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Perspective

The desirability of transitions in demand: Incorporating behavioural and societal transformations into energy modelling

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ABSTRACT

Quantitative systems modelling in support of climate policy has tended to focus more on the supply side in assessing interactions among technology, economy, environment, policy and society. By contrast, the demand side is usually underrepresented, often emphasising technological options for energy efficiency improvements. In this perspective, we argue that scientific support to climate action is not only about exploring capacity of "what", in terms of policy and outcome, but also about assessing feasibility and desirability, in terms of "when", "where" and especially for "whom". Without the necessary behavioural and societal transformations, the world faces an inadequate response to the climate crisis challenge. This could result from poor uptake of low-carbon technologies, continued high-carbon intensive lifestyles, or economy-wide rebound effects. For this reason, we propose a framing for a holistic and transdisciplinary perspective on the role of human choices and behaviours in influencing the low-carbon transition, starting from the desires of individuals and communities, and analysing how these interact with the energy and economic landscape, leading to systemic change at the macro-level. In making a case for a political ecology agenda, we expand our scope, from comprehending the role of societal acceptance and uptake of end-use technologies, to co-developing knowledge with citizens from non-mainstream and marginalised communities, and to defining the modelling requirements to assess the decarbonisation potential of shifting lifestyle patterns in climate change and action.

1. Acknowledging the problem

2020 remains the first of a series of milestones to tackling climate change and delivering on the Paris Agreement, despite postponing the 26th Conference of Parties (COP26) due to COVID-19[1], which could play a decisive role in the direction and ambition of new pledges[2]. Parties to the UNFCCC are expected to submit updated Nationally Determined Contributions (NDCs) towards 2030 and mid-century greenhouse gas (GHG) emissions development strategies, followed by the 2023 Global Stocktake of collective progress and gaps. In some cases, this is not as straightforward a process as the original submission of NDCs in 2015–2016, involving significantly larger amounts of effort. For example, the European Union (EU), being both among top emitters and one supranational body with a collective action pledge, faces the additional challenge of achieving and monitoring progress at both Community and Member State level [1]. Regardless of scale, however, effective climate action requires that a jigsaw of regulatory initiatives be put together, altogether comprising effective, socially acceptable, and robust climate policy in a globally coordinated, cooperative and timely manner. It must also consider the Sustainable Development Goals

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[1] https://www.gov.uk/government/news/new-dates-agreed-for-cop26-united-nations-climate-change-conference
[2] https://www.climatechangenews.com/2020/04/02/governments-still-due-submit-tougher-climate-plans-2020-despite-cop26-delay/

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(SDGs) [2], which loom large in global and regional policymaking, thereby adding a further layer of complexity.

Science in support of developing mitigation pathways—heavily underpinned by energy system, sectoral and integrated assessment models (IAMs)—attempts to assess interactions within the spectrum of highly intertwined pillars of technology, economy, environment, policy and society [3]. Whatever the theory, structure and coverage of these tools [4], modelling practice tends to focus predominantly on the supply-side action space [5], despite most well-below-2 °C-compatible mitigation scenarios describing transformations in both energy supply and demand.

Relatively, demand is largely underrepresented, via technological options in energy efficiency improvements. Values, choices, cohesion, culture, and lifestyle shifts in society are indirectly narrated as assumptions [6] not interacting with the vividly modelled flows between technology, economy, environment, and policy. Even modelling scenarios looking at end-use transformations, like digitalisation of daily life and pervasive integration of new information technologies into energy services [7], mostly explore the maximum potential of technological breakthroughs taking into account a number of behavioural changes but not fully exploring how they could come about or how realistic they are. They overlook that, without the necessary behavioural and societal transformations, the world is very possibly looking at a generalised, society-wide rebound effect resembling known paradoxes [8,9]. This diverse range of possible, potentially large rebound effects is not sufficiently explored.

