or less powerful, more or less institutionalized instructing rules. They are actualized in practical usage, thus simultaneously reproduced and altered, or changed, as needed*" [81]. One strong indicator for conventions in modeling are features/issues/determinants that are decided upon only by a reference to others: the authority of the source is the primary or only justification of the assumption.

4.2.1. Current cost conceptions

The current cost of every depicted technology is the base for all calculation of a cost optimization model: learning rates apply to this cost, and together with a few other variables (e.g. the discount rate) they determine the energy mix in each time step. The current cost assumption is thus critical for the result.

Typically, modelers refer to this parameter as "current" or "today's" cost, indicating that there is an empirically observable, correct number. Yet, the assumptions are very different across models. MESSAGE, for example, assumes a range of current costs depending on the storyline (see Sections 4.1.1 and 4.1.3) of each scenario: for PV costs in 2005 (base year), they assume global PV costs of 2500–3500 $/kW [77]. REMIND, in contrast, uses point costs and assumes 4900 $/kW for PV in 2005 [62]. These large differences on a seemingly uncontestable data point reflects the discursive background of these models: one must use different input data depending on what the model is to show and depending on how radical learning (see above) is deemed "realistic".

Even when using the same (empirical) data, modelers use this data in different ways depending on the specific technology belief. Often, renewable energy studies refer to IRENA publications, as this is an authoritative source, for example the "Renewable Power Generation Cost" series [82]. IRENA here (p. 64) shows the cost development of PV over the last decade, but when used as input for a model, a range of different assumptions can be motivated. For example, a PV-enthusiastic modeler would see low costs and a strong cost reduction trend, whereas a PV-critic modeler could justify the narrative of PV costs that are twice as high as for coal power, and a flattening cost trend in recent years. Thus, even empirical data input such as "current observed technology cost" is strongly discourse-dependent.

4.2.2. Discount rates

The discount rate – which in energy modeling is often synonymous with the weighted average cost of capital (WACC) – describes the rate that future revenues/costs are devalued compared to today. It is closely related to project risk: for energy projects of higher perceived risk – e.g. in an unstable country, or with a new technology – the WACC is higher, reflecting that investors need higher revenues to compensate for the risk of loss. Hence, IRENA assumes a 7.5% discount rate for projects in OECD and 10% for other countries [83]. The discount rate is pivotal for capital-intensive projects (e.g. renewables or nuclear power): the levelized generation cost of wind power, for example, is twice as high with a 15% discount rate as with 5% [84].

Often, energy modelers refer to a specific discount rate as a convention without any further explanation [85], for example 5% [78], 7% [86,87], or 10% [88]. Sometimes, this assumption is justified, such as the REMIND assumption of a 5–6% discount rate, which is "*in line with the interest rates typically observed on capital markets*" [62]. This convention refering to interest rates was also used by Nordhaus in the famous Stern-Nordhaus controversy in climate economics. Whereas Stern rejected any pure rate of time preference (PTP) on the grounds that future generations must be equally much worth as our, other economists, prominently Nordhaus, argued that the PTP is 3%, giving the discount rate of about 5% (depending on growth expectations) that can be observed in actual market interest rates and real savings [89,90]. While Stern thus based his choice on a philosophical-ethical discourse that includes a moral obligation of equality, Nordhaus related his argumentation to a technocratic-economical tradition of referencing only to empirical figures. Therefore, discussions about discount rates, like the Stern-Nordhaus controversy, seem like but are not really disputes about the "correct" discount rate, but a clash of competing discourses; it is the perhaps most prominent example of a discursive element in models, strongly showing the problem of using conventions without deeper reflection on the assumption [91,92].

4.3. Phenomenal structure

The phenomenal structures of a model determine the space in which meaningful conclusions can be made. Models are created by modelers who formally define every single aspect of the model, thereby determining the world of the model, what it can and cannot see. Hence, all decisions and all relationships within the model produce the space for knowledge production while also delimiting the world about which the model can produce new knowledge.

4.3.1. Problem definition

The first step of model development is to define the problem to solve. This is done by the modeler, and sometimes the problem to address is defined by funding actors. The problem definition process is done for each single scenario (see Sections 4.1.1), but also for the model itself: "a model's structure exemplifies its fundamental approach for representing and analyzing a problem—it does not change from one implementation to the next" [75]. Thus, the problem definition is a critical step, as it defines what a model can see – and which alternative solutions a model cannot see.

