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A review of linking models and socio-technical transitions theories for energy and climate solutions

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Abstract

In the last decade, a new strand of energy and climate research emerged that links quantitative models and socio-technical transitions theories or frameworks. Linking the two enables capturing the co-evolution of society, technology, the economy and the environment. We systematically review this literature (N = 44) and describe the papers' trends, scope, temporal and spatial foci, and methodological strategies. The reviewed literature aspires to find solutions to the energy and climate challenges, to increase realism in models and theories, and to enable interdisciplinary learning between the two scholarly communities. The outcomes in this literature show benefits of interdisciplinary learning between modellers and transitions theorists. However, the literature rarely identified practical insights for energy and climate solutions or for improving realism in models and theories. We conclude by suggesting that integrative research should be continued, but redirected to provide more practical outcomes to meet energy and climate targets.

Research Highlights

- Energy and climate papers that link models and socio-technical transitions theories or theoretical frameworks are reviewed.
- Three aims are identified: *Solutions to energy and climate challenges*, *increasing realism*, and *interdisciplinary learning*.
- Most studies demonstrate substantial benefits of interdisciplinary learning.
- Few studies demonstrate concrete findings on how to meet climate and energy targets or to improve realism of models.

- We suggest redirecting such integrative research to provide more practical outcomes to meet energy and climate targets.

Keywords
Integrated assessment models (IAMs) ; Energy system models ; Socio-technical transitions ; Multi-level perspective ; Energy ; Climate mitigation

1. Introduction

Over the last decades, threats of fast-evolving climate change due to anthropogenic activities have unveiled the urgency of a transformation to low-carbon energy systems of whole societies (IPCC, 2018). The 2015 Paris Agreement sets the process for long- term greenhouse gas emissions (GHG) stabilisation to maintain the mean global warming temperature well below 2 °C above pre-industrial levels (UNFCCC, 2015). This context urges scientific and policy communities to identify rapid and transformative solutions for reaching these long-term energy and climate targets. Such transformative solutions require a simultaneous transition of multiple systems, including society, technology, the economy and the environment.

Among others, two approaches were used to date in order to understand how to foster these transitions for energy and climate challenges: quantitative models and socio-technical transitions theories or theoretical frameworks[1] . There are many reasons to employ models (see e.g. Epstein, 2008; Holtz et al., 2015), in particular because models are powerful tools for a systematic, quantitative and forward-looking analysis. Models can investigate the co-evolution of technology, the economy and the environment in order to reach predefined environmental targets under a given policy and societal conditions (Holtz et al., 2015; Li et al., 2015; De Cian et al., 2018). Models generate quantitative, forward-looking scenarios that describe the future behaviour of non-linear socio- technical systems and quantify the associated uncertainties (Huntington et al., 1982; Millner and McDermott, 2016; Moallemi et al., 2017b; Moallemi and Malekpour, 2018).

Three types of computational models are used in the context of energy and low-carbon transitions: first, Integrated Assessment Models of climate change (IAMs), which are the global-level models that aim to support climate policy by bridging long-term climate goals and the evolution of the economy, technology and the environment. IAMs are extensively used in the IPCC reports (Rogelj et al., 2018). Second, Energy System Models (ESMs) which can be applied at all spatial scales, from a city to the global level, and can quantify the transition of energy systems with the focus on technical feasibility and energy-economy-environment-policy interactions (DeCarolis et al., 2017; Hourcade et al., 2006). Third, Socio-Technical Transition models (Li et al., 2015), such as Socio-Technical Energy Transition (STET) models, System Dynamics (SD) or Agent-Based Models (ABMs), aim to model the co-evolution of tech- nology and society, e.g. including behaviour and interactions of various actors.

