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Knowledge claims in European Union energy policies: Unknown knowns and uncomfortable awareness

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ABSTRACT

Despite the concerted efforts of the scientific community and politicians to contain greenhouse gas emissions, the CO_2 level in the atmosphere continues to increase monotonically. This raises the question whether the scientific representations and related knowledge claims used to inform energy policy have been incomplete or incorrect. Are there alternative relevant knowledge claims that have been overlooked or ignored in the discussion of energy policies and if so, why? We answer these questions by elaborating three case studies, energy efficiency improvements, liquid biofuels, and decarbonization of electricity, and using a novel procedure for quality checking policy narratives that is based in post-normal science and developed in the EU project Moving Towards Adaptive Governance in Complexity: Informing NEXUS Security (MAGIC). The focus of our approach is on the coherence of the *why* (concerns or justifications), *what* ("solution"), and *how* ("scientific evidence") of energy policies. We show that for all cases studied alternative knowledge claims, mostly derived from the relatively new field of non-equilibrium thermodynamics, would be available for better informing energy policy, but that they are unknown knowns in the chosen framing of the issues. We conclude that the idea that the various concerns identified in EU energy policy can be solved simultaneously is unrealistic. This idea can only persist by virtue of banishing uncomfortable knowledge and the creation of implausible socio-technical imaginaries. When considering different aspects of the problem and integrating different narratives and knowledge claims, a smooth and painless transition to a zero-carbon economy seems unlikely.

1. Introduction

The past four decades have been marked by combat against climate change and a considerable amount of public funds has been poured into scientific research to support strategies/policies to reduce greenhouse gas emissions. Despite the concerted efforts of the scientific community and politicians, the level of greenhouse gases in the atmosphere continues to increase monotonically (Fig. 1). This raises the question whether the scientific representations and related knowledge claims used in the problem framing and the formulation of solutions (energy policies) have been incomplete or incorrect. Are we using, in the energy domain, all pertinent knowledge available to inform policy? This question is relevant, given the current geopolitical situation in which a quick transition to renewable energy sources is considered highly desirable. Indeed, the ongoing war in Ukraine has made painfully evident the dire implications of the EU's dependence on energy imports and fossil energy (associated with GHG emissions) and of the lack of alternative energy sources that can be scaled up, in the short/medium term, to guarantee the existing levels of secondary energy use in the economy.

It is well known that when dealing with complex issues the use of quantitative analysis to inform policy is problematic [2–6], especially with regard to sustainability [7–9] as it involves large-scale changes where stakes and benefits are difficult to anticipate [10–15]. The recent COVID-19 pandemic has clearly shown the fragility of the Cartesian dream of prediction and control when scientific advice is urgently needed to inform policies that seek to solve important problems involving a plurality of legitimate concerns and a weak understanding of the causal relations to be addressed [16]. In such situations, it is unclear how to select and prioritize the different legitimate concerns found in the society and how to select useful knowledge claims, supported by weak "scientific evidence" (i.e., affected by large doses of uncertainty),

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that often are contrasting. For energy policy, the issue is, if possible, even more complex, given the difficulties in defining the concept of energy security [17–20].

The purpose of this paper is therefore twofold. First, to illustrate the practical usefulness of the novel approach that was developed in the recent EU project Moving Towards Adaptive Governance in Complexity: Informing NEXUS Security (MAGIC) for assessing the quality of the processes used in selecting the problem definition and the relevant knowledge claims for informing policies in the sustainable development domain. One key outcome of the project was a new way to carry out this quality check: Quantitative Storytelling (QST). Second, to specifically examine the quality of the scientific knowledge claims currently used to inform energy policy in the EU. The results of three case studies, carried out in the context of this project, are used to flag the systemic neglect of available alternative knowledge claims in the problem framing and the selection of “scientific evidence”. Thus, our specific research questions are: Are the existing knowledge claims used to inform energy policy sound? Are there alternative relevant knowledge claims that have been overlooked or ignored in the discussion of energy policies and if so, why have they been ignored? Through answering these questions, we endeavor to validate the usefulness of the approach developed in MAGIC.

The rest of the paper is organized in five sections. Section 2 presents the conceptual framework developed in the project MAGIC for checking the quality of the process used to produce and use scientific information in decision-making, and the QST proposed to implement the framing. The approach is grounded in Post-Normal Science (PNS) and aims at handling two sources of uncertainty in the analysis of sustainability issues: identifying and prioritizing the perceptions of concerns and related goals found in society (on the political side) and identifying and selecting useful representations of external referents and causal relations observed in the external world (knowledge claims resulting from scientific inquiry). In this paper, we will focus on the scientific side of the process. The remainder of the text illustrates the approach for selected knowledge claims supporting EU energy policy. Section 3 describes the disciplinary field of energy analysis as a source of knowledge claims pertinent to EU energy policy. It explains how, in the 1970s and 1980s, the debate over the limits to growth has not been properly informed by robust scientific analysis because of a systemic failure of this academic field. It then briefly introduces concepts relevant to properly address the complexity of energy transformations that have been made available by the development of non-equilibrium thermodynamics. In Section 4, we elaborate 3 cases, (i) energy efficiency improvements, (ii) biofuels, and (iii) decarbonization of electricity, by confronting the knowledge claims that have been used to inform policy with alternative knowledge claims that have not been considered. Section 5 discusses the possible reasons why these alternative knowledge claims have been overlooked or ignored and reflects on the implications of complexity for the quality of the governance of sustainability. Section 6 concludes.

2. Methodology: how to handle complexity in science for governance?

2.1. Conceptual framework

In this paper, we build on the conceptual framework developed in the MAGIC project. In this project, we adopted the insights suggested by PNS [4,5,21] and the theory of modeling relation [22] to identify the relations over the different choices that must be made when framing a given sustainability problem in search for solutions. An overview of this conceptual map is given in Fig. 2.

According to the seminal work of Knight [24], there are four types of uncertainty associated with the process informing policy/action: (i) uncertainty about the robustness of the problem definition; (ii) uncertainty about the robustness of the anticipatory models; (iii) uncertainty about the consequences of our future action; (iv) uncertainty about the ability to properly implement our decisions. Funtowicz et al. [25] observe that “the objective of scientific endeavor in this new context may well be to enhance the process of the social resolution of the problem, including participation and mutual learning among the stakeholders, rather than a definite solution or technological implementation. This is an important change in the relation between the problem identification and the prospects of science-based solutions” (p. 104). Other authors have suggested that in this situation the production and use of scientific information should involve an iterative process of participative deliberation in which the steps of problem definition and selection of solutions should be repeated by “opening and closing down” different framings (epistemic boxes) rather than having experts discussing only over a given framing [3,14].

As illustrated in Fig. 2, we define a PNS sphere operating on the interface between the political and scientific sphere. It is here that we can check the quality of the two sets of pre-analytical choices (WHY and HOW in Fig. 2) that must be made to arrive at a framing of “the problem to be addressed” that is fit for purpose. The first set of pre-analytical choices (left side of Fig. 2) belongs to the political sphere and involves the identification of relevant concerns and aspirations associated with

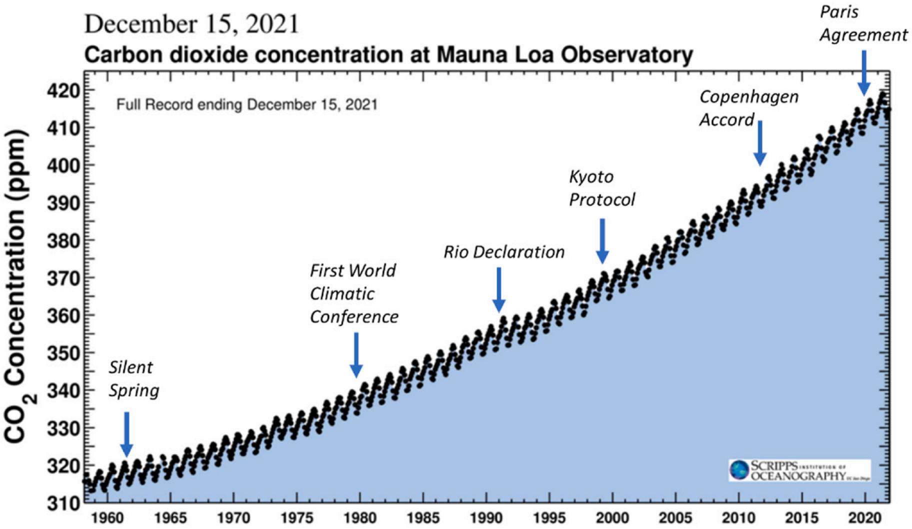

Fig. 1. The Keeling Curve measuring the accumulation of carbon dioxide in the Earth's atmosphere since 1958 with a few dates superimposed, referring to agreements aimed at reducing emissions (adapted from [1]).

