



Perspective

Transforming innovation for decarbonisation? Insights from combining complex systems and social practice perspectives



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ABSTRACT

Technological innovations seem to be among the great promises for achieving the urgent modernisation of economies towards carbon-neutrality. Ranging from fusion energy, bio-based fuels, carbon capture and storage to PV panels and so-called smart energy systems, plenty of technologies promise to reduce use or greenhouse gas emissions of carbon based energy sources. This techno-centric view disregards to a great extent that technological change affects and is affected by societal practices and norms.

The present paper argues that contemporary methodological approaches informed by complex systems and social practices theories provide urgently needed insights into innovation for decarbonisation. It specifically addresses the following questions: Why are current conceptualisations of innovation narrowly framed and with what consequences? How would a framing of innovation grounded on complex systems and social practice theories improve the understanding of opportunities and challenges at stake with innovation for decarbonisation? How could this framing help uncover and deploy an important and still often neglected social innovation potential? In a nutshell, the authors advocate for research and policy agendas that are firmly grounded in social practices and take complex and dynamic interactions of energy supply and demand as departing point to seriously reflect about the transitions that are put before us.

1. Introduction

This paper argues that current research and policy approaches to innovation for decarbonisation are too narrow and often misleading, mostly because they rely on the assumption that energy supply and demand can be addressed exogenously and separately. After illustrating some main implications of this dichotomy and how it impedes fully deploying the existing innovation potential, the paper discusses

how and why methodological approaches informed by complex systems and social practice theories can greatly improve the current understanding of challenges and opportunities at stake with decarbonisation. The paper illustrates then how the combination of these approaches can allow deploying a still largely neglected innovation potential represented by social practices situated in socio-cultural history and developed by collectivities of citizens. In so doing, this paper positions itself within the quite recent literature

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exploring the fundamental contribution that social science can give to innovation for energy transition and decarbonisation (see e.g. [1–4]). The combined approaches being proposed in the manuscript are however informed by two specific theoretical frameworks¹ and, as argued in the following sections, this combination represents an important and still quite unexplored research area [5,6]. The final sections of this paper provide therefore suggestions for a new research-policy agenda informed by this new conceptualisation.

2. What is hindering the full deployment of the existing innovation potential?

Scholars have already dedicated a lot of effort to study hindrances to the deployment of radical technical innovations for decarbonisation. They have found these hindrances in existing socio-technical path dependencies and infrastructures, entrenched institutions, vested interests, and in the inseparability of technology and culture, among others [4,18]. There is however one important hindrance that is still not well covered in existing literature and not widely recognised by researchers and policy makers; one that relates to a broader type of innovation potential associated with the social practices through which people's daily lives are organised and accomplished. This blind spot is the consequence of the dichotomous framing whereby researchers and policy makers conceive of innovation and transformation.

Technology R&D activities, as well as scenarios and policy strategies that aim to stimulate what is generally called a radical transition to low-carbon technologies, are still entrenched in the assumption that energy supply and demand can be addressed exogenously and separately. This constructed dichotomy consists, on the one hand, of assuming that energy demand will not be modified over time, while energy supply is being changed. This change relies on a sort of *deus ex-machina* which can exogenously develop innovative low CO₂ emission technologies capable of fulfilling people's present needs and wants. On the other hand, the dichotomy results from framings and representations which set energy supply technologies as a given and assume that energy demand can be driven by yet another type of *deus ex-machina* which changes individual behaviours around innovations by relying again on other exogenous factors represented by price signals, information, education, training courses, nudging and the like.²

The origins of the separation between demand and supply (which resonates today with the dichotomy of technology and society) are very old. They can only be identified through a serious historical enquiry [5,20–22]. This dichotomy typically leads to neglecting how energy supply and demand co-evolve and influence each other in ways that can work towards or against low-carbon societies and sustainability (see Fig. 1). Due to this dichotomy, circumstances where *endogenous* and local factors determine this co-evolution have been scarcely studied and have been mostly disregarded by researchers and policy makers. As we will explain in the next paragraphs, these factors are mostly represented by the social practices that generate and emerge from the intricate and extended flows of energy and matter associated with production and consumption activities. The main reasons why the supply-demand dichotomy prevents realisation of the existing innovation potential are illustrated in Box 1.

¹ For social practice theories, see e.g. [7–9]. For complex systems theories, see e.g. [10–17].