Transitions theories and frameworks enable the analysis of sustainability innovations within a broad context and with the explicit focus on actors and dynamic pathways (Geels et al., 2016). A number of analytical frameworks exist that act as heuristics to represent the complexity and multi-dimensionality of sustainability transitions and shifts in socio-technical systems (Köhler et al., 2019). The main frameworks reported in detail by Köhler et al. (2019: 4) include the *Multi-Level Perspective (MLP)* (e.g. Geels, 2002; Rip and Kemp, 1998), the *Technological Innovation System* approach *(TIS)* (e.g. Bergek et al., 2008; Markard et al., 2015), *Strategic Niche Management (SNM)* (e.g. Rip and Kemp, 1998; Schot and Geels, 2008), and *Transition Management (TM)* (e.g. Loorbach, 2010; Rotmans et al., 2001). These analytical frameworks frame sustainability transitions as the evolution of socio-technical processes, and provide big-picture insights for long-term energy and low-carbon transitions and cover the role of actors and their interactions, cultures, practices, innovation development and implementation, governance arrangements and so on (Geels, 2012, 2002; Rip and Kemp, 1998; Sovacool and Hess, 2017). As these considerations are typically oversimplified or even excluded from the models, transitions theories or frameworks provide an essential and complementary view to transitions. The MLP on transitions has become a prominent analytical framework in transition research (Köhler et al., 2019; Rauschmayer et al., 2015; Svensson and Nikoleris, 2018) and, as we will later show in this systematic review, it was also the most popular framework to be used in combination with modelling.

In the last ten years, an integrative thread of energy and climate research has emerged that links quantitative models and transitions theories or frameworks (Cherp et al., 2018; Geels et al., 2016; Köhler et al., 2019; Moallemi and de Haan, 2019). On the one hand, modelling has been increasingly applied in transitions research for various conceptual analyses using for example the MLP and TIS frameworks or evolutionary approaches (Holtz et al., 2015; Papachristos, 2011; Papachristos and Adamides, 2016; Safarzyńska et al., 2012; Safarzyńska and van den Bergh, 2013, 2011, 2010; Walrave and Raven, 2016) as well as to sustainability transition cases (Geels et al., 2015; Köhler et al., 2018b; Moallemi and Malekpour, 2018; Papachristos and Adamides, 2016; van Sluisveld et al., 2018). On the other hand, linking computational models and transitions frameworks to study energy and climate topics is suggested as a strong and complementary way to address the complex and uncertain co-evolution of society, technology, the economy and the environment and increases the knowledge of socio-technical transitions (see e.g. Geels et al., 2016; Li et al., 2015; Li and Strachan, 2017; Papachristos, 2014; Trutnevyte et al., 2019). This new research thread has fostered tumultuous discussions, in particular why, when and how these two approaches can be brought together and which methodological strategies are appropriate. The degree of integration may vary depending on the model employed: ABM approaches integrate actors, Socio-Technical Energy Transitions models focus on the temporal dimension and path-dependencies, whereas the integration with existing models, like global IAMs, is the most challenging.

Although the body of this integrative literature is clearly growing, an overview is still missing. Earlier reviews have focused on the field of sustainability transitions (Markard et al., 2012), reviewed existing modelling approaches and their ability to address key aspects of transitions (Köhler et al., 2018a), provided a taxonomy of STET models at the interface of energy modelling and socio- technical transitions (Li et al., 2015), and looked at linking ABMs (Hansen et al., 2019) or system dynamics models with transition theories (Mekhdiev et al., 2018). No existing review, however, systematically reflected on what integrative research has done so far in the case of energy transitions and climate mitigation strategies. In the present study, we carry out a systematic literature review of this emerging body of integrative literature with a particular focus on applications in the energy and climate fields, and we then point to the remaining issues for future research.

The paper is structured in the following way: in Section 2, we outline the methodology of the literature search and analysis; in Section 3, we overview the latest status and trends in projects and publications; in Section 4, we present the three main categories of aims that have been used to justify the need to link models and transitions theories or frameworks to study climate mitigation strategies and energy transitions cases, and then assess whether the intended aims were subsequently fulfilled in the findings and conclusions; in Section 5, we analyse the methodological strategies employed for choosing frameworks, applying models, and linking them together; in Section 6, we discuss our findings and propose directions for the future research needs.