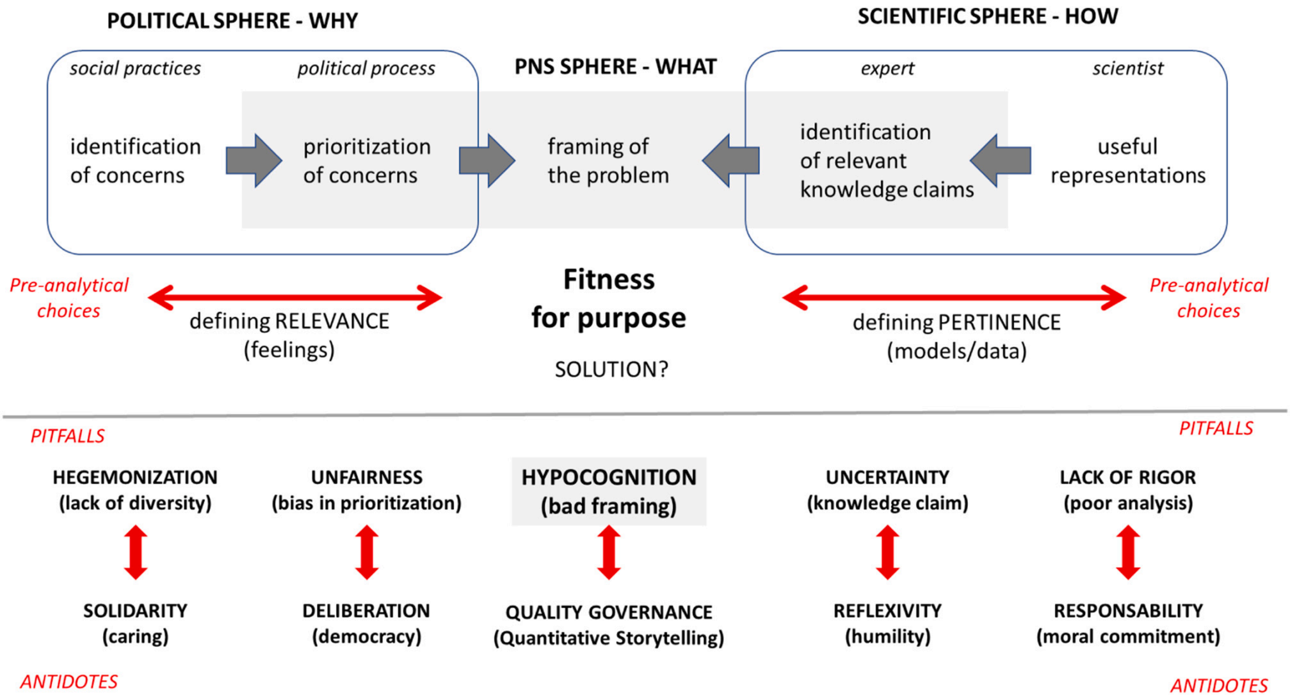

Fig. 2. Conceptual map: the relations among the choices involved in decision-making about complex problems (adapted from [23]).

social practices in society (translating into potential reasons for action), as well as the prioritization of these concerns in relation to the "common good" (the WHY or justification). The second set of pre-analytical choices (right side of Fig. 2) belongs to the scientific sphere and concerns the selection of representations and anticipatory models from among those made available by scientific inquiry in different disciplines according to their robustness and usefulness for guiding action (the HOW or explanation/mechanism). Both sets of choices are necessarily made under uncertainty (Knight's first three sources of uncertainty [24]). In addition, they affect each other in an impredicative way. The lower half of Fig. 2 shows several reflexive criteria, suggested by PNS, for assessing the quality of the process used to frame the problem to be addressed and its possible solutions (the WHAT). In this paper, we mainly focus on the scientific sphere, that is, the selection of useful representations and related knowledge claims in the field of energy policy.

2.2. *Quantitative storytelling*

Relational complexity and hierarchy theory tell us that a complex system cannot be fully represented by any one model in particular [26,27]. Those wanting to use quantitative information for decision-making about complex issues therefore face the standard predicament identified by [28]: "all models are wrong, but some are useful". This does not mean that scientific inquiry is useless. Even if "true models" do not exist, we can still tell useful stories about complex problems by selecting different perceptions of the system that we judge useful for our purpose (e.g., for guiding action) [29].

Building on this premise, the project MAGIC has proposed "quantitative storytelling" (QST) as a possible way to check the quality of the process of selecting narratives in the framing of a given policy problem (on the left side of Fig. 2) while double checking the relevance and the robustness of the models and indicators used in the analysis (on the right side of Fig. 2). Hence, QST is a heuristic approach that uses the conceptual map in Fig. 2 to explore the existence of both concerns and knowledge claims that could possibly challenge the fitness of purpose of a given policy. To this end, QST focuses on the consonance of the WHY-WHAT-HOW entanglement:

(1) Justification—the WHY associated with the selection of the concern(s) to be addressed. Why is a given policy or innovation needed in the first place?
(2) Normative—the WHAT associated with the "solution to the problem". What solution(s) should be implemented, i.e., the strategies and tactics to be adopted toward achieving the goals (actions to be taken), such as provisions in directives.
(3) Explanation—the HOW associated with the "scientific evidence". Are the proposed solutions plausible and relevant in relation to the concerns to be addressed, and how do we know that?

As detailed in [30], QST does not consist in a strict protocol but is a semantically open procedure, iterating steps of "opening-up" and "closing-down" the analysis. The identification of alternative concerns and knowledge claims is an essential part of this procedure and can be obtained in various ways, such as interviews and discourse analysis (for concerns) and trans-disciplinary research (knowledge claims). The conceptual map in Fig. 2 serves to keep coherence in the handling of this heterogenous information. For instance, the problem framing used in the selection of a given policy can be opened up, by comparing it with alternative framings ("stories") found among social actors (left side of Fig. 2) that have to be substantiated by quantitative data or by comparing it with alternative scientific explanations coming from different disciplinary fields (right side of Fig. 2) (e.g., [31]). This entails confronting the original analysis (the "scientific evidence" referring to a given scale and a chosen disciplinary problem framing supporting a given choice of policy) with alternative analyses carried out at different scales or from different perspectives. We will illustrate this approach in Section 4 for the energy policy domain by using an unconventional formulation of energy analysis based on the concept of metabolic patterns (that builds on insights from non-equilibrium thermodynamics). By comparing non-equivalent scientific representations, new insights may emerge as well as incongruences in the "scientific evidence" used in the policy discussions (e.g., [32,33]). Indeed, the set of relations in Fig. 2 clearly shows that the rigor of scientific evidence alone does not guarantee the quality (i.e., fitness for purpose) of scientific input when dealing with governance related research. Mismatches between justification, problem-framing/solution and explanations used to select policies indicate a poor quality of the process.