As there are several, competitive conceptions how to characterize the problem of climate change and appropriate energy policy options [93], the modeler must decide on a specific problem definition: each model (run) can only address one particular problem set. The currently dominant problem framing in energy/climate modeling communities is that climate change is caused by too high CO_2 emissions, resulting from a market failure to account for the externalities of emissions. Within that framing, a change to climate-friendlier sources and technologies is needed [94], and a carbon price, making low-carbon energy more competitive, is an appropriate instrument for that. Often, this framing defines carbon pricing as "climate policy" [56,95,96], thus implying that regulatory policies are deviant and inacceptable climate instruments, and largely ignoring institutional and infrastructural changes may others perceive as important to support the establishment of a whole new, climate-friendly energy system [65,71]. Yet others perceive climate change as caused by wasteful energy consumption and see efficiency and sufficiency measures as imperative, which may include carbon pricing but may also hold demand-side regulations [97]. Depending on how modelers perceive the roots of the problem to be solved, they will design the model structure, including possible instruments and relationships within the model accordingly. Hence, the very structure of a model depends on the modeler's beliefs about the functioning of society.

4.3.2. Perfect foresight

Modelers need to define the behavior of agents in reaction to specific stimulus as price changes. Decisions about investments, allocation of capital and resources over time are influenced by agents' degrees of (im)perfect foresight of the market [98] (as applied in game theory explanations with infinite reiteration). Often (e.g. WITCH, REMIND) models assume perfect information and perfect foresight over several decades, whereas others (e.g. IMACLIM and POLES) are "myopic", allowing agents to base their decisions only on current or near-term prices and costs; some models have different modes and can do both (e.g. MESSAGE, TIAM) [99]. There is little discussion of the implications of foresight, and in the model documentation the reason for choosing one mode over the other is often only briefly touched upon [77], or it is omitted completely [62].

Following one or the other option, the behavior of economic agents determines the kind of information that the model will generate: the perfect foresight assumption means that there is no uncertainty over future events – everything that will happen is known – and actors thus make no mistakes or invest in assets that are suboptimal from a societal welfare perspective. This has far-reaching implications, as risk – of which uncertainty is a key part – is a main factor affecting reactions of economic agents in energy models [100]. Perfect foresight has concrete effects, for example by prolonging the investment cycle, thus reducing the levelized cost of capital-intensive assets like renewables or nuclear power, as investors know exactly when in the future investments will be most efficient. This thus represents the cheapest possible future – consistent with the basic functioning of a cost-optimization model. These models often view policy longevity and stability as key for efficient mitigation, especially a long-term stable carbon pricing scheme, allowing actors to incorporate the expected (and relatively certain) carbon price in their investments [101,102]. This, however, is an *assumption* of perfect-foresight models and thus a basic belief of the modeler about the rationality of market developments and not a result. Thus, the epistemic capabilities of agents in the model are another implicit, but for the phenomenal structure very relevant decision of modelers and the kind of knowledge which will be produced and pronounced.

4.4. *Classifications*

Classifications have powerful effects by making distinctions and thus defining the “norm” and the “deviant” from each other [103]. Classifications implicate certain legitimacy for using taxonomies that decide about inclusiveness and exclusiveness concerning actors and parameters. In this Foucauldian way of analyzing classifications, they can be conceived as “social instruments” [104] to create and limit discourses. The modeler must define parameters and decide on their taxonomy – and these classifications directly determine the modeling output.

4.4.1. *Defining technologies*

The modeler must define the technologies included in a model, so that they can be explicitly represented in input data and results. Typically, models have fixed sets of technologies that do not easily change, but some (e.g. TIMES) allow users to define the technologies that are relevant to them [75]. The results and policy implications can be very different if a model, for example, looks at coal, petroleum, natural gas and solar energy (for hydrogen production (e.g. the early MESSAGE [105]), or if it also introduces renewables as individual technologies (e.g. REMIND [62], 2012-MESSAGE [106]), or even splits solar PV into subunits (e.g. roof-top PV and large-scale PV (e.g. Calliope [107]). In practice, the choice of technologies is not arbitrary but closely connected to the problem definition (Section 4.3.1) and “story” of a model (or single scenario, see Section 4.1). For example, whereas the early MESSAGE was built in the era of the oil crises and set out to find ways to secure enough energy it is strong on the fossil energy side, other models designed to seek cost-efficient decarbonization (REMIND) or broader “sustainability” (newer versions of MESSAGE) are more detailed in terms of new energy technologies, and especially renewables.