2. Methodology

A systematic literature search was designed in order to be replicable and reduce bias. We searched the Institute for Scientific Information (ISI) Web of Science platform with pre-defined keywords that were organised into three layers. The first layer contained keywords related to transitions theories and frameworks that study the co-evolution of social, technical, environmental, and other systems (Geels, 2018a). The chosen keywords with logical operator OR were: socio-technical transition, sociotechnical transition, socio-technical energy transition, societal transition, societal transitions, multi level perspective, multi-level perspective, MLP, sus- tainability transition, sustainability transitions, sustainable theory, sustainability theories, transition pathways, transition theory, transition theories, energy system transition, energy system transitions, narrative, storylines, scenarios, socio-technical scenarios, sociotechnical scenarios. The second layer of keywords related to computational modelling, referring to a broad range of models, such as IAMs, ESMs, STET, and so on (DeCarolis et al., 2017; Li et al., 2016). The keywords with logical operator OR were: modelling, modeling, quantitative, quantitative modelling, quantitative modeling, model, scenarios, simulation, energy system modelling, en- ergy system modeling, energy systems analysis, techno-economic. The third layer contained keywords that refer to energy transitions and climate change mitigation strategies and which were also linked with the logical operator OR: energy, climate, mitigation, renewable, electricity, power, low-carbon, emissions, carbon, transport. The three layers of the search criteria were connected with the logical operator AND in order to find any article that contained at least one keyword from each layer.

We restricted the initial literature search to the period from 2008 to 2018. The search first produced 1077 papers. The second screening involved two successive abstract analyses, each carried out by two independent researchers in order to find literature that involves both modelling and transitions theories to study climate- or energy-related topics. This narrowed down the selection to 31 papers. As the search was conducted in July 2018, it does not include any papers added to the ISI Web of Knowledge later. Two relevant studies from 2019 (Köhler et al., 2019; Li and Strachan, 2019) were therefore added manually. We made sure that eight studies (De Cian et al., 2016, 2018; Geels et al., 2018a; Köhler et al., 2018b; Rogge et al., 2018; Turnheim et al., 2015; van Sluisveld et al., 2016, 2018) from the H2020 *PATHWAYS* project's website were added too because this project was identified as one of the key projects in the field (Section 3.1), and not all its publications were available on the ISI Web of Knowledge. Finally, three more relevant papers we were aware of were also added manually (Karslen et al., 2019; Köhler et al., 2009; Papachristos, 2018a). The final number of papers analysed was 44.

We then carried out a detailed analysis of the identified papers in a four-step process, which consisted in reporting the nature of the articles (step 1), uncovering the aims and delivered outcomes of the papers (step 2), analysing the main methodological strategies (step 3), and identifying the limitations and future research needs (step 4) (Table 1). For most of the analysis, we focused on all 44 papers identified in the search. In step 2, we defined a subset of 35 papers, only encompassing studies that practically tried to link quantitative models and socio-technical transitions theories, and hence excluding general and review papers. In step 3 (specifically see

Section 5.3.1), we also focused on this subset of 35 papers that carried out a linking exercise *and* proposed concrete re- commendations for transitions pathways towards meeting energy and/or climate targets. In step 4, we identified some limitations and suggested future research opportunities for this integrative field of study, when applied to energy transitions and climate mitigation strategies.

Table 1. Four-step procedure to analyse the identified studies.

Step 1: Reporting the nature of the papers	- Trends in publications and projects - Background of the authors - Scope (i.e. energy or climate mitigation) - Temporal and spatial foci
Step 2: Uncovering the aims and delivered outcomes	- Aims and justification for linking theory and modelling - Actual outcomes and empirical findings from linking
Step 3: Summarizing the methodological strategies	- Application of models - Choice of an analytical framework - Methodological strategies of integrative research
Step 4: Limitations and future research needs	- Limitation(s) - Future research needs