² The presence of the described dichotomy can be easily verified, for example, in the recent report of the Intergovernmental Panel on Climate Change, notably under report chapter 4: Strengthening and Implementing the Global Response [19].

Box 1

What do we mean by demand-supply dichotomy and why doesn't it allow for the full deployment of the existing decarbonisation potential?

- a) The demand-supply dichotomy results from a focus on energy/technology *inputs* which are often simply imagined as substitutable into a “black box”³. This avoids questions about where such inputs come from, their historical and social embeddedness and the limitations posed by available natural resources. There are clearly good practical and political reasons for this focus, since these inputs provide readily governable objects, more so than the actors, systems and practices using them. This however neglects how inputs shape people's doings and sayings and the wider opportunities for reshaping energy demand by changing these doings and sayings.⁴
- b) Being focused on energy and technology inputs, this dichotomous approach renders people as energy/technologies end-users and consumers reinforcing the need for and dependence on experts' assistance [25]. Whilst people should in principle have a voice in deciding how energy services should be provided and arranged, as *end-users or consumers* they are at most invited to take informed decisions concerning how to use or buy technologies and services devised by others. Yet, the participatory design and of energy systems, where people actively enrol in design and innovation processes, remains mostly untapped [26,27].
- c) Part of the supply/demand dichotomy is the implicit representation of linear material flows that precludes the closure of material cycles and poses huge problems in terms of non-renewable resources and sustainability. For instance, multiple metals have to be extracted and manufactured to produce electronics required by the large-scale deployment of renewable energy sources; and these electronic devices are hardly recyclable (including for thermodynamic reasons) [28]. Upstream and downstream flows of material inputs remain hidden behind the general terms of technological supply and social demand.
- d) This approach reinforces dominant social imaginaries [29] developed around technologies, in turn limiting the evolution of existing social relations, reinforcing an impression of predestination, and so inhibiting truly transformational changes. Deterministic approaches adopted in energy/technology consumption forecasts have a part in this and prevent innovation in the field. Policy-makers in search of highly reliable forecasts remain usually unaware that the forecasts actualisation may mean that people have mostly behaved as predictable machines and therefore innovation has actually not taken place [30]. By assuming a machine metaphor of human and technology interactions, it is somehow unsurprising that the system operates within pre-determined parameters and then wears down, not exhibiting features of emergence and self-organisation common in natural (non-machine) systems.
- e) Being focused on energy and technology inputs, this approach downplays social and political aspects of negotiations processes entailed in the adoption of proposed solutions.
- f) Being focused on energy/technology inputs, it necessarily neglects how changes in these inputs are accompanied by changes in practices and demand which can result in counterproductive effects.⁵ Due to this narrow focus, the latter changes are destined to be unexpected, and often unwanted.

³ The authors refer here to the social process of *black boxing* whereby the internal complexity of a machine or physical process is made invisible and rendered just in terms of its inputs and outputs (see e.g. [23]).

⁴ For example, in the case of mobility, there is an assumed large scale substitution of gasoline vehicles by electric and/or more energy efficient vehicles supposed to be able to fulfil without change existing mobility needs, which does not take into sufficient account the way people's mobility can be reorganised to their advantage, e.g. by focusing on “walkability” and reallocation of spaces (see e.g. [24]).

⁵ More efficient vehicles can e.g. foster the diffusion of more vehicles and ultimately make mobility less efficient, the diffusion of low cost renewable energy or more energy efficient technologies can in principle lead to increased consumption, etc. (see [31]).