2.3. Case studies

All the case studies presented in this paper were developed in the context of the project MAGIC (for more details, see [34,35]). In the energy efficiency case study, dominant and alternative concerns were identified through interviews with EU policymakers and members of the European Parliament as well as discourse analysis of EU policy documents [36,37]. Alternative knowledge claims were obtained from an analysis of the metabolic patterns of EU countries and China, using an analytical framework (MuSIASEM) based on thermodynamics of non-equilibrium as described in [38,39]. In the biofuel case, dominant and alternative concerns were identified through qualitative content analysis of EU policy documents [32,40] and subsequently confronted with alternative knowledge claims. The latter were derived from the application of a novel analytical framework purposefully developed for this case and detailed in [41]. This framework is based on a biophysical characterization of both the supply function of the biofuel system and the corresponding societal demand. It was applied to the EU and selected EU countries [32,41]. The case study on the decarbonization of electricity focuses predominantly on knowledge claims and is based on a detailed biophysical study of the electric grid of Germany and Spain described in [33]. It was inspired by concerns about the German Energiewende identified in policy documents and documented by Renner et al. [33].

In the remaining sections, we illustrate the usefulness of the conceptual framework and QST for selected aspects of energy policy. In Section 3, we first describe the problems of the disciplinary field of energy analysis as a source of knowledge claims for supporting energy policy. In Section 4, we then demonstrate, using the case studies, the existence of alternative knowledge claims from this field and their pertinence for energy policy in the EU. In Section 5, we return to the framework proposed in Fig. 2, to discuss the possible reasons why these knowledge claims have been ignored and link to the phenomenon of social construction of ignorance in science and the sustainability discourse first described by Rayner [9].

3. Energy analysis as a source of knowledge claims

> “It is important to realize that in physics today, we have no knowledge of what energy is. […] It is an abstract thing in that it does not tell us the mechanism or the reasons for the various formulas” [42].
> (Chapter 4)

In Section 3.1, we describe the historical context of energy analysis and summarize the difficulties encountered by the field of classical thermodynamics in providing useful scientific input based on representations of energy transformations as linear input/output processes. In Section 3.2, we show that, despite the innate problems of the concept of energy, energy analysis can be a useful source of knowledge claims if the principles of non-equilibrium thermodynamics are acknowledged, i.e., purposeful energy transformations take place within autocatalytic loops.

3.1. Energy analysis: the historical context

The industrial revolution and notably the development of the steam engine in the second half of the XIX century led to the development of the scientific field of thermodynamics. However, in relation to energy analysis, early thermodynamic studies did not provide any practical, operational tools that met the expectations of the traditional, reductionistic scientific paradigm. Indeed, perhaps one of the key results of classical thermodynamics was exactly that energy transformations are impossible to represent in a deterministic way because they are irreversible and therefore all “special” and path dependent. Classical thermodynamics only arrived at representing “ideal transformations” referring to typologies (equivalence classes) of thermodynamic cycles and, as a result, remained largely confined in the realm of physics and engineering [43].

In 1973–74, the OPEC crisis put energy on the front burner in all developed countries [44]. The oil crisis shortly became part and parcel to a perfect storm threatening the very ideological foundation of Western civilization—the idea that infinite economic growth was possible on a finite planet came under question. A series of books [45–47] were forcing a societal reflection about: (1) the fact that the (energy) resources needed for economic development might be finite; and (2) the existence of trade-offs between food security, energy security, sustained economic growth and the preservation of ecosystem health. A particular influential contribution at that time was the report of the Club of Rome: ‘The Limits to Growth’ [48].

In response to this growing concern, scientists working in energy analysis scrambled to quickly generate a new disciplinary knowledge able to provide pertinent and useful scientific inputs. But the paradigm of scientific reductionism (still dominant in quantitative analysis at that time) crashed against the complexity of the processes of energy transformations. In spite of the tremendous effort of a large mass of outstanding scientists, in those two decades conventional energy analysts were unable to provide any coherent explanation and representation of the energetic predicament of economic growth based on biophysical narratives [43]. As concluded by Maddox [49] (p. 136), one of the leading experts in the field: “these general methods to establish a standard measure by which to conduct net energy analysis fail, and these failures are crucial. They signify that there is no universal net energy calculation, because there is no unambiguous energy measure that allows one energy form to be compared to another. Energy cannot be treated as a single entity, because its various forms possess irreconcilable qualitative distinctions”. After a series of open recognitions of the generalized failure of energy analysis from leading experts, the field quickly faded away and the numerous new departments of “energetics” that had appeared after the crisis scattered across Western universities simply disappeared. This paved the way for the development and hegemony of the field of energy economics.

In the second half of the XX century a new branch of thermodynamics, non-equilibrium thermodynamics, brought the analysis of energy transformations into the realm of complexity with the introduction of the idea of surplus entropy disposal proposed by Schrödinger [50] (in an added note to Chapter VI of *What is Life* from 1945). Schrödinger's idea was developed further by the work of the Prigogine school [51–54], with the introduction of the class of open dissipative systems. The outcome of non-equilibrium thermodynamics was that the representation of any energy system is special because of its history and hence diametrically opposite to the solution opted by classic thermodynamics (i.e., classes of “ideal transformations”). The acknowledgment that thermodynamic systems operate in a non-equilibrium situation had profound epistemological implications: It implies that it is simply *impossible* to use crispy relations based on predicative definitions of the characteristics of energy systems. Probably this, as well as the highly specialized scientific jargon of the field, explains why this groundbreaking development went largely unnoticed in the scientific community, even during the height of the energy crisis.

3.2. The revolution implied by thermodynamics of non-equilibrium

What is relevant for a discussion of the quality of energy analysis is that, according to the new conceptual developments of thermodynamics of non-equilibrium, energy analysis must always be contextualized. It can only be carried out in relational terms, i.e., by looking at the expected characteristics of the interaction of a special open dissipative system with a special context. An approach based on this idea must answer questions that are taboo in reductionist science: (1) who is carrying out the energy transformation of interest and why do we have this energy transformation in the first place? and (2) what are the implications of the identity of the system carrying out the energy transformation? Indeed, the definitions of "what energy is" and "what energy transformations do" depend on the history, purpose, and the identity of the energy system. This means that these questions cannot be answered in a deterministic way using a "one size fits all" protocol, thus putting limitations on the practical usefulness of conventional energy analysis.

The implications of the findings of thermodynamics of non-equilibrium can be summarized in four points. These points are essential to understanding the predicament of conventional energy analysis and the problems experienced by those trying to inform energy policies using quantitative analysis:

(1) Energy cannot be defined in a predicative way, nor can energy be made. This means that a system using energy (a dissipative structure)—e.g., an organism, a city, an economy, a country—must have available a stable supply of two different forms of energy: (1) primary energy, i.e., sources coming from its surrounding; and (2) energy carriers (secondary energy), ready to be used, internally, in the reproduction of its own identity. The processes that produce primary energy sources are outside of the control of the dissipative structure and the processes that use secondary energy for reproducing its identity are under the control of the dissipative structure.

(2) A dissipative structure is generated by an autocatalytic loop (it is subject to a chicken-egg paradox). This means that it must already have an amount of secondary energy (energy carriers) under its control to exploit primary energy sources. For example, humans must have carbohydrates, proteins, and other nutrients carriers (food energy carriers) in their body, to be able to exploit agricultural processes such as the required biological activity of cereals, vegetables, and animals (primary energy sources) to get food. As for the energy sector, it must have available and use secondary energy (e.g., fuels, electricity) to exploit primary energy sources (e.g., oil fields, wind, hydropower) to generate a stable supply of secondary energy (e.g., fuels, electricity).

(3) The conceptualization of non-equilibrium thermodynamics entails that there is an impredicative relation between: (1) what we define as energy carriers used inside the system; and (2) what we define as primary energy sources supplied by the environment. As explained by Cottrell [55], it is the type of activity carried out *inside the autocatalytic loop* by the dissipative structure that defines "the identity of energy carriers" and "the identity of primary energy sources". For example, hay is a primary source for a cow (determined by her physiology) allowing the cow to generate its internal nutrient energy carriers. However, hay is not a primary energy source for a fox. The biomass of rabbits is a form of primary energy source for a fox. Electricity is an energy carrier for a refrigerator but not for the present fleet of airliners. Even ham (a form of food energy that could be used by humans), depending on the path dependent definition of identity of the dissipative structure, may or may not represent an energy carrier: it is food energy for a Christian but not for an Islamic consumer.