For instance, with consumers enjoying access to a multiplicity of energy-efficient yet easier and openly accessible services, living potentially outside environmental limits, energy use may instead grow [10]. This has been the case over the last quarter century, with energy consumption increasing far quicker than population growth, despite the uneven distribution of benefits from increased energy access [11] and energy efficiency being considered a top priority in some regions. More recently, increasing Google services users tripled respective energy consumption during the past eight years. The annual carbon footprint of cryptocurrency mining networks is now comparable to national economies [12]. The majority of global bandwidth is consumed for video streaming. And so on [13]. And, although free access to emerging digital services is socially beneficial and contributes to sustainability in various manners (for instance, by reducing inequalities), it may not be in keeping with the traditional climate policy model and required sustainability efforts [14], when referring to highly energy-consuming lifestyles. Nevertheless, to date, only limited attention has been paid to the demand side of energy transition. Recent, yet scarce, examples of research in the demand side include the multiple dimensions of structural changes [15]; the role and readiness of individuals and households [16]; psychological barriers at the household level [17], the importance of social innovation and systemic forms of social change [18]; challenges of energy sufficiency [19] and living within planetary boundaries; social justice [20] and gender aspects [21].

These observations and knowledge gaps have been evident in the coronavirus health emergency as well. The policy and market responses to the pandemic, including imposition of social lockdowns [22] and disruptions to global supply chains [23], have led to unprecedented short-term reductions of GHG emissions that are expectedly comparable to the Paris-compliant, year-on-year decrease rates necessary in the coming decades [24]. Fuelled by confinement rather than freewill, however, most of the changes contributing to the environmental silver lining of COVID-19 are likely to be temporary as they do not reflect the desired structural changes in the economic, transport and energy systems [25]. Moreover, a socio-economic rebound of COVID-related consequences has already shifted burdens, reallocating the care work and diverting electricity costs over to households and individuals, opening further discussion on gender roles, energy poverty and justice [26]. While discussions focus on the governments' eagerness to recover, make up for lost economic ground and even push towards a rebound with even higher emission pathways compared to pre-pandemic trajectories, with implications for progress on climate change [27] and sustainable energy infrastructure [28], there appear to be little targeted planning and communication strategies for a recovery based on more sustainable practices and lifestyles. In this scientific 'opportunity' to ground a new research agenda [29], behavioural science is critical [30] to explore and model the ways, in which such extreme situations could alter future trajectories [31]: should the coronavirus-related massive and rapid behavioural responses of the general citizenry [32] be taken for granted, or are citizens to be considered eager to return to the previous norm, with the expected exception of some social distancing measures [33] and voluntary working-from-home habits [34]? Again, the question on 'who benefits' from these arrangements is highly relevant, given that not everyone has the same opportunity to socially distance or work from home.

Given the over-reliance on supply-side solutions to address climate change [5], there is increasing focus on the realism of such solutions, particularly negative emissions technologies, in light of large-scale feasibility uncertainties [35], window of opportunity [36], resource requirements [37], and potential to induce prevarication [38,39]. Hence, there is an increasingly urgent call for focus on demand-side solutions [40,41], with examples emerging of pathways that lean heavily on demand and behavioural measures [7,42]. There is also a clear realisation that, despite increasing interest in bold supply-side solutions [43,44,45], such solutions will not work unless they pass the political economy test, including on the distributional, equity and justice fronts [20,46]. With progress happening on all fronts of transitions studies [47] and acknowledging the potential of complementarities among disciplines [48] in capturing the broad capacity and implications of climate action and improving the quality of knowledge interactions [49], researchers from the quantitative systems modelling community and those from social sciences and humanities have been reaching out to one another, calling for convergence [1,50,51,52,53,54].