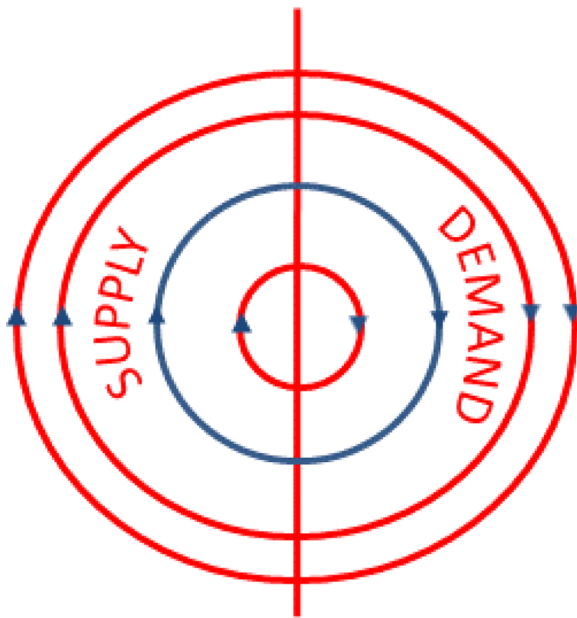


Fig. 1. Schematic representation of the demand-supply dichotomy and co-evolutions that might be observed following a change occurring on the supply side (represented by the semicircles on the left side) and/or on the demand side (right side). When assessing resource impacts of a change devised on existing supply or demand of natural resources and technology (see solid line semicircles), mainstream research and policy approaches to innovation typically assume either that supply can be changed without affecting demand or that demand can be changed without taking into account interactions with existing supply infrastructures. In this way, they always neglect possible demand-supply co-evolutions where changes occurring on the supply side are accompanied by changes on the demand side and vice-versa (see dashed line circles). All together, these changes can generate either an increase (see larger dashed line circles) or a decrease (see smaller dashed line circle) in the amounts of used natural resources as represented by the diameter of the various circles.

3. How can we improve the current understanding of challenges and opportunities at stake with decarbonisation?

3.1. Complex systems perspectives

Anthropogenic greenhouse gas (GHG) emissions abatement can only be reasonably addressed through a whole system approach that reflects existing and increasing interdependencies between social and environmental actors [32,33]. Within these interdependencies, human activities are reinforcing existing mutual interactions and create global dependencies. Due to the progressive strengthening of internal interactions, the evolution of global socio-ecological systems is becoming highly unpredictable and these systems are becoming increasingly vulnerable to failure at all scales [34]. This poses fundamental challenges to any endeavour aimed at controlling their GHG emissions.

For this reason, innovations for decarbonisation cannot be addressed by only focusing on the substitution of individual technologies or on attempts to change individuals' behaviours. They have to be addressed through research and policy approaches informed by complex systems theories.

There is no single unified theory of complex systems; yet complex systems approaches in physical systems⁶ generally deal with

⁶ For methodological clarity and historical reasons (complex systems theories are indeed historically rooted in physics, biology and cybernetics), the authors of this paper restrict their considerations on complexity by referring only to those approaches and theories which are presently applied to describe and study *physical* systems (including theories applied to study control and

information feedback loops associated with energy and matter flows occurring within and through open systems, in a non-equilibrium state,⁷ these potentially generating non-linear interactions among their parts. Thus any open system with social actors will always be complex and demonstrate the following characteristics: hierarchical organisation, emergent order formation, i.e. temporal (oscillations, chaos), spatial (patterns) and/or spatial-temporal (dynamic patterns) order; multi-stationarity, self-organisation, as well as emergent properties such as adaptation, resilience, etc.⁸

Rather than focusing on mechanistic, closed and predictive knowledge frames, complex systems approaches frame sustainability issues in terms of self-organised open systems that exchange matter and energy with the external environment.⁹ Matter and energy are understood as “flows” or “processes” through a purely relational ontology. These generally very intricate flows are studied and monitored through computer technologies and are considered as the actual information driven constituents of the entities that constitute the world around us. The gurus of complexity typically describe the dynamical and relational nature of its constituents through recursive statements and define complexity e.g. as: (i) a resonance between “a recipe inducing processes and processes inducing recipes” [14]; (ii) a resonance between “DNA making metabolism and metabolism making DNA” [37]; (iii) a process of self-organisation driven by “informed autocatalytic loops” [15]; (iv) a process of self-organisation “closed to efficient causation”, i.e. a process that, rather than being the expression of efficient causation, is about expressing a final cause about reproducing itself and making itself more adaptable [16]; (v) learning about the validity of beliefs by using them to guide action [17,38].

Complex systems approaches can enable important advancements towards decarbonisation in a plenty of respects. By allowing monitoring the energy and material flows constituting the ‘metabolism’ [39] of societies, they can assess the viability and feasibility of the large-scale diffusion of low carbon technologies and its implications to the organisation of production and consumption activities. This monitoring activity is also what can improve the management of unexpected co-evolutions of resource demand and supply¹⁰ and of the increased vulnerability of the global networks expected to enable decarbonisation. On shorter time scales, complex systems approaches also conceive of large-scale management tools that potentially enable a real time match between energy demand and a fluctuating energy supply. Moreover, the associated systemic view allows taking advantage of systems interactions which are still mostly neglected.¹¹ Consequently, complex systems

(footnote continued)

communication systems existing in the animal, the environment and the machine). Many more knowledge fields (as e.g. linguistic, social science, anthropology, etc.) are now engaging with a complexity theoretical framework (see e.g. [35]) making the set of ideas developed under complexity theory an all-encompassing paradigm embraced by natural science, social sciences, humanities, professions, applied sciences. This cultural phenomenon is certainly very interesting and would deserve dedicated studies. Under a scientific point of view, attention should however be paid to whether all these extensions can be justified on counterfactual grounds or are just the result of the transposition of concepts developed in one research field to another through analogies.