(4) To analyze the performance of energy transformations within dissipative structures it is essential to adopt the concept of *end-uses*. In fact, the conversion of primary energy sources (outside human control) into secondary energy carriers (under human control) requires not only the presence of these energy forms but also the supply of additional inputs. That is, to have purposive energy transformations you need energy converters (e.g., muscles, engines, technology) and controls (e.g., humans with appropriated know-how to guide the conversions). These energy converters and controls do have an energetic cost because they must be produced, repaired, and adapted in time. For this reason, we can define metabolic systems (the more elaborate class of dissipative structures) as being organized into two functional compartments: (1) a catabolic compartment—in charge of gathering primary energy sources (and other materials/resources) from the context; and (2) an anabolic compartment—in charge of both building the structure required to express end-uses and providing control. The coexistence of these two complementary functional components generates an internal competition inside the metabolic system in relation to the allocation of end-uses that determines the strength of the autocatalytic loop.

These systemic features of metabolic systems (i.e., dissipative systems based on autocatalytic loops of energy forms) are very important for energy analysis. Indeed, the competition between the catabolic and anabolic compartment for the use of available energy carriers defines the quality of primary energy sources. Primary energy sources requiring an excessive investment of end-uses (labor, power capacity, and internal consumption of energy carriers) to supply energy carriers to the rest of society are of poor quality. A high requirement of end-uses needed to produce a net supply of energy carriers (in the catabolic compartment) limits the ability of the metabolic system to express a diversity of functions and structures in the anabolic compartment, that is the production and consumption of goods and services in the economy.

Unfortunately, as we will illustrate in the next section, none of these insights from non-equilibrium thermodynamics are currently used in the discussion of energy policies. These insights therefore represent "unknown knowns". The energy discourse still appears to be informed by a set of relatively simplistic, predicative, out-of-context definitions (e.g., ham is a secondary form of food energy for humans whose quantity can be measured in kcal per kg independently from the religious identity of the consumer) and the quantitative analysis is still based on fixed protocols and flat conversions ratios applied to linear input/output representations of energy transformations.

4. Unknown knowns in the energy policy domain in the EU

In this section we elaborate three examples from the energy policy domain, focusing on knowledge claims. They are based on case studies from the MAGIC project and draw on the insights from non-equilibrium thermodynamics presented in the previous section (Section 3.2). The case studies were selected because of their relevance for current energy policy in the EU and because of the evident availability of alternative knowledge claims.

4.1. Energy efficiency

A particularly problematic set of narratives in the energy policy domain concerns the idea that increases in "efficiency" are effective solutions to reduce the consumption of secondary energy (energy saving) and related emissions (e.g., [56]). In this example, we will show that we are dealing here with an extremely complex concept—energy efficiency—being addressed with simplistic indicators derived from the field of energy (resource) economics.

Returning to the history of energy analysis, it is worth noting that Carnot, who developed the quantitative definition of thermodynamic efficiency for thermal engines, ends his seminal book 'Reflections of the motive power of fire and on machine fitted to develop that power' [57] by cautioning that the thermodynamic indicator of efficiency he proposed should be considered as just one of the possible criteria of performance useful for guiding action, and not even a good one: "We should not expect ever to utilize in practice all the motive power of combustibles. *The attempts made to attain this result would be far more harmful than useful if they caused other important considerations to be neglected.* The economy [efficiency] of the combustible is only one of the conditions to be fulfilled in heat-engines. In many cases it is only secondary. It should often give precedence to safety, to strength, to the durability of the engine, to the small space which it must occupy, to small cost of installation, etc." [57] [p. 59, emphasis added]. The modesty of Carnot in defining the relevance of the indicator of efficiency he developed is in stark contrast with the words of the EU Commissioner for Energy: "Energy efficiency is a key concept in the fight against climate change. Being more efficient will immediately cut our emissions, ease the pressure on the environment and reduce the need for energy and other resources to support our way of life" [58]. Indeed, the Keeling curve illustrated in Fig. 1, suggests it might not be that simple.

Several epistemological problems limit the usefulness of efficiency indicators and our ability to anticipate the effects of changes in efficiency:

1. The development of thermodynamics and the growing interest in more effective descriptions of the functioning of complex material systems has led, already at the beginning of the previous century, to an enrichment of the categorization used to generate quantitative data [59,60]. More specifically, a biophysical characterization of systems can be obtained by combining:
   i. extensive properties (using quantitative variables referring to extent/size)—numbers that can be summed, e.g., mass or volume; and
   ii. intensive properties (using qualitative variables referring to qualitative characteristics of the material defined per unit of size)—numbers that cannot be summed, e.g., temperature or pressure.

   This distinction is essential when dealing with the analysis of the characteristics of metabolic systems and their efficiency. Intensive variables are determined by specific flow/fund ratios (e.g., the level of consumption per unit of size), flow/flow ratios (input/outputs) or fund/fund ratios (relative sizes of the different elements). These are qualitative characteristics observable inside the "black box", the resulting quantitative values cannot be summed. Extensive variables are assessments of the size of the funds or the size of flows (quantitative characteristics determining the size of the system or its elements in relation to its environment) [61,62]. These latter quantities can be summed. When dealing with changes in metabolic systems it is essential to simultaneously consider both quantitative and qualitative aspects of the changes. For this reason, efficiency indicators obtained by calculating flow/flow ratios are irrelevant for sustainability analysis. For instance, consider the relation between CO_2 emissions and GDP using the equation $CO_2 = [CO_2 / \$ \text{ of GDP}] \times [\$ \text{ of GDP}]$. If a decrease in carbon intensity (the first term in the equation) of 30 % results in an increase in GDP (the second term) by 60 %, the overall value of CO_2 will still go up despite the increase in efficiency. The same applies to the variable "emissions per capita" if changes in this variable are not considered in combination with changes in "population size". The growth in population can compensate a reduction in emission per capita. Indeed, it is important to note that not only the quantification of the concept of "efficiency" in economic narratives is always based on intensive variables, but it is associated by default with the idea of "improvement". This assumption is never supported by a check on the coherence of predicted changes with the forced relation between extensive and intensive characteristics of the system and its context. Indeed, such a check is impossible because of the epistemological problems discussed under the points following.
2. Complex adaptive systems are "becoming systems" [54] to which the ceteris paribus assumption does not apply. If we accept that metabolic systems are generated by autocatalytic loops in which secondary energy is invested in order to get more secondary energy (a concept very compatible with economic narratives: money spent to make money), we should expect that if a system learns how to better use secondary energy carriers in order to get a larger quantity of secondary energy carriers—becoming more efficient in what it does—the consequence will be the expression of a stronger autocatalytic loop and not a reduction in the use of secondary energy carriers. As a matter of fact, in his 1865 book *The Coal Question*, William Stanley Jevons [63] (a very important figure in the economic discipline!) warned about the expectations associated with improvements of energy efficiency. Indeed, he correctly anticipated, in what is now known as the "Jevons paradox", that increasing the efficiency of steam engines (using coal at that time) would increase rather than decrease coal consumption, since it will multiply the possible end-uses of the engine. His argument was straightforward: increasing the energy efficiency of the use of a resource for a given end-use in the catabolic compartment may backfire by generating an increase in end-uses in the anabolic compartment, which grow faster than the reduction in the losses of the conversion in the catabolic compartment [64,65]. The same phenomenon has been described as an impredicative relation between the minimum entropy generation principle (the tendency of living systems learning how to be more efficient in expressing internal tasks) and the maximum power principle (the tendency of living systems to use the saving obtained by internal increases in efficiency for expanding their adaptability through their interactions with their context) in theoretical ecology [66]. Even the economic perception of autocatalytic loops is in dissonance with the current perception of efficiency in energy policy. An economic investment aimed at obtaining a higher return is an autocatalytic loop in the economic narrative. No economist expects that an investor, after finding a more profitable economic activity, will reduce the original investment to maintain the original level of return. Nonetheless, this is exactly what the EU Commissioner for Energy expects to be the effect of efficiency improvements: the investor of energy will respond to the increase in efficiency by reducing energy uses.
3. An economy is a classic example of a dissipative system, which must be open. This entails that assessing the "efficiency of an economy" is extremely tricky. For instance, a comparison of the national "economic energy efficiency" of China and the EU is meaningless, it being a comparison of "apples and oranges" [38,39]. As illustrated in several studies carried out in MAGIC, the energy efficiency of a country strongly depends on the relative contribution of the various economic activities to the generation of its GDP and its terms of trade. For example, China has a strong industrial sector—a set of end-uses demanding large amounts of energy carriers—whereas, most EU countries are specialized in services and financial operations, i.e., end-uses requiring far less energy carriers and generating a large fraction of their GDP [39]. The EU can afford to specialize in services and financial operations because it externalizes its energy intensive activities (energy sector, mining, industrial sector) to other economies, like China. In the MAGIC project, it was found that the EU is using, on an annual basis, the equivalent of more than 120 million worker-equivalents (operating elsewhere) embodied in imported products [67]. The EU imports roughly 80 % of its primary energy sources [68] and 70 % of the animal feed required to sustain its agricultural sector [69,70]. In this way, a large amount of energy uses and related emissions (as well as land and labor requirements and associated environmental pressures) is externalized to third countries. Obviously, the more the EU externalizes the production of its goods to other economies, the lower its emissions will be. But should this be considered as an improvement in efficiency? Does it solve the problem of climate change?
4. Demographic variables are key factors determining the efficiency of a socioeconomic system, a factor totally missed by the current economic indicators of efficiency. Particularly relevant is the size of the dependent population. For example, in the year 2010 China had in its economy 1300 h of paid work per capita (i.e., the total number of hours in the paid work sector divided by the population size), almost the double of the 730 h of paid work per capita in the EU [71]. When comparing the efficiency of these two economies it would be important to consider this difference.