The scientific community has acknowledged that more research is needed in behavioural change, on extremes, and from multiple disciplines and communities, but it does not yet have an integrated analytical framework for doing this. This commentary addresses the gap and proposes a framing for a holistic perspective on the role of human choices and behaviours in influencing the energy transition. Starting from the desires of individuals and communities, and analysing how these interact with the energy landscape, the framework provides direction on how this could lead to systemic change at the macro-level. Below, we highlight the role of societal acceptance and uptake of end-use technologies; the importance of engaging with, learning from and co-developing knowledge and solutions with citizens from non-mainstream communities (i.e. intentional projects and groups that are disinterested or have been systematically marginalised and even excluded from decisions-making processes); and the modelling requirements to assess the decarbonisation potential in shifting lifestyle patterns. In doing so, we emphasise the role of different scientific disciplines and of bodies of knowledge in understanding the micro- and macro-level changes in societal, technological and energy transitions.

2. Disaggregated understanding of the diffusion of social innovation

The first goal of bridging disciplines to tackle climate change lies in scaling up low-carbon innovation, from individual to community and then to wider society, and developing characteristics of user profiles based on various economic, political, and socio-cultural backgrounds. This helps to acquire a more disaggregated understanding of the diffusion of technological innovation, including product and services [55], and social innovation [56]. Understanding individual behaviours and preferences, and how these aggregate up to group and society levels leading to fundamental change across the entire economy and society [57], is vitally important, as it allows an understanding of the acceptance and viability of different policies and measures. But it is also a critical step in designing models of technological and behavioural transitions to reflect real-life conditions more realistically. Attention must be paid to how people's social relations influence energy demand [58], while aspects of 'energy sufficiency' [59], 'downscaling' and 'energy descent' [60] must be explored, as drivers of behaviour change through direct and embodied energy use that cuts across electricity and heat, buildings, transportation, the food system, and as drivers of degrowth with potential impacts on industry. At the end of the day, framing energy as a social relation is crucial given that the political nature of nature–society relations can arguably be best manifested over energy decisions and the social power constellations these give rise to [61,62].

Another important dimension that has so far been understudied lies in impacts on environmental, energy and climate justice [63,64]: shifts in behaviour, energy provision and access to services may lead to unequal distributional outcomes and further social injustices across generations [65] and across income groups, labour, race, and gender [66], with the latter being underrepresented in the literature [67] yet central in formation, response and responsibility bearing of energy transitions [68] and intertwined with climate justice itself [69]. At the same time, resulting changes in material consumption may significantly impact manufacturing and, in turn, employment in associated industrial sectors. Strictly formalised modelling frameworks alone are insufficient to delve into such impacts, and this is where quantitative evidence can be qualitatively supported, for example via sparking the imagination of "what if" scenarios [70].

Systems of Innovation frameworks can be used to carry out extensive sociotechnical analyses that further and more meaningfully inform quantitative systems modelling exercises [71]. Such approaches can help capture the real-life context and better explore, and map [72], societal innovations in terms of lifestyle changes. These need not be limited to supply-side technologies [73], as is mostly the case in the literature, but extend their scope to behavioural shifts, such as dietary selections [74], energy and other consumption profiles, investment decisions, means of transportation and modal shifts [75], and broader lifestyle changes, exploiting the capabilities of the diverse multiplicity [76], or combinations, of these frameworks [77].

Computational modelling can play an influential role in research and high-level policymaking on the diffusion of technological and social innovation and understanding interactions between key characteristics of consumers' behaviour affecting investment decisions. For example, there are integrated assessment models [78,79] that explicitly simulate the decision-making processes of heterogeneous decision makers (with different objectives, search strategies, and decision methods) in the energy system [80]. Such models, combining top-down approaches with agent-based modelling, allow the integration of several decision-making steps towards capturing a realistic representation of energy markets in transition, including information gathering, performance assessment and alternative option selection [81].