⁷ Whilst classical thermodynamics deals mostly with closed systems evolving through near equilibrium states, complex systems approaches deal with open systems far from equilibrium [11–13].

⁸ See, e.g. [10] for an overview.

⁹ See this discussion in [5,36].

¹⁰ A series of studies informed by complexity already point, for example, to how a large scale substitution of current fossil-fuel technologies with existing renewable energy technologies would alter the existing balances between energy demand and supply by making current lifestyles unsustainable under the energy point of view due to existing natural constraints on renewable energy availability [39–41].

¹¹ See, for example, the benefits generated by closed loop regenerative processes like those associated with so called cradle-to-cradle industrial design approaches for products ([42]:216).

approaches generally accommodate alternative and more regenerative socio-economic systems [43] by taking inspiration from ecosystems as a model and overall energy and material constraints as a driver.¹² At a governance and policy levels they can enable researchers and policy makers to be more reflexively aware as they always consider the information feedback loops generated among observer, objects of observation and the surrounding environment [45].

Thus, complex systems approaches are ideal to address the global transformation towards decarbonisation in so far as they can deal with large scale and intricate physical dynamics concerning our environment and economies [46].

3.2. Social practice perspectives

Although highly needed, complex systems theories represent quite abstract perspectives on innovation for decarbonisation. Social and economic impacts of innovation can only be understood by situating¹³ complex systems within history and culture. Complex systems and their dynamics are rooted in situated human actions across the sites comprising them [48]. Energy and matter flows therefore need to be situated in the contexts where human activities take place, from policy making and technology design to the activities leading to demand for energy services. To this aim, it is crucial to consider social practices, as these allow a deeper understanding of how complex systems dynamics are generated. This requires research and policy framings that, rather than by abstract concepts and principles of complexity, start by addressing people's actions and language, the experiential and *practical knowledge*, and wisdom of social bodies made of people, their artefacts and environment [49]. In other words, innovation for decarbonisation necessarily has to be addressed and studied as a specific type of *social innovation* consisting of endogenous, relational and reflexive processes [50]¹⁴ where technologies are entangled rather than deterministic. Rather than as the outcome of a seamless and large-scale diffusion of ready-made technical solutions, decarbonisation should be devised as the outcome of new social practices whereby technical solutions are altered and enacted.

Theoretical approaches that deal with social innovation for decarbonisation draw on theories of social change which constitute a broad and heterogeneous spectrum ranging from individualistic/action theories to actor-network and social practice theories ([50]:21).¹⁵ Within this spectrum, social practice theories provide concepts which enable a better understanding of a range of relations in the processes of creation, imitation and adoption of innovations. They have been a mainstay of social science research for over fifty years, most probably since Erving Goffman's work [47]. Although not constituting a unified research field, *social practice theories* can aspire to become the central starting point to achieve a more comprehensive view of the concept of social change and to develop a theoretical grounded concept of social innovation intended as the emerging of new combinations and configurations of social practices [50]. Hence, they can provide the appropriate lens through

which the complex system dynamics of decarbonisation and associated innovation processes could be approached. Social practice theories take social practices as a fundamental unit of analysis to get insights about social change, and challenges and opportunities of decarbonisation. Both social order and individuality are seen as the result of distributed practices which consist of (see Fig. 2): material arrangements (i.e. materials, technologies and tangible physical entities), know-how and routines and *teleo-affective* structures (domain of symbols, meanings, beliefs and emotions) [8]. Rather than energy and material inputs, they take the dynamics of practices as a starting point to study a transformation towards decarbonisation.¹⁶