Modelers often refer to such differences between models as models having “different strengths” [108,109], but by allowing or excluding contested technologies such as CCS or nuclear as “clean technologies” modelers position themselves, often without explicitly reflecting on it, in a specific epistemic community, thereby strengthening its central aims. Thus, models depict, reproduce and strengthen a particular discourse by defining the technology choices.

4.4.2. *Business as usual*

Another pivotal classification concerns the definition of the default case, the baseline or the *middle of the road* as the “normal”, or the “non-extreme case” [110]. To calculate the costs of an emission target, modeling exercises normally entail “alternative” scenarios, which are compared against a “business as usual” (BAU) scenario. The BAU scenario represents a future in which no further policy interventions towards the central aim, often climate protection, are made. The result is that decarbonizing the energy system is viewed as a cost penalty compared to a fossil-fueled, climate-harming future. This basic structure is present in most energy scenario-based studies e.g. for EU policies. Such targets relative to a BAU/baseline are also written into legislation, for example the European energy efficiency target (which is a 20% demand reduction compared to a BAU, but 14% primary energy demand reduction compared to the base year) [111], or the INDCs of many countries, including China, Korea, Mexico and Indonesia [112].

However, what is defined as the BAU scenario depends on the modeler’s expectations about, for example, the (relative) cost development of all possible technologies and fuels in the future. This puts modelers before a problem, as encountered in the model intercomparison project RECIPE, where “*the three models embody three different visions of future evolution of conventional fossils and low-carbon technologies and make different assumptions on the role of technical change in improving energy efficiency and enhancing de-carbonization*” [21]. The aim of that project was to harmonize model assumptions and scenarios, but the disagreement already about the BAU was too large for harmonization. However, they all agreed on the global commons perspective, assuming that climate-friendly futures are more expensive than fossil-fueled, climate-harmful ones (otherwise no policy intervention would be required for decarbonization). Scientists adhering to the evolutionary perspective, in which increasing returns to scale make desired technologies competitive over time, would disagree even with that premise: to them, there would perhaps be no BAU, but only the future that *we decide* to enact [50,65,91,113]. Thus, by choosing the default case, modelers make strong assumptions about how the energy system and the current policies work. These assumptions are based on the modeler’s beliefs towards the role of progress, the human development in general and the market-policy interface development.

5. Discussion and conclusions

Pindyck and others have accused energy models such as IAMs and their assumptions as being arbitrary. We showed in this article that this is not true, but modeling assumptions and decisions of modelers always, usually implicitly, reflect and reproduce wider societal or scientific discourses. The models are thus not arbitrary, but they are discourse-dependent and socially constructed – something that is as clear to the constructivist scholar as it may be feared and rejected by the positivist modeler.

We used four different analytical units to structure the ways discourses come into energy models – narratives, conventions, the phenomenal structure and classifications – and showed that modelers must make numerous choices regarding all four, and these choices are the places where discursive elements enter the model. All of the 9 specific entry points for discursive elements we identified are key elements of a model: what one assumes for any one of these 9 items will determine the model output, and hence the model output is to the largest (or full) extent socially constructed. Viewed from a strict positivist perspective these choices may appear arbitrary, and most certainly they may seem *wrong*, but they are not: they are contingent to a particular discourse.

This means that scientific knowledge in the form of modeling outcomes and the models that produce them both depicts and reproduces particular discourses. Given their usage in policy advice and the use of models and their assumptions to calibrate and validate other models, energy models such as IAMs are performative and affect the probability that a specific discourse will become (or remain) dominant, regardless of whether this is the modelers' intention. In this article, we did not analyze which specific discourses are found in modeling and why, but identified key entry points for discursive elements. In further research, it would be exciting to do that analysis and see which specific discursive structures are reproduced in the big, impactful models and whether they differ or are similar in all frameworks.