5. Last but certainly not least, the role of credit leverage is not considered in current energy efficiency assessments. For example, in the period 2009–2015, at the global level, credit leverage (debt) has grown *more than* the GDP of the global economy [72]. Most of this debt was created in developed societies, such as in the EU, where the import of goods is greatly helped by the continuous printing of money and consequent boosting of the financial sector. In this way, the generation of added value is no longer associated with biophysical processes of production and consumption, i.e., we deal with the creation of "virtual added value". In this situation the meaning of the concept of efficiency can no longer be related to the characteristics of energy transformations.

4.2. Biofuels: if the people do not have bread, let them eat cake

Considering the performance of biofuel production from a metabolic perspective, it becomes clear that we are dealing with an end-use expressed for producing secondary energy carriers of extremely low quality. Two macroscopic problems with this end-use are evident to those willing to see them: (1) the low density of the primary sources used to produce biomass (translating into a large requirement of land for this end-use); and (2) the resulting low productivity of the inputs used in the end-use (requirement of labor, power capacity, secondary energy carriers per unit of net supply), when compared with other end-uses producing liquid fuels. It should be noted that in 1945 Samuel Brody (an expert of energy conversions in agriculture) observed about this idea: "it is said that we should use alcohol and vegetable oils after the petroleum energy has been exhausted. This reminds one of Marie Antoinette's advice to the Paris poor to eat cake when they had no bread" [73] (p. 968).

As for the first problem, it is relevant to recall the recent evolutionary trajectory of modern societies. The fossil energy revolution made it possible to dramatically reduce the dependence on land, labor, and power capacity (end-uses) in the energy and agricultural sector (catabolic compartment) by using fossil oil rather than biomass. This phenomenon, known in the present day as "the Industrial Revolution", locked modern societies in a set of social practices associated with a characteristic pace and density of energy flows that is simply out of the reach of a supply of secondary energy carriers based on the set of end-uses needed to produce biofuels [74]. Proposing now, in a post-industrial society, to reduce the dependence on fossil energy by using more land, labor and power capacity in the primary sectors seems an unpractical idea. Smil [75] has analyzed this issue from the perspective of the differences in density between requirement (end-uses) and supply (primary energy sources) in space. His self-explanatory analysis is shown in Fig. 3.

The differences in power density between biofuel, fossil energy and urban uses in Fig. 3 are so large that it requires the use of a logarithmic scale. This huge difference explains why before the Industrial Revolution urban population was below 10 % of the total population all over the planet and why urban population exploded due to the increasing consumption of fossil energy.

Regarding the second problem, an excessive requirement of end-uses in the primary sectors of the economy would reduce the fraction of end-uses in the anabolic ("consumptive") compartment and hence reduce the strength of the autocatalytic loop in the metabolic pattern. In fact, it is in the anabolic compartment that the EU generates the vast majority of its GDP (more than 90 %), through the combined activities of production and consumption in the industrial, service and household sectors [61]. These end-uses of the anabolic compartment concern activities that *use* secondary energy (energy carriers) to *produce and consume* goods and services. Increasing the amount of human time and resources invested in the catabolic compartment (energy, mining and agriculture), just for producing energy, mineral and food commodities, would generate a reduction in the amount of generated added value (both in absolute terms and in relation to the required investments) and therefore generate an unbearable opportunity cost for the economy [61]. No developed country derives a significant fraction of its GDP from nor invests a significant share of its work force in either the agricultural or energy sector (catabolic compartment). Indeed, with few exceptions (e.g., countries with large and easily accessible domestic oil reserves—the oil exporter countries), primary sectors in developed countries generally

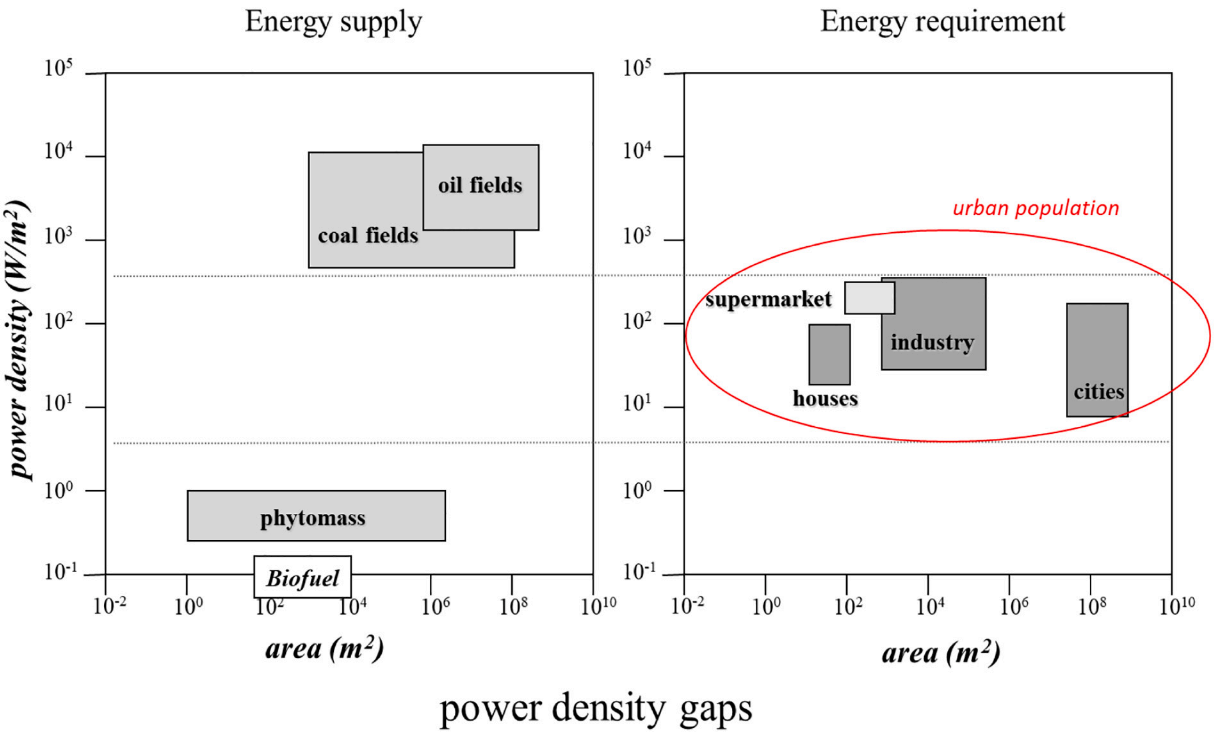

Fig. 3. A comparison between the density of the flows of supply (primary sources) and requirement (secondary carriers) when considering fossil energy, biomass, and biofuels. Figure adapted from [75] (Figs. 5.2 and 5.3).

require substantial subsidy support to survive economically.