3. Results: General trends

3.1. Trends in publications and projects

We observed a clear increase after 2013 in the number of publications that link quantitative modelling and transitions theories or frameworks in energy and climate research (Fig. 1). The increase in the number of publications is connected to major inter- disciplinary projects that took place over the last 10–15 years: the *MATISSE* project (6th Framework programme, 2005–2008) that sought to develop prototypes of models to understand, assess, and support transition processes; the *Transitions Pathways* (TP) project (UK EPSRC and E.ON UK, 2008–2012) that investigated transitions towards the UK low-carbon electricity system using historical insights and a forward-looking qualitative and quantitative approach; the *Realising Transitions Pathways* (RTP) project (UK EPSRRC, 2012–2016) that continued the legacy of TP project and addressed the energy policy "trilemma" of delivering low-carbon, secure and affordable energy services for the UK; and the *PATHWAYS* project (7th Framework Programme, 2013–2016) that investigated possible transitions to a low-carbon and sustainable Europe.

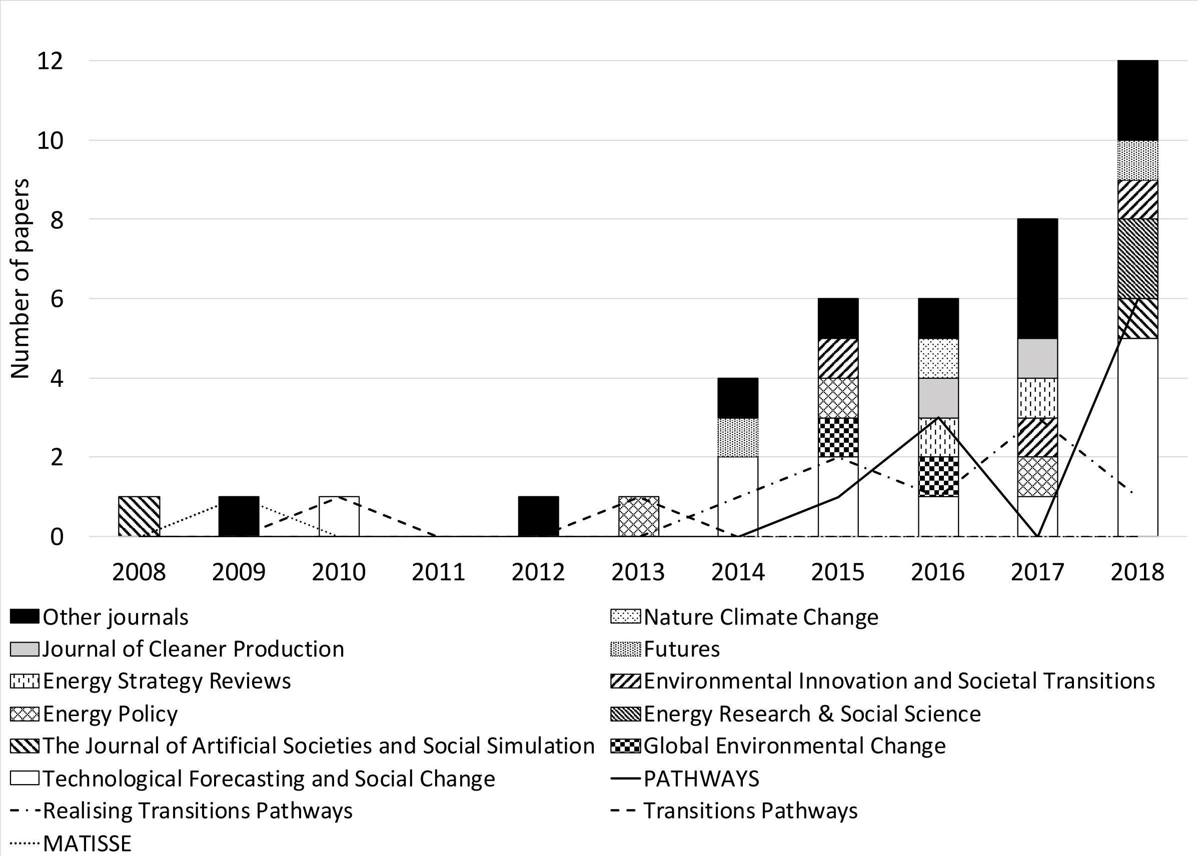

Figure 1. The identified trends in papers, projects and journals.