A focus on *practices* highlights completely different sites of intervention to effect change compared to complexity approaches and to approaches focused on technological substitution and behavioural change. A transformation towards decarbonisation becomes a question of re-crafting practices by changing their constituting elements (i.e. involved materials, competences and meanings), substituting whole practices with alternative ones (e.g. with different practices that can allow fulfilling same needs and wants), changing how practices are interlocked (e.g. by changing existing links among mobility, shopping and eating practices) [9]. A change in practices can be very radical and systemic, for example through adopting different meanings and social imaginaries developed around technologies. Moreover, social practices are situated in sociocultural history. This implies, for example, that a transformation towards decarbonisation has to be addressed by starting from (and will certainly be influenced by) existing practices and associated lock-in effects, which vary from place to place. At the same time, however, social practice theories re-conceptualise hierarchies, as well as macro/micro and global/local distinctions into a flattened plane of distributed agencies carried out by human and non-human actors which assemble into large bundles of practices. By doing so, these theories deny the necessity of presence of “one macro-micro relationship”¹⁷ and of “stability, equilibrium or closure” within single practice bundles ([7]:38), as instead done e.g. in some transition theories.¹⁸ Without prioritising neither stability nor change, social practice theories depict a flat society where moments of gradual and predictable developments can alternate with sudden, unpredictable and large-scale dislocations and transformations [7]. These theories also lead to a specific epistemology centred around ideas of knowing as a situated activity and of materiality of knowing as originally formulated by [56]. In the epistemology of practice, the knower and the thing to be known do not pre-exist but are rather the outcome of their “entangled intra-relation” [57].

All in all, social practice theories deconstruct technologies, knowledge, as well as roles and functions of human and non-human actors. They can account for social exploitation, advantage, power, social class, etc., as produced and reproduced through practices. Social practice theories therefore allow 1) deconstruction of traditional dichotomies established between producers and consumers, experts and non-

¹² For example, the organisation and function of natural ecosystems (in terms of energy and nutrient flows) exhibit a trade-off between efficiency and redundancy [44]. This allows for high system performance but without sacrificing too much resilience. Natural systems also aggrade and develop stores moving them further from equilibrium – i.e. they regenerate, opposed to techno-human systems constrained by the machine metaphor with expectations of dissipative losses wearing out and breaking down.

¹³ In this respect, see also Goffman's notion of ‘situated activity systems’ ([47]:84-85).

¹⁴ On this point, see also the framework for responsible innovation as described e.g. in [51].

¹⁵ Although mostly focused on technological innovation, the evolutionary multi-level perspective (MLP) represents another important contribution to the understanding of the dynamics of innovation processes in the context of social change [52,53].

¹⁶ Practices can be of all kinds. There are practices implied in the reproduction of largest social systems, as well as practices entailed in reproduction everyday life; practices involved in the production of means of production, and practices producing stuffs and goods for households, as well as practices of disposing of waste.

¹⁷ Schatzki describes e.g. the case of the purchase of a fast food hamburger and the encompassing economic system as an example of micro and macro phenomena ([7]:37) and discusses how no systematic relation of causality and supervenience can link them. As he points out, the variety of action chains, also originating at large distances, that converges on and support the transaction and constitutes the relationship between micro and macro in this case can neither be intended as “the micro-macro relationship”, nor can it be captured by some smaller-larger distinction.

¹⁸ This is the case e.g. of the Multilevel Perspective (MLP) where so-called socio-technical regimes are described as stable ([54]:2) or where landscapes are assumed to remain stable in absence of some kind of external pressure ([55]:46).

information feedbacks or by achieving an optimal balance between efficiency and diversity of resource inputs within service infrastructures) can be combined with approaches focusing on stimulating collective learning processes in variable contexts [63] whereby new practices can be generated and existing socio-technical capacities [64] can be exploited to deal with unexpected disruptions.

In all these proposed combinations there is always a general and clear complementarity at stake. This stems mainly from the fact that complex systems theories mostly describe and target a world made by structures evolving by following the rules of thermodynamics and information theory, while social practice theories target practices and material arrangements populating the world where people conduct their everyday life. Methodological approaches to innovation for decarbonisation that can be adopted by researchers and policy makers by combining these perspectives can in principle vary widely, depending on the research questions and policy issues they aim to address. These combinations can however hardly represent an integration of one perspective into the other. Indeed, besides providing some elements showing the complementary character of the two perspectives, this section just aims at opening a discussion about some promising research areas concerning the *articulation* that can be established between them to deal with innovations for decarbonisation.