Furthermore, the transitions research agenda should acknowledge the need to explore game-changing business models and novel regulatory frameworks that can monetise and maximise the value of technological capability so as to engage citizens and incentivise changes at the household level. In this respect, modelling frameworks can help explore the benefits of different technological configurations towards energy autonomy [82], as well as the ways in which envisaged innovations can be adopted by and diffused into households of different profiles [83]. From a modelling perspective, research can also delve into policy instruments and market models that target low-carbon investment or purchasing decisions [84] based on consumer preferences, explore policies that go beyond market models [85], as well as simulate real-life behaviour and modal shifts [86,87]. In doing so, demand-side insights can complement supply-side research, by better informing tipping points or barriers for electrification strategies, evolution of infrastructure and introduction of low-carbon or carbon–neutral fuels.

3. Co-developing knowledge: discursive and fun engagement

Energy transitions cannot be detached from society [88], nor idealised by theoretical modelling alone, in questioning the societal desirability of sustainable transitions. How can we gain an understanding of individual, group and societal behaviours and preferences in respect to climate change and action, if not by engaging with society itself [89]? Initiative-based learning has for years been proposed as an approach to understanding expectations and strategies of actors on the ground [90,91], and therefore to exploring and evaluating transitions [92]. But, despite its strength in dealing with the complexity of transitions at the local level, its short-term, micro-scale insights [93], however valuable, are not tailored to inform or draw from the more generalised modelling exercises dominating the climate science literature. As a result, the role of community, e.g. grassroots initiatives, in social transformation towards decarbonisation is often underestimated. The combined effort of these initiatives, when scaled up, pose as alternative viable and desirable pathways, rather than standalone cases operating in silos.

Citizen-led transformations link mobilisation, network formation and institution building for sustainability transitions, and interact with state- and market-led transformations in many ways [94]. Political agency is central to such endeavours by challenging assumptions and engaging with alternatives that may be invisible to the mainstream view [95], such as post/degrowth initiatives at the local and regional levels [96]. These transformations also engage in societal innovation by navigating the transformative climate action 'in, against and beyond the state' in the transnational space [97]. These groups, however, along with their societal and cultural power, are not fully taken into consideration in shaping global future scenarios, such as those given in the Shared Socioeconomic Pathways (SSP) narratives and quantitative trajectories [98].

Among other criticisms, including infeasibility [99], incompatibility [100] and anchoring to storylines that may be invalidated from a risk perspective [101], SSPs in particular have been challenged by localisation and down-scaling attempts leading to several-fold increases of plausible futures [102]. It is, therefore, imperative that socioeconomic model scenarios be grounded with diverse local communities, where most of the unexpected transformations occur. In doing so, key research questions can be answered:

- How do people in different levels of organisation, in the grassroots organisations, neighbourhood associations and local authority levels, perceive and contribute to the representation of global socioeconomic pathways?
- What types of scenarios, model outputs and futures are imagined, represented, and legitimised?
- What are the barriers and enabling factors for envisioning desirable future scenarios regarding transformative climate action across different organisational levels?

These knowledge gaps must be explored, by looking at where and why unexpected transformations take place [103], what are the root causes and drivers of these new waves of transformation, how transformational leadership plays a role and spills over to the masses, and how grassroots innovations for decarbonisation [104] can move beyond business-as-usual for transformative change [105,106]. Such an agenda can help co-produce cutting-edge knowledge with societal end-users in combining horizontal (across diverse social groups, across space) and vertical (across time) dimensions of societal scenarios towards shared futures, and address the 'failure of imagination' [107] on climate change, from an interdisciplinary perspective. Imagining new societal futures, including the policies, technologies, behaviours, values and change processes, is something that scientists and decision-makers need to learn, visualise and put into practice [108].

Micro-scale projects can also help gain insights into, duplicate and upscale local success stories, for example by understanding the concerns, motives and preferences of citizens coming from intentional, non-mainstream communities, in which climate-friendly lifestyles and energy profiles are already a reality: eco-villages [109], transition towns [110], slow food [111], alternative housing models [112], youth movements [113], etc. Science is well-equipped with appropriate tools to facilitate engaging [114] with stakeholders at the local scale, towards capturing the ambition driving their motivation [52], as well as their concerns and factors hampering further action, as lessons to be learnt and diffused. These can include multi-criteria group decision aid [115] and consensus measuring [116], to capture the ambition driving engaged individuals' motivation.