In conclusion, the analysis of EU policies of biofuels done in MAGIC reveals a profound lack of understanding of the biophysical roots of the economy (i.e., the societal metabolism of energy). Adopting basic principles from non-equilibrium thermodynamics—i.e., metabolic pattern associated with an autocatalytic loop of energy forms—we find that the substitution of fossil energy fuels with biofuels produced in the EU is neither viable nor feasible. For instance, all the secondary energy consumed in a year by one EU citizen is currently supplied by only 8 h of labor in the energy sector in that year [39]. If the energy sector would have to produce biofuels (rather than simply process fossil energy products), the energy productivity of labor in the sector would plummet, from GJ/h of net supply of secondary energy carriers to MJ/h [74].

The quality check in MAGIC has shown that "scientific evidence" used for informing biofuel policy is often based on blunders. An outstanding example is given by the policy supporting the production of biodiesel from used cooking oil. This end-use does not rely on a primary source (such as biomass) but on a tertiary flow (a recycled feedstock) to produce biofuel. However, adopting a metabolic perspective, we can calculate that the limit of what can be produced with this end-use, looking at the availability of this recycled flow, is extraordinarily low. About 4 kg of used cooking oil is available per capita per year in Europe—recycled from the 6–8 kg of cooking oil consumed per capita per year in the food system [32]. Considering the energy losses when converted to biodiesel, we can at best obtain about 2 kg of biodiesel per capita per year [32]. This supply represents less than 1 % of the diesel currently consumed per capita in the EU. Not surprisingly, large amounts of biodiesel produced in Europe are obtained from imported used cooking oil. Even if we were to assume that the process of importing and recycling used cooking oil was economically viable, it would not solve the EU's dependence on the import of energy sources. As shown in [32], EU policy encouraging the production of used cooking oil to replace first-generation biofuels (finally deemed unsustainable) has led to fraud (used cooking oil being in reality palm oil) that could have been anticipated with simple back of the envelope calculations on its feasibility.

EU policies for biofuel production have changed in time as explanation narratives have become increasingly difficult to uphold in view of the dominant justifications (rural development, guaranteeing security of energy supply, reducing emissions). Consequently, biofuel targets have been patched accordingly in the various amendments to the directives. The only plausible justification for the continuous expenditure on first generation biofuels, found between the lines in EU documents, is "to protect the investors operating in this sector" [32,76]. It should be noted that in the last text of the European Green Deal [77], the term biofuels is not even mentioned. The clear incoherence among justifications, normative choices and explanations casts doubts on the quality of the process of decision-making adopted thus far in this policy domain.

4.3. *Decarbonization of electricity: the difference between electric power, end-uses, power capacity and storage capacity*

This last case concerns the current narrative on the issue of decarbonization of electricity, in which "electricity" is conceptualized as a mere energy commodity regulable by the market [33]. In the biophysical reading of the issue, on the other hand, "electricity" is a special form of secondary energy—historically called *vis electrica* because it cannot be stored as such. The movement of electric charges within wires is comparable to the movement of water in pipelines. As in the case of water flows, three factors determine the flow of electricity in the grid: (1) the amount of electric charges (measured in amperes)—in the analogy this would be the amount of flowing water; (2) the electric potential driving the movement of the charges (measured in volts)—in the analogy this would be the pressure applied to the water; and (3) the electric power output that can be put to use by those getting the electricity out from the grid, determined by multiplying the quantity of charges moving in the wires by the strength of the electric potential (measured in watts)—in the analogy this would be the mechanical power made available to those using the flow of water coming out of the pipe.

Given these characteristics of electricity, we can distinguish two non-equivalent definitions of "viability" (interpreted as the ability of matching supply and requirement) for electricity. In the first one, we can define a *biophysical viability* referring to the ability of stabilizing the distribution of electric power in the grid at any moment in space and in time in terms of supply and consumption of electric charges at a given power level. In the second one, we can define an *economic viability* referring to the formation of prices in response to the choices made by economic actors to match the "end uses" associated with both production (supply) and use (demand) of electricity. In relation to biophysical viability, without buffer storage, if you wish to have water flowing in a pipe you must simultaneously have: someone putting water in it, and, someone else getting the water out of it. That is, if an end-use requiring electricity (e.g., air conditioner) is not ready to use the electricity when it is produced (e.g., the electricity from a windmill park), the produced electricity must be converted into a different energy form to store it or curtailed.

Final consumers, paying "electricity", express their preferences through a variety of end-uses associated with consuming "electricity" that is expected to be biophysically viable. Different is the situation of those producing "electricity". They have a perception of costs and benefits that refers only to their specific set of end-uses (technologies) needed to transform a given quantity of primary sources (nuclear fuel, solar radiation captured by photovoltaic, natural gas) into a given quantity of energy carrier (kWh supplied to the grid). That is, *individual* power plants are not concerned with providing biophysically viable electricity, and therefore, when coming to the stabilization of biophysically viable electricity in the grid, they are not in competition with each other. From this perspective, the narrative of formation of prices does not have anything concrete to do with the phenomena determining the biophysical viability of flows of electric charges. In relation to the demand of electricity consumers may be private households, industries, or hospitals. This mix of consumers express different preferences associated to their own end uses and have a different option space for adjusting their patterns of consumption. Producers may be a mix of operators of different types of power plants (including very large and very small), with different perceptions of costs and benefits and different time lags in relation to adjustments in their supply and their power capacity. It is important to reflect on the fact that these consumers and producers are not dealing with the same commodity "electricity". The kWh paid by the consumers are "biophysically viable electricity", whereas the kWh sold by producers are mere inputs of electric charges that still must be blended and harmonized in the grid.

Framing the issue in this way, we can immediately detect a systemic problem with the biophysical viability of the class of end-uses producing electricity from intermittent primary sources: they may produce electricity when it is not needed, and they may not produce electricity when it is needed. In other words, not all kWh generated are the same when considering biophysical and economic viability—they do not have the same value. There are storage solutions that can convert electricity into chemical energy such as batteries or hydrogen fuel, or into mechanical-gravitational energy such as pumped-hydro. However, without the availability of large-scale storage capacity, intermittent end-uses do not have the same usefulness for running the grid as traditional end-uses.

Having stated the former, we can now clarify the confusion over different concepts essential to understanding the existing predicament experienced with the attempt of a large-scale integration of intermittent sources of electricity (solar and wind) into existing grids. We can distinguish between four factors: (1) the quantity of electric power that is distributed in the grid (produced and used at any moment), a concept associated with biophysical viability; (2) the mix of different end-uses expressed by those producing and using electricity (referring to different types of technology and social practices), a concept associated with economic viability. These end-uses can be changed by the market mechanism, but at a slow pace. Changes in patterns of production and consumption of electricity are not determined by changes in "consumer behavior" but by changes in social practices; (3) the amount of power capacity and infrastructures associated with the different end-uses supplying secondary energy carriers in the form of electric power; and (4) the amount of storage capacity available in the grid to compensate mismatches between supply and consumption. The latter factor is the missing character in the existing storytelling about the decarbonization of electricity supply. Storage capacity can dramatically change the usefulness of intermittent sources by allowing to store electricity produced when it is not needed and release electricity when required in excess of the available supply. However, for the moment we do not have large scale solutions.

Reflecting on the problems experienced with the *Energiewende* in Germany, a MAGIC study [33] explored the forced relation of congruence between these four different factors in the electric grid of Germany (in addition to that of Spain). The graph presented in Fig. 4 clearly shows that the common belief that "when the cost of the kWh of alternative sources will be lower than that of the conventional sources, the conventional producers will be forced out of the market" is simply not true. Power capacity related to intermittent sources grew dramatically in Germany, but the size of power capacity related to conventional sources remained largely unaffected. Due to a lack of an adequate storage capacity, conventional sources are still needed to guarantee biophysical viability. As a matter of fact, before the arrival of alternative electric sources, the cost of producing electricity with "baseload end-uses" and "peak end-uses" was different, and still the two types of end-uses (techniques of production) coexisted without there being an issue.