4. So, which types of innovation do we need?

A transformation towards decarbonisation cannot be effectively addressed by research and policy approaches which are dichotomous and focus on stimulating production and diffusion of given low-carbon technologies together with promoting environmentally friendly behaviours.²⁴ We argue that these approaches are certainly necessary, but they are deeply insufficient as they fail to take into account complex systems dynamics and how innovations and new social practices actually develop and diffuse, aside from their implicit optimism about their ability to get people to act in prescribed ways. We live an extremely fluid time with new technologies imagined and made, and demand and supply being constantly and unexpectedly re-combined and recomposed at every scale. Low intensity and highly distributed renewable energy sources are imagined, for example, to enable everybody to provide for their own energy needs, while selling or buying energy units within highly interconnected distribution networks regulated by suitable market rules.²⁵ However, 'everybody' is not located in places with the same environmental, social, or technical resources. The uneven distribution of renewable energy is a hallmark of the associated technology, both in social dimensions as well as environmental ones; some places have existing strong social relations that enable deployment of renewables (e.g. cooperatives and community organisations) others less so. Innovative low-carbon technologies that sustain demand, supply and distribution of products and services, and the so-called smart network/ICT based innovations are needed (e.g. decarbonisation requires large scale and ICT based redistribution of available renewable energy and material resources). But, their large-scale adoption has to be devised under a complex systems perspective whereby their long-term and large scale interactions could be assessed and monitored. Moreover, their diffusion has to be supported by research and policy approaches that are *situated* in the history and culture of the place where technical innovations are enacted in practice.

Whenever this is honestly done, the presence of an additional and important innovation potential comes immediately to the foreground. For example, it generally does not come as a surprise that also the re-discovery and adaptation of pre-existing and old social practices - whereby people have organised production and consumption in given geographical areas toward their appropriate criteria - can result in extremely innovative and beneficial solutions also from a systemic

perspective to decarbonisation. Lower levels of delegation to machines and lower consumption of *exosomatic* energy,²⁶ higher levels of renewable energy inputs and higher levels of social control over the whole production and consumption cycle are some of the main elements that make these practices very relevant. Social practices where the above elements can be identified seem to naturally re-compose a series of problematic role distinctions (created e.g. between producers and end-users, administered and administrators, experts and other citizens, etc.) by partially or totally re-conducting production-consumption cycles under the responsibility of people served by these cycles.

We suggest therefore that research and policy approaches that can be developed in this area require *humility* and protracted care,²⁷ because social practices are the place where a fundamental type of innovation knowledge is located. This type of knowledge does not originate top-down from paid experts and formal science applied to solve a particular problem. It comes from tradition, history, political imaginaries, local practical knowledge, expertise and innovation. The endorsement of this important and still scarcely considered social practice perspective by current research and policy approaches demands their radical revision.²⁸

Although still facing some difficulties in accommodating the roles of collective actors, strategic action, and purposive collective projects in social change [69], social practice theories can enable recognition and study of another relevant innovation potential, namely social innovation initiatives set-up by *collectivities* of citizens. These initiatives relate e.g. to community energy, community supported agriculture, local currencies, social technologies, socially useful production and many, many other fields of activity.²⁹ Overall, these initiatives can be considered as participatory and collective actions whereby innovation on energy and technology inputs is addressed in combination with outputs re-arrangements. Collective initiatives can prove extremely cost-effective and efficient in reducing GHG emissions generated by bundles of interconnected social practices related to mobility, food preparation, consumption and conservation, shopping, dish washing, etc.. They can contribute to create the conditions whereby, for example, fresh food can be easily bought from nearby farmers, locally-made hydrogen can power island ferries, non-mainstream innovators can improve technological systems or small scale heat and power systems are owned and managed by communities [70], generating new arrangements of social practices with much lower GHG emissions. What is interesting is that considerations about food quality and local benefits of energy production and distribution are often the main driver in cases like these, whilst those who contribute to generate and engage in such new practices not even being necessarily aware of the associated GHG emission reductions advantages.

Clearly, collective action initiatives do not certainly represent the silver bullet for decarbonisation and certainly can also exhibit problematic aspects.³⁰ Nor are they quick to implement. Community-led

²⁶ Contrary to *endosomatic energy*, *exosomatic energy* is the "energy converted *outside* the human body with the goal of amplifying the output of useful work associated with human activity" [66].

²⁷ See work on 'care' in making techno-science worlds, for example, in [67].