Deliberative settings [117], in particular, can promote co-creation of the future and unlock capacity for long-term climate action [118]. Scaling well-proven methods of deliberative democracy to reach critical mass can show the road to relevant or accepted policies and communication activities towards the general public [119]: engaged citizens of truly diverse profiles in such discussion platforms are free of agenda and vested interests [120]; as such they are representative of the diversity of their country or community [121], and hence reflect the blockades and drivers for change. They furthermore go through a condensed process of education, through interaction with experts and other stakeholders, as well as deliberation, since the diverse groups go through a process of collective intelligence [122]. They can, therefore, output a set of recommendations that find collective acceptance because of this inclusive, fact-based, deliberative process [123], thereby overcoming 'societal ceilings' [124] boosting uptake of sustainable lifestyles [125].

Lessons from participatory settings can fuel meaningful engagement, with actors whose voices often go unheard and with unengaged communities and people with no representation in the low-carbon agenda [126] or limited interest/understanding and efforts to reduce carbon footprint and improve quality of life. Fuzzy cognitive maps [127], for instance, have been established as a communication and learning tool in scenario studies [128] and extended to assess strategies and their vulnerability to uncertainties [129], allowing citizens to evaluate climate policy strategies from their point of view, and inform [130] or improve [131] modelling exercises. As a commitment, however, the scientific community at large needs to embrace the true meaning of knowledge co-production and move beyond the sole realm of validation of results or consultation without any transformational impact, towards the ethos of creating partnerships with society [132]. Such settings, going beyond symbolic effort to creating alliances of science and society, can genuinely help understand how society's aspirations can be mapped [133] onto requirements and opportunities of a transition driven by lifestyle changes, building on evidence of the importance of dialogue to achieve distributional justice and gender equality [134].

A recent example of deliberative co-creation has been observed with the Climate Convention in France. In this dialogue, 150 citizens were given the power to propose legislation to reduce GHG emissions by 40%, before 2030, in a social justice spirit[3], eventually calling for a referendum to modify the French Constitution in protection of biodiversity, the environment and the fight against climate change and to introduce the 'ecocide' crime in the penal code.

Another means to encourage action during participatory educational processes lies in gamification [135]. 'Role playing' and 'serious games' have been used for social learning and simulating transitions across various environment, energy, and climate issues [136,137,138]. Via companion modelling [139], models can be coupled with such games to capture insights of different collaborators and allow them to interact with or give rise to decision rules and behavioural elements, revealing stakeholder-induced effects. This interaction of actors with a simulated environment according to specific rules can be useful to transitions research aimed at citizen engagement, raising awareness, and understanding lifestyle changes [140]. On one hand, robustness and completeness of analysis of sustainable transitions pathways are enhanced: climate and climate-economy modelling can be integrated with game outputs [141], by incorporating elicited information, including players' lifestyle choices, which can determine emissions reductions from reference scenarios when scaled up from individual to local, to national and global levels. On the other hand, gaming can be both educational [142] and entertaining [143] for the players: upon linking bottom-up preferences to top-down modelling assessments of behaviours and policies across energy, transport, food and buildings, engaged citizens can interact with one another, be informed on latest scientific findings, explore lifestyle options [144] leading to different climate results, and experience the role of one another, increasing mutual understanding [145] and social learning [146]. Nevertheless, few studies have so far looked at the long-term maintenance/feasibility? of positive behavioural shifts resulting from gamification [147].