The 44 identified papers were published in 20 different peer-reviewed journals and 11 journals published at least two studies (Fig. 1). Most of the papers were published in *Technological Forecasting and Social Change* (12 articles) that focusses on methodologies and practices in relation to technological forecasting and future studies linking environmental, technological and social factors (Elsevier, 2019)

3.2. Background of the authors

The papers analysed suggest that linking models and transitions theories or frameworks is attracting a diverse range of scholars, however we notice that many authors have a background in social science-related disciplines. Indeed, we found that 13 % of the authors had a background in energy system modelling, 5% in IAMs and 18 % in other types of modelling (e.g. ABM, system dynamics or economic modelling). Twenty-two percent of the authors had a background in socio-technical transitions theories, 29 % in in- novation studies and 22 % in various other disciplines from social sciences and humanities (e.g. behavioural economics or economic geography).

We also observed that the absolute majority of the authors are based in Europe, which is in line with the fact that the afore- mentioned projects have been conducted in Europe and primarily funded by EU member states or the EU (Section 3.1).

3.3. Scope, temporal and spatial foci of the studies

More than half of the analysed papers addressed the potential and challenges associated with the decarbonisation of different systems (Fig. 2A): 29 % on power (electricity) systems (e.g. Trutnevyte et al., 2015), 12 % on whole energy systems (e.g. Li et al., 2016), 14 % on transport systems (e.g. Köhler et al., 2009), and only a small share (4%) on heating systems. Hence, these papers did not yet cover other parts of the climate challenge. Another small share of the analysed papers (2%) addressed international shipping. Thirty-nine percent of the papers were not assigned to a specific area as their contributions were methodological, conceptual or theoretical, or they were review papers.

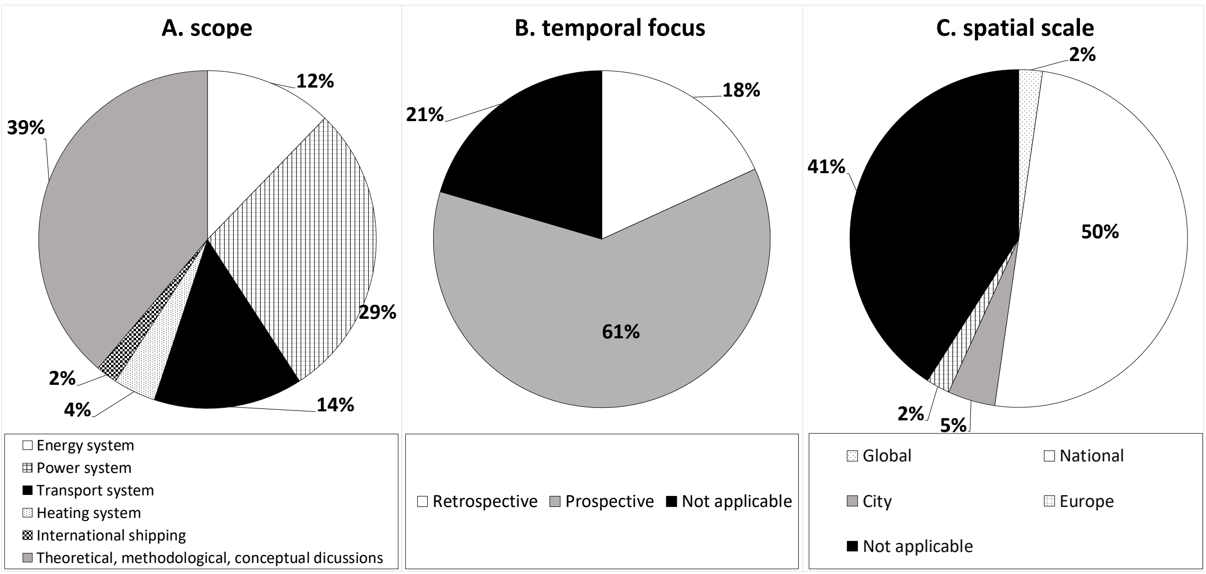

Figure 2. The scope (a), the temporal focus (b) and the spatial focus (c) of the reviewed studies (N=44).