In conclusion, the problem of a large-scale integration of intermittent sources of electricity in the existing typology of centralized grid lies with the lack of storage capacity and not with the "right" price of kWh. This entails that, if we do not have adequate storage capacity, further investments in power capacity with the goal of harvesting variable renewable energy sources (windfarms and photovoltaic plants) will not only fail to solve the problem of the decarbonization of energy but may worsen the situation by increasing costs and stressing the grid. An increase in installed power capacity (GW) is not an applaudable achievement if it is not linked to an equivalent stable increase in the amount of electricity produced and consumed in the grid. Boasting of increasing investments in renewable power generation capacity while this capacity is not utilized is simply a sign of poor understanding of the problem to be solved. Unfortunately, a large-scale increase of storage capacity based on batteries can further result problematic in relation to the limited availability of critical material. A point acknowledged by analyses of the Commission [78]. Again, by looking at the set of relations illustrated in Fig. 2 we cannot but conclude that, also in this case, the process of selection of knowledge claims used to inform policy seems to have been poor.

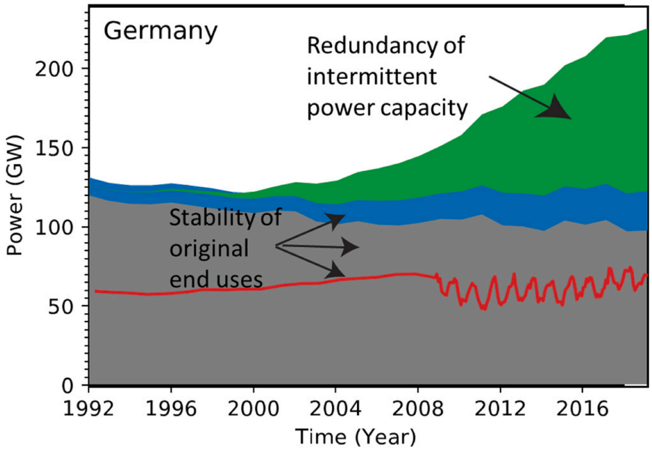

Fig. 4. Changes in time (1992–2018) of electricity generation (red) and different types of power capacity (conventional: grey; intermittent: green; other renewables: blue) in Germany (adapted from [33]).

A last observation about this example is that any narrative about "success solutions" must be contextualized. The distinction between baseload, peak and intermittent electricity is not the sole key factor in understanding the nature of the problem of decarbonizing electricity. The scale of the system and its geographic location are equally important. For example, the success of Denmark in utilizing decarbonized electricity is due to its relatively small size and location. There are multiple weeks during the year in which Denmark imports 60–80 % of the electricity it consumes—i.e., peak electricity, imported when needed [33]. Denmark has the possibility to do so because it is a small economy located by Norway and Sweden, which have enormous hydropower capacity and can easily dispatch their surplus to Denmark when needed. This option is unavailable to, for example, Germany or Poland, because of the much larger size of their economies, their geographic location and, perhaps, geopolitical constraints.

5. The quality of the process of decision-making in the energy policy domain

In this section we explore why the knowledge claims presented in Section 4 represent unknown knowns in the decision-making process. To this purpose, we return to the framework presented in Fig. 2 and look at the coherence among justifications, normative solutions, and explanations. However, it should be noted that, as explained in Section 3, the inherent elusive nature of the concept of energy and the highly specialized scientific jargon of the field of thermodynamics of non-equilibrium constitute part of the problem.

5.1. The choice of justifications – the weight of the political imperative

In the 1970s, Habermas [79] predicted a systemic legitimation problem in those "social welfare state-mass democracies" basing their justification on the claim that the state can guarantee a life without stress to their constituencies. This perceived need to simultaneously solve all the sustainability challenges of society is evident in the justification given for the "Clean energy for all Europeans" package [80], namely: (1) reduction of greenhouse gas emissions, *and* (2) increased energy security (a more secure and diversified energy supply), *and* (3) economic growth, creation of jobs, and increased competitiveness, *and* (4) inclusiveness and justness. In addition, the text explicitly states that the clean energy transition must benefit *everyone*—no EU citizen or region should be left behind. This last goal is taken a step further in the European Green Deal [81].

We deal here with an overlap of two different types of justifications:

i. Because institutions need legitimacy, they must solve simultaneously all the different sustainability concerns identified as relevant. This type of justification calls for an endorsement of "rosy scenarios" in which it is possible to deliver panacea solutions capable of solving all the problems at once.
ii. Because relevant problems must be solved, each proposed policy solution should be able to address, one at the time, specific concerns. This type of justification calls for an exploration of the potential drawbacks of proposed solutions to avoid blunders.

Adopting these two types of justifications simultaneously spells trouble for the process of decision-making. In fact, it poses a dilemma associated with the existence of trade-offs across different policy solutions—e.g., solving the problem of how to reduce the use of fossil energy may aggravate the problem of how to sustain economic growth.

Returning to Fig. 2, we thus see that an ideological bias in the prioritization of the concerns to be addressed (coming from the left side) imposes a filter on the knowledge claims admissible from the right. This specific problem has been identified by Anne Glover, at that time chief scientific adviser to the president of the European Commission, who said: "when selecting scientific evidence, it is difficult to keep separated evidence-gathering processes from the "political imperative"" (the Guardian, 2014). Rayner [9] refers to this phenomenon as uncomfortable knowledge, which he defined as: "To make sense of the complexity of the world so that they can act, individuals and institutions need to develop simplified, self-consistent versions of that world. The process of doing so means that much of what is known about the world needs to be excluded from those versions, and in particular that knowledge which is in tension or outright contradiction with those versions must be expunged. This is uncomfortable knowledge". Hence, uncomfortable knowledge is knowledge that must be suppressed, in policy discussions, for the "common good", i.e., to make the discussion manageable. The concept of uncomfortable knowledge helps explain the systemic neglect of the alternative knowledge claims presented in Section 4. Indeed, the poor representation of an essentially biophysical problem (energy issues) by the specific disciplinary domain of energy (resource) economics (right side in Fig. 2) makes it easier to avoid a critical appraisal of selected solutions.

5.2. The choice of solutions: irresponsible management of expectations

The very strong pressure on the institutions for solving all our sustainability problems at once pushes them toward the search for "panacea solutions" rather than "practical solutions". Indeed, EU energy policy discussions appear to have fallen into the attractor of unrealistic visions of the future based on unrealistic technological solutions. The concept of socio-technical imaginaries is helpful here. Socio-technical imaginaries, present in any society, are defined as "collectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology" [82]. However, it is essential that these socio-technical imaginaries are not based on unrealistic visions of the future and unrealistic technological solutions. Otherwise, the discussions over policies in the energy sector would be restrained to "technical issues" and would no longer be considered as political issues [4,11–13,83]. While solving individual energy concerns leads to policy confrontations, solving all the problems of sustainability at once is an easy recipe for reaching consensus. This entails that, on the political side of the decision-making process, implausible imaginaries are essential for handling the contradictions (or the plain impossibility) of achieving multiple and contrasting objectives, e.g., continued economic growth, quick reduction of emissions, quick reduction of (fossil) energy imports, protection of marginal social actors, and so forth [84]. In a context like the EU, in which different member states operate in different situations and adopt different priorities, a smooth integration and coherence over communal policies can only be obtained in relation to implausible imaginary solutions. "In this context, the role of innovation is 'cutting the Gordian Knot' of the policy nexus, regardless of whether the actual technological solution will ever be delivered and implemented" [84]. This strategy leads to the selection of policies that do not have the required fitness for purpose. The lock-in on the discussion over carbon taxes and tradable permits, the stubbornness in supporting policies endorsing biofuels, and the problematic operation of the electric market used as a tool for integrating intermittent electric sources in centralized grids are all examples of implausible solutions that are adopted based on a poor framing of the problems to be solved.