4. Expanding global action space: a new 'model' for modelling

Apart from designing and simulating modelling scenarios heavily orienting on different magnitudes of lifestyle changes across a diverse set of dimensions and socioeconomic groups, the transitions research agenda must first take note of the criticisms and shortcomings of the current generation of models, in both the supply [148] and the demand side [149]. For instance, modelling work should distinguish voluntary behavioural changes from changes due to policy implementation—e.g. how people adapted to the COVID-19 reality and what part of this new norm was enforced by the policy response. This distinction should be made before delving into behavioural change to the level of understanding the drivers of such changes and how these may develop, or how interventions can help push macro-level developments towards desired trajectories [150]. Any modelling exercise aimed at building this understanding must therefore begin by defining model parameters, assumptions and scenario drivers in terms of efficiency, technological substitution and lifestyle change [41], and in terms of efficiency, consistency and sufficiency [151] and other distinctions or frameworks [40]. Models can help identify the role of diverse lifestyle profiles among different social groups, thereby serving to assess the impact of top-down mitigation policy on different groups in society and allowing to explore the impact of potential growth of specific lifestyle profiles on achieving emissions cuts.

Anchoring modelling scenarios to maximising the potential of negative emissions technologies [152], or assuming complete lifestyle change-driven decarbonisation scenarios [42] can be both meaningful and insightful but potentially detached from reality and policy, compared to exploring different levels of behavioural changes. Scenario design must orient on existing and emerging knowledge gaps, considering understudied socioeconomic conditions. These should include but are not limited to societal value changes, such as those across the usership-ownership spectrum [153] or diet change elasticities [154]; alternative or emerging business models and sociotechnical trends, such as those sustaining a sharing economy [155]; novel legal frameworks and voluntary inter-industry agreements; socio-technical innovation rates; and integration of digital services [156].

Meanwhile, the modelling community should rapidly accelerate its initial efforts to investigate alternative deliberation options: those that go beyond the "cost-effectiveness" mode [157], which prioritises understanding how to achieve the warming cap at the lowest possible cost. Such options can include: exploring a diversity of scenarios that reflect a range of desirable transitions to achieve different decarbonisation goals [158]; understanding "robust" strategies to achieving such goals [159] in the face of a range of future scenarios; seeking mechanisms to handle counter-GDP-growth scenarios of negative growth; and downscaling and degrowth/post-growth implications. At the same time, the modelling community has realised that there is no "one model fits all" approach and it should build on its efforts to make IAMs increasingly sophisticated by supplementing them with a range of other tools and analytical

[3] https://www.conventioncitoyennepourleclimat.fr/en/

techniques, to cover temporal and spatial scales that currently cannot realistically be represented [148]. For example, by combining long-range IAMs with short-term models of the macro-economy, useful insights can be gleaned on the full range of potential impacts of shocks, such as COVID-19 and associated policy and societal responses.

Different implications of pervasive technological change can be considered in models, including negative effects and ways to mitigate them [160]. These could encompass overall rebound effects linked with the emergence of new energy-expensive services and improved efficiency in digitalisation and future convergence of currently individual services, considering recent past trends, such as data transfer, search engine innovations, streaming needs, cryptocurrency and associated computing demands [161]. They can also encompass a broader consideration of emerging social trends, such as the increased substitution of artificial intelligence and robotics for labour, or mega-trends emerging from movements (with implications) for climate action, like flight-shaming ('flygskam'), train bragging ('tågskryt') and vegan lifestyles ('Veganuary') [162]. Such considerations, along with their positive and negative effects [163], including the arguments regarding individualisation of responsibility [164] can affect the employed modelling approaches and scenario building, so that digital capacity and accumulation of human and social capital be considered, and pervasive uncertainties be represented in the scenarios, building upon and augmenting the standardised energy demand, intensity assumptions and flexibility of the SSP framework.