²⁸ Moezzi and Janda [68] propose e.g. the category of "social potential" (in analogue to the conventional technology-centred terms of technical and economic energy saving potential) as a conceptual space to point to the ability of normal people to create practices to reduce energy consumption as adapted to local contexts and circumstances.

²⁹ For example, see EU H2020 projects on community-led renewable energy initiatives in Orkney, Scotland, such as BIG-HIT, Building Innovative Green Hydrogen Systems in Isolated Territories, or the H2020 project COMETS (Collective Actions for Energy Transition and Social Innovation).

³⁰ E.g. they seem so far to mostly result from initiatives undertaken by mid-to-higher income segments of the population, they can generate issues of legitimacy and accountability vs. own members and wider society in general. As happening with an increasing number of governmental institutions, they are then exposed to closure-openness dilemmas in relation to resource exchanges with the external world.

²⁴ For an interesting historical overview on the different framings adopted by policies for science, technology and innovation since World War II, see [4].

²⁵ See e.g. [65].

projects require for example sustained engagement over years (rather than a consultancy approach), and a careful balance of volunteer and paid labour to prevent burnout. Nevertheless, they indirectly prove that, whenever suitable conditions to move demand and supply closer can be identified by reducing the number of technological and human intermediaries and intermediations, a series of effective possibilities emerge to reduce the amount of non-renewable energy inputs via increasing the quality of technology outputs and their social usefulness. In these circumstances, existing relationships between inputs and outputs are more easily foregrounded and can be reshaped by people with much less assistance from “top-down” experts. *Re-approaching* demand and supply makes it generally possible that a larger variety of innovative solutions emerge and generate higher flexibility and adaptability to the various geographical and political contexts where those develop (putting it in more technical words, the solution space becomes easier to find due to couplings and synergies of production and consumption). It is in this way that communities can paradoxically manage and implement solutions producing large amounts of non-renewable energy savings starting from non-technical decisions concerning how to reorganise outputs, e.g. by considering aspects of social justice. Existing intricate relationships between demand and supply can certainly make it very hard to quantitatively assess the GHG impacts of this innovation potential. However, this limitation should not lead to neglecting its relevance because it can allow GHG emissions reductions by increasing social well-being.

Certainly, we do not want to downplay that a transformation toward decarbonisation necessitates delegation to machines and large renewable energy distribution networks. These networks and the associated technologies are the condition *sine qua non* for such transformation because it needs to be based on the exploitation of highly distributed and low intensity energy sources.

The point is however, that large-scale decarbonisation approaches mostly relying on the promotion of innovative technologies (typically within competitive market settings) entail a progressive resources commodification, with problematic extraction ontologies that take ownership of what is understood to be local. Moreover, there is a shift from human activity to the devaluing of labour combined with an increase in visible mechanical activity. This generally implies an increasing use of resources and reduces the possibilities that social practices can be regulated politically, generating also issues of procedural and distributional justice.³¹

Relying on diversified ways to organise production and consumption, the innovation approaches just described are necessarily much more difficult to initiate and will easily escape from prescriptive descriptions and quantitative forecasts that now dominate planning for low-carbon technologies and transitions. They are based on a more active involvement of people and on a high variety of social imaginaries concerning how decarbonisation could be achieved. It is for these reasons that they cannot be easily reflected within current decarbonisation roadmaps and forecasts. Yet, they are pivotal to contribute to making future energy systems much more flexible, adaptable, and sustainable for larger societal sectors. Their serious consideration entails that the function of those forecasts is entirely rethought.³²

To summarise, we are arguing that a series of alternative approaches to innovation needs to redirect current mainstream approaches focused on technologies and behavioural changes, since they alone will not lead to sustainable and large scale decarbonisation. Further research is certainly needed to understand how this can be achieved and be mainstreamed in policy-making. A research agenda intended to inform policy making for de-carbonisation needs much more than just mapping or experimenting with social innovations. There are root problems that have led us to taking the current planned

decarbonisation route which need to be made visible.