Half of the papers focused on a national level (Fig. 2C), e.g. addressing the transition of the power system in the UK (e.g. Foxon, 2013). Only a few studies focused on smaller scales (e.g. 5% cities) or larger scales (Europe, 2% and global 2%). Forty-one percent of the papers were methodological, theoretical or conceptual contributions and reviews, and did not focus on a specific scale. They were therefore placed in the "non applicable" category in Fig. 2C.

As shown in Fig. 2B, slightly over 60 % of the papers were prospective analyses that are common practice in modelling studies (Trutnevyte, 2016), e.g. investigating future transition pathways towards a low-carbon electricity sector to 2050 (Foxon, 2013; Geels et al., 2018a; Trutnevyte et al., 2015). Since transitions theories or frameworks alone are typically used in retrospective rather than prospective analyses (DeCarolis et al., 2017; Trutnevyte, 2016), the reviewed integrative research that links modelling and transition theories seems to have helped to apply the transitions theories or frameworks in a prospective manner. On the other hand, modelling was rarely applied in a retrospective manner in the reviewed papers (slightly less than 20 %, e.g. Bergman et al., 2008). Twenty-one percent of the papers were methodological, theoretical or conceptual contributions and reviews; these papers were neither retro- spective nor prospective studies and were therefore placed in the "non applicable" category in Fig. 2C.

4. Results: aims of the integrative research versus its actual achievements

Most reviewed papers devoted a substantial amount of space in the introduction sections to justify the need to link modelling and transitions theories or frameworks to study energy transitions and climate change mitigation strategies. The review of the arguments of the authors in their introduction sections helped us identify three main categories of aims for this integrative research which was also reported in Trutnevyte et al. (2019): *Solutions to energy and climate challenges, increasing realism* and *interdisciplinary learning*. A single paper at times may have used some or all of these arguments to justify the need for linking models and transition theories or frameworks. In Section 4.1, we present in detail these three categories of aims and provide examples. In Section 4.2, we analyse to what extent these aims were achieved by looking at how the findings and conclusions were reported by the authors of the analysed papers.

4.1. Aims of the integrative research found in the analysed papers

In the top part of Table 2, we present summaries and frequencies of the three main categories of aims (*solutions to energy and climate challenges, increasing realism* and *interdisciplinary learning*) that were used by the authors to justify the need to link models and transition theories or frameworks to study energy transitions and climate change mitigation strategies.

4.1.1. Solutions to energy and climate challenges

The first aim of the authors to justify the need to carry out integrative research is to find *solutions to energy and climate challenges*.

Indeed, there is a recognized and pressing need to tackle ever-growing climate change threats and meet the targets of the Paris Agreement, by developing practical transformative solutions (Holtz et al., 2015; IPCC, 2018; Li and Strachan, 2017; Turnheim et al., 2015). More specifically, authors argue that there is a need to enact and meet an energy- or climate-related target. Approximately half of the total papers articulated this aim (22/44), and slightly over half of the papers in the subset that excluded reviews (57 %) (Table 2).

Table 2. Comparison between the aims of the paper for linking models and socio-technical transitions theories or theoretical frameworks and the actual outcomes.

		Categories of aims		
		Solutions to energy and climate challenges	***Increasing realism***	***Interdisciplinary learning***
Aims in introductions or objectives	***Number of papers***	20/35†; 57% (22/44*; 50%)	23/35†; 66% (30/44*; 68%)	25/35†; 71% (31/44*; 70%)
	Summary of these aims	In light of the climate change challenge and implementation of the Paris Agreement, there is an apparent need to find practical solutions to the energy and climate challenges and not to uniquely identify problems.	There is a need to increase realism in models and transition theories by better accounting for the complexity and uncertainty in transitions.	Both analytical approaches and scholarly communities can learn from each other and circumvent some of their respective drawbacks.
Actual outcomes reported in findings or conclusions	***Number of papers