Apart from co-developing inputs, effort must be put into enhancing the robustness of modelling outcomes and providing policymakers with information on the level of certainty over selecting feasible technologies or policies [165,166,167]. Significant work in the modelling community must also be done in improving transparency, by opening the scientific processes to stakeholders. This goes beyond the open nature of models and refers to the input data and scenarios driving these models. This is especially relevant for the civil society, the motives, strategies and concerns of whom must be thoroughly considered and addressed [168] when looking into behavioural aspects, allowing for increased ownership and therefore robustness of resulting policy prescriptions [1]. Upon explicitly linking outputs with assumptions, modellers should therefore focus on harmonising common socioeconomic and technological parameters as well as scenario narratives for modelling activities and invest in clearly exploring the scope of modelling interlinkages, defining the capacity for data exchange, enabling sequential or parallel integration of the models. This will allow for model inter-comparison projects, where the differences among trajectories resulting from different models can be attributed to their specificities alone.

Here, various frameworks [169,170] can be used to scrutinise how changes also come about: whether it is bouncing back, i.e. maintaining the status quo, mainstream pathways, as could be the case of recovering from COVID-19 only to return to the previous norm of exclusion and inequality [171]; whether it is about transitions, i.e. incremental changes or on-stream/off-stream pathways, as is the case of Green New Deals; or whether it refers to transformational, radical change, which implies not only a socio-cultural shift but also a political undertaking, rethinking dynamics of power and practice [172]. In the latter options, the question of legitimacy is raised on who gets to be a part of the decision-making process, taking on board transformative principles of inclusivity and diversity of voices.

5. An interdisciplinary and transdisciplinary integration process

Co-producing knowledge is a challenging task that must be carried out from both an interdisciplinary (across different disciplines) and a transdisciplinary (cross-actoral and cross-sectoral) lens. These are widely used in addressing the current tranformations in the relations between research, economy and society. Interdisciplinarity is a mode of research that integrates data, tools, perspectives, concepts, and/or theories from multiple disciplines to advance fundamental understanding or to find solutions beyond the scope of a single discipline [173]; while transdisciplinarity is a reflexive, mutual learning, method-driven scientific principle [174], that aims at solving societal problems characterised by complexity and diversity. It does so by differentiating and integrating various bodies of knowledge and inputs [175] from a wide range of stakeholders [176,177], like community, practitioners, and indigenous perspectives [178]. In this context, co-production entails a collaborative process of knowledge production, which uses integration as a means to combine scientific and local/traditional bodies of knowledge contributing to a holistic understanding [179].

Integration is widely regarded as the core process underpinning interdisciplinary and transdisciplinary research [180], enabling scientists to combine different disciplinary theories, methods and perspectives with an overarching aim of arriving to common ground. It includes insights, practices, frameworks, or concepts shared by multiple or all participants in different phases of a research process [181]. There is no universal model of how integration should be developed because interdisciplinary and transdisciplinary projects vary in purpose, scale and scope, and because it depends on the problems and questions at hand, the mix of expertise, and the degree of coordination [182]. Through integration, the framework proposed in this study goes beyond the spatial disaggregation of where we are, where we want to go and how we get there [183]. It rather makes a case of reinstating science in society and legitimising different types of knowledge [180] towards exploring the broad spectrum of the potential for and impacts of behavioural changes, based on individual, community, national and global action for climate change. In understanding the desirability of sustainability, transitions research can employ an agenda fuelled by knowledge co-produced by scientists and citizens alike from a transdisciplinary lens, one that bridges different disciplines and agendas in an interdisciplinary setting, and one that can explore and provide holistic insight into the interplay between individual behaviours and macro-level changes, and with factors such as language, culture and economy setting the drivers toward this change (Fig. 1).

We also acknowledge that, as the basis to build a collaborative endeavour inter alia promoting novelty and rigor in energy social science [184], integration cannot happen automatically. It requires time and resources to build spaces of trust and deliberation [181,185], as well as a "shared understanding" for collective learning that considers the real complexity of the local context and governance [186]. Rather, it must be guided by a structured method [187] and supported by interdisciplinary integration of specific tools and methods [188]: theoretically in terms of ontological and epistemological relations, and practically in terms of interconnections in the local contexts that the transdisciplinary agenda must aspire to engage and represent [189], thereby fostering unity across practices and adaptability to local domains [190].