The followings are suggestions for a research-policy agenda to address this question along the lines discussed so far:

- a) Develop tools and methods that make visible, and experiment with, interconnected socio-technical dimensions of current and desirable transformations of energy systems.³³ *Complex systems* and *social practices theories* are in good position, together, to respond to this challenge and work through this transition. Social practice research needs to embrace broader notions of practice as done within contemporary developments in social practice theories, such as by considering infrastructures and other material arrangements as well as know-how and routines, *teleo-affective* structures and distributed human and non-human agencies as constituents of ‘practices’. Additionally, we should identify upfront all fields of academia that could meaningfully contribute to this endeavour (e.g. history, anthropology, political economy, etc.) rather than relying only on existing energy research fields.
- b) Draw upon current social and complex systems theory to investigate and possibly conciliate dichotomies that are now taken for granted, such as demand/supply, producer/consumer, subject/object, machine/nature, that underpin energy policy and technology.
- c) Critically examine and deconstruct narratives, vocabularies and social norms now entrenched in research and policy discourses [73]. For example, look at taken for granted terms, such as ‘limits’, ‘scarcity’, and ‘market’, exploring their meanings and how these travel across institutions and disciplines, making visible how such terms reflect, foster or hinder particular narratives of past, current and future energy research and policy.
- d) Co-create new vocabularies and ontologies that better reflect current theory and practices by engaging with different actors. For example, work with energy communities and other loci of social innovation with regard to energy governance, or communally deconstruct narratives toward awareness of, or liberation from, the assumptions they embed.
- e) Identify advantages of diversity in institutions and citizens *collectivities* in the energy sector; are these *collectivities* transition drivers? For example, look into procedural and distributional consequences of the rise of different forms of local, decentralised energy supply providers. Explore mechanisms to ensure diversity in different national or regional contexts.
- f) In relation to community-based energy projects, work needs to be done to map what is already happening; through comparative studies, explore diverse contextual conditions determining the implementation of collective actions to govern the energy sector; to work with local actors to identify goals, needs and strategies to foster these actions (rather than impose assumptions).
- g) Acknowledge that a serious examination and development of strategies needs sustained and long-lasting engagement.
- h) Recognise that policy, and research, are part of the systems they seek to reshape, not external to them, and adopt reflexive aware approaches informed by complexity science.

Finally, we need to work collaboratively to develop better stories and better futures, in diverse media that can travel to audiences across policy, industry, academia, and local communities, which both take stock of all complexities of any change (energy transition or not) and actively work to enact change and new sustainable energy futures.

5. Conclusions

This paper has discussed how mainstream research and policy approaches to innovation for decarbonisation are in need of

³¹ See e.g. [71,72].

³² See e.g. what discussed in [4] on how anticipation of collateral effects and consequences of innovation might generally be achieved.

³³ See e.g. the notion of socio-technical system transition has defined in [4].

transformation. The authors suggest starting by challenging the demand-supply dichotomy that informs those approaches. The reasons for this quite unusual and apparently narrow departing point are to be found in how the dividing line that it is created between demand and supply is closely linked to the separations imagined to exist between subject and object, between humans and technology, between everyday life and institutions since several centuries. This separation impacts deeply on the way in which societies are organised and conceived at the political and economic level and still frames most of the theories informing research and policy approaches adopted to deal with any kind of innovation. In our opinion, transforming innovation for decarbonisation requires finding ways to overcome the problems generated by the mentioned dichotomy in all these dimensions, as all these dimensions are implicated in a transformation towards decarbonisation. Complex systems and social practice theories represent the compelling frameworks whereby to deal with this transformation because they are in our opinion the outcome of the most relevant research efforts so far undertaken to overcome the mentioned dichotomies.

The ultimate reasons why these theories and frameworks have to be considered in combination need to be found in the fact that, despite these efforts, neither of the two can completely overcome the above mentioned dichotomies and produce a fulfilling description of the “transformation” in isolation. Whilst the first framework is rooted in physics, biology and cybernetics, the latter is rooted in humanities. As the separation existing between these areas has not yet been overcome within our culture, it cannot probably be pretended that better results can be achieved even by the most advanced theories developed within this culture. Complex systems approaches are anyhow highly needed for the reasons mentioned earlier in the paper. Their systemic perspectives are particularly important. In principle, they e.g. allow monitoring whether a progress towards decarbonisation in a region of the world (e.g. Europe) is not taking place at the expenses of an increased use of fossil fuels in another region (e.g. China). Moreover, they can demonstrate with numbers the dangers of not participating in global and collective actions for a transformation towards decarbonisation, which are particularly relevant in present times of resurgence of nationalist and identitarian movements. Social practice approaches are then equally highly needed when it comes to address the political dimension of this transformation, to study the agencies involved in expected changes and how these changes might be activated.

The proposed combinations represent however something relatively new and this paper aspires to open a discussion suggesting the grounds for some promising development paths.

Declaration of interests

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.

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