5.3. The choice of explanations: avoiding the trap of epistemic boxes

When science is used to support a strategy of legitimation of institutions, it becomes difficult to trust the scientific evidence used in the process. Jasanoff [85] notes that predictive methods such as "risk assessment, cost-benefit analysis, climate modelling are designed to facilitate management and control, even in areas of high uncertainty" (p. 238). This facilitation is obtained by simplifications of a given issue into a sealed "epistemic box". The choice of a particular epistemic box necessarily generates unknown knowns in the discussion. As mentioned previously, many policy decisions tend to be made on the basis of what has been called "policy based evidence", rather than "evidence based policy" [83,86]. This phenomenon is particularly relevant in energy policy and energy modeling [87] and deserves more attention given its destabilizing effect on the "normal" operation of the decision-making process [31,88–90]. For instance, Giampietro and Funtowicz [91] have argued that an uncritical mobilization of expectations based on simplified assumptions about how to solve problems undermines the scientific quality of the process of policymaking because: (1) assumptions are taken for granted and no longer subject to critical appraisal [92,93]; (2) no longer is there space for reflection or a genuine social discussion of the option space for solving the problems to be addressed [94–96]; and (3) the resulting unanimity about the solution to be adopted is used to justify large investments in technological innovations [95]. In this situation the systemic bias against uncomfortable knowledge leads to the selection of "bogus explanations" (associated with the formation of policy legends) that are instrumental for the stabilization of the establishment (see Fig. 2). As shown in Section 4, the quantitative analyses that have been used to support current policies of decarbonization, biofuels and renewable electricity are at best "not sufficiently robust" to inform policy.

A complexity revolution requires a radical change in the use of science in the process of decision-making. In particular, the results of the MAGIC project suggest the need to move away from the concept of "evidence-based policy"—used to individuate "the best course of action"—toward the concept of "quantitative storytelling"—used to check the quality of the narratives used to select policies. When the policy discussion remains locked inside a given epistemic box, it is impossible to check the connection between the chosen solution and the original set of different concerns to be addressed. "The deepening of the analysis corresponding to a single view of what the problem is, has the effect of distracting from what could be alternative readings" [88] [p. 62]. The case studies presented here show that very often the plausibility and desirability of proposed policies is simply assumed even though, in most of the cases, this assumption can be shown incorrect.

5.4. The social construction of ignorance: the "ancient regime" attractor

The results of MAGIC's QST case studies represented a "problem" for the EU institutions with which MAGIC interacted. Indeed, it was difficult to openly discuss the findings in official workshops or meetings [97,98]. In the four years of interaction between the MAGIC consortium and the European Commission, its Agencies, and the EU Parliament, we experienced marked differences in their reaction to "uncomfortable knowledge". Politicians (EU Parliament) were interested in the existence of "unknown knowns" useful for informing their political activity. On the contrary, public functionaries of the EU (EC and the Agencies) cannot opinionate in public on the plausibility of existing policies (even if they may agree in private that they are not plausible). Indeed, the same EU institution that funded the MAGIC research project to check the quality of the process of policymaking was unwilling (or incapable) to openly discuss the findings [97]. It seems that within governmental institutions, uncomfortable knowledge must be ignored because it is perceived as a threat to the legitimacy of the institution. Funtowicz and Ravetz [5] refer to this as the ancient regime syndrome. Especially in a situation in which the establishment is facing a series of sustainability challenges for which there are no practical and painless solutions (e.g., Ukraine war), it is difficult for institutions to address the existence of uncomfortable knowledge and to admit that there are problems for which panacea solutions do not exist. This is an important finding requiring further reflection by the general scientific community as this phenomenon makes it easier for lobbies to put a spin on the scientific advice coming from experts on the frontier of regulatory capture [99].

Uncomfortable knowledge (the existence of unpleasant unknown knowns) tends to be kept out from the discussion within specific policy domains through a variety of mechanisms, including selective research funding (e.g., innovation actions), the curriculum of higher education (there are no programs in energetics or biophysical economics) and expert selection for advisory functions. As for the latter, it is interesting to note that out of the nine members of the High-Level Panel of the European Decarbonization Pathways Initiative (a panel operating during the MAGIC project), only two were educated in natural sciences—-physics of the atmosphere and chemistry. All the others were trained or experienced in economics, finance, insurance, business management and/or politics. It is not our intent, as the authors of this article, to question the quality of the report these individuals produced [100]. However, to identify decarbonization pathways answering the question: "Which strategy should be adopted in research and innovation in order to speed-up and foster mitigation policies in the EU that respond to the goals of the Paris Agreement, while growing the competitiveness of the EU economy?", it could reasonably have been expected to find a few experts of energetics among the members of the panel. It is not that such experts do not exist.

6. Conclusions

In this paper, we have shown the existence of pertinent knowledge claims, most derived from the theoretical concepts developed in non-equilibrium thermodynamics, for informing energy policy that have not been considered in the current formulation of solutions for current energy concerns. As shown by the case studies, these unknown knowns include: (i) the Jevons paradox and a more complex reading of the concept of efficiency in relation to EU decarbonization strategies based on increasing energy efficiency; (ii) the factors determining the feasibility, viability and desirability of the metabolic pattern of human society (low density of flows, low productivity of labor, high internal requirement of end-uses) in relation to biofuels and the decarbonization of the transport sector; (iii) a biophysical reading of the functioning of the electric grid that entails that not all kWh are the same and that, therefore, the market alone will not necessarily solve the problem of the integration of different types of electricity production in relation to alternative sources of electricity.

The case studies presented do not claim to present the "truth" about a given energy issue—i.e., scientific evidence—nor that the quantifications used in the presented storytelling are uncontested or uncontestable. When dealing with wicked issues, all numbers can always be calculated in a different way and any choice of narrative is always contested. The usefulness of QST is about exploring the existence of alternative stories about given policy issues that can help to check the quality of the original framing and to enrich the diversity of insights. The adoption of different perceptions of the problem framing and related solution(s) can flag relevant information about specific policy issues that does exist in some disciplinary knowledge but that is not considered by the chosen (official) storytelling (i.e., unknown knowns).

Using the conceptual framework developed in the MAGIC project for quality checking policy narratives in the energy domain also showed the existence of a set of systemic problems that explain the inertia of the energetic predicament in the EU:

1. The current hegemonic use of economic narratives in the discussion of energy policies and the consequent endorsement of simplistic analysis (explanations) for representing the nature of the energy concerns (problems) to be addressed has led to the systemic adoption of implausible assumptions about the validity of the proposed policies in the EU energy policy domain, i.e., improvements in energy efficiency will lead to the reduction of emissions; biofuels can substitute fossil energy fuels; the market can smoothly integrate different technologies for producing electricity.
2. The idea that the various concerns identified in EU energy policy can be solved simultaneously is unrealistic. This idea can only persist by virtue of banishing uncomfortable knowledge and the creation of implausible socio-technical imaginaries. When considering different aspects of the problem and integrating different narratives and knowledge claims, a smooth and painless transition to a zero-carbon economy in a few decades seems unlikely.
3. An informed policy discussion on the renewable energy transition would require the expansion of the types of experts providing advice, including experts of metabolic analysis studying the implications of autocatalytic loops of energy forms. These experts are currently not readily available. Given that energy is an elusive but ubiquitous concept, the study of energetics in higher education should receive more attention.

The existence of all these problems shows the need for a conceptual change in the policymaking process. As stated by the MAGIC project, it is high time to move from a strategy of governance OF complexity (e.g., solving the problems with simplistic analysis generating implausible socio-technical imaginaries) to a strategy of governance IN complexity (e.g., analyzing the different aspects of the problem considering the co-existence of non-equivalent legitimate concerns and relevant storytelling). The strategy of decisions based on "evidence-based policy" should be replaced by a strategy based on the concept of "quantitative storytelling" involving in the quality check a variety of social actors carrying different types of expertise and different legitimate concerns while exploring the implications of all available knowledge claims. The experience of MAGIC has shown that quantitative storytelling can support this transition by providing a procedure for checking the robustness, usefulness and fairness of the narratives used to discuss, select, and evaluate policies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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