6. Concluding remarks

Scientific support to climate action is not only about exploring capacity of what, in terms of policy and outcome. It is also about assessing feasibility and desirability, in terms of when, where and especially for whom. The world stands at a critical crossroads, where big investments are needed in supply-side technologies. Policy and business alike are increasingly aware of the huge potential for behaviours and lifestyles to help or hinder the sustainability transitions, and of the need to understand them better before making said investments. An undesired glimpse of a rapid reorganisation in societal and individual behavioural change was experienced with the COVID-19 crisis. However, despite the trauma, lessons can be learnt. In science, many have pointed to the need for a new transitions research agenda that integrates social science and modelling, but few have demonstrated how to coherently do so. In this perspective, we have made an effort to contribute to bridging this gap, by outlining a framework to do this from multiple perspectives and across multiple disciplines.

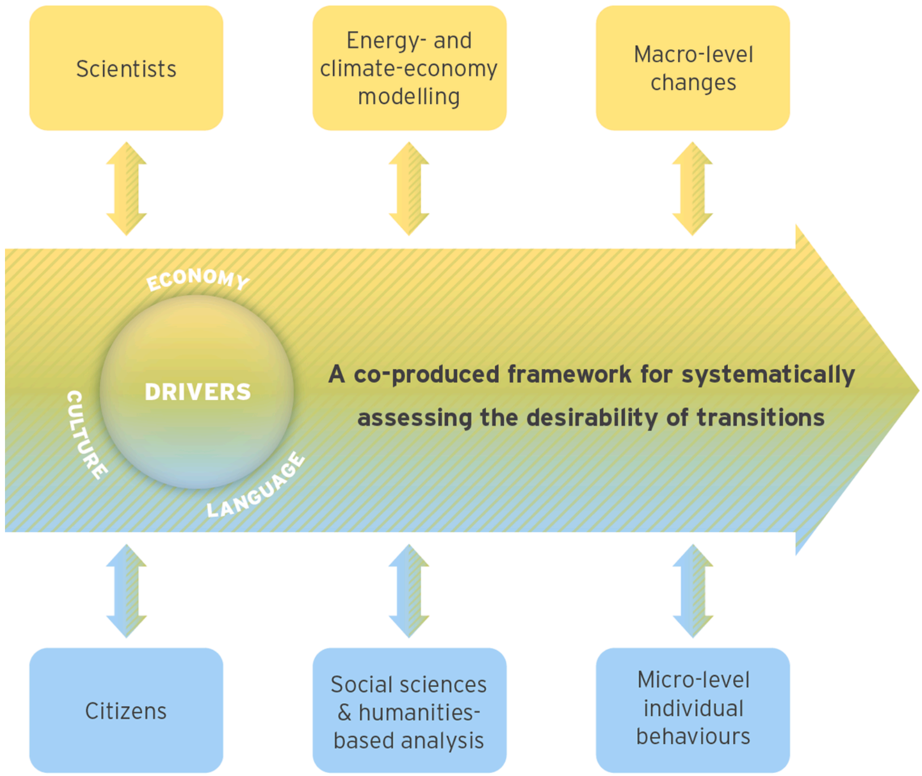

Fig. 1. A holistic framework for capturing behavioural and societal transitions in energy modelling.

From a scientific point of view, theoretical modelling does not capture reality but can provide a conditionally useful approximation to it [191]. In the case of human behaviour and the purpose of understanding it, science can benefit from insights from the agents themselves. Society can also gain from such an agenda: not only can citizens have some grasp of science by gaining access to how knowledge is produced [192], but they can also be a part of the knowledge production (or "co-construction" [193]) and help co-define the policy agenda, thereby gaining greater control over the decisions that affect their lives [194]. And the policy perspective can take on a political ecology agenda, committed to big changes with citizens and ecology at the heart, with hope and imagination fuelling new forms of governance.

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.

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