While narratives and conventions can be understood as representations of discourses into the model, classifications and the phenomenal structure let the model function as a knowledge producing device, as an apparatus that reproduces a particular discursive structure. While a numerical assumption or a scenario narrative can be altered between model runs, the general structure of the model and its classifications determine what the model can see and what it cannot – these are typically hard-coded and do not change over time. Thus, looking at the classifications and phenomenal structure no longer means looking only at an image or representation of a discourse but on a discourse-producing device itself. A model thus can indeed provide "new" knowledge, but this new information is only producible within the space given by the model classifications and structures.

By applying a discourse analytical perspective, we thus come to very different conclusions than model comparison projects. While these seek "*to explore and reduce model uncertainty*" [21], this aim is epistemologically impossible in a discursive perspective. This is particularly important as the key questions that model intercomparison projects seek to answer – which assumptions or model structures are *correct* or most *realistic*, *useful* or *relevant* – are not analytically solvable, as the differences are founded in differences in discursive settings such as worldviews, beliefs and deeper epistemic understandings of different discourses. We conclude that IAMs and energy system models are extreme cases of artefacts that can produce knowledge only within their own world. The model is the "material infrastructure", the "apparatus" [43,110] that defines what is to be seen and which problems are to be addressed, how economic knowledge about the decarbonization of the energy system is communicated and what solutions are feasible. Energy models are thus formalized *dispositifs* in the scientific macroeconomic cost discourses. Just like in quantum mechanics the outcome of an event is changed when observing it, the economic cost outputs of a model are created by the attempt to measure them, so that the calculated cost of the energy transition is a value that does not exist outside the calculation tool itself. Outside the world of the model, such cost statements lose meaning – not because they are wrong, but because they are contingent on the social context and thus carry meaning only in their own discourse.

However, models produce knowledge that *is* used outside the modeling community, which is particularly important in fields where not technical or physical feasibility of a solution is dominant, but economics and policy instruments are assessed too, such as in the models we analyzed here. Such models work as meaning-making machines, having the power to define and delimit the solution space in which to search for possible solutions, and this space is determined by the discursive structure. Although modelers often make explicit that their results are not predictions but explorations of possible futures, model results are powerful tools to legitimate specific arguments or policies and to reproduce and strengthen a specific political goal without explicitly referring to the social context of the numbers. The "hard" numbers that models produce *can* be and *is* used by policymakers in a purposeful and performative manner – by referring to results that support a particular strategy, or by commissioning studies either with a strict set of boundary conditions or by funding modeling teams with models that reproduce the desired discourse. Hence, models are not only powerful scientific tools, they are also – and in particular – powerful political instruments as meaning-making machines that define what is possible and what is best. To describe it illustratively, models can be used for *policy-based evidence making*, instead of the *evidence-based policy-making* that scientists and policy-makers alike claim to strive for.

For modelers, this means that they need to be more aware of the discursive structures of which their models are composed. Critical energy and IA modeling should therefore more explicitly consider questions of *why* a classification, phenomenal structure, convention or narrative is used, what other options would be possible, and what the reason and effect of making one choice over another are. Currently, energy research like most other scientific fields is struggling to increase openness, transparency and reproducibility, but most such initiatives (e.g. the OpenMod initiative) aim at making data and source codes publicly available. Whereas this is both laudable and necessary, it is insufficient: simply stating *what is* – which equations and data assumptions are used – is not enough if the justification of each assumption and each trade-off are omitted: why did I use this equation and not another one; why did I assume 5 and not 3?

Such reflection and transparency about modeling choices is necessary as modelers and users alike need to understand the thought experiment character of a model. Still, complete openness and reflection on each parameter is wholly unfeasible for the complex and gigantic structures of IAMs and energy system models. For this purpose, models would have to become simpler instead of getting more complex: it is unlikely that the newest mathematical finesse will have a profound impact on the policy strategy chosen, but it is very likely that the broad strokes that are already included but hidden behind myriads of largely intransparent but discursively shaped modeler decisions will. Instead of building more complex models that answer all questions at once (hence improving the "integration" of integrated assessment modeling), it may be more useful to reduce complexity and improve understandability by splitting the models into more targeted, smaller models. It is not necessary to investigate the climate impacts, land use, the stability and cost of the technical energy system, the most efficient policy options for transition and macroeconomic impacts all at once: it may be scientifically more useful and politically more legitimate to investigate these aspects one by one in detail.

Declarations of interest

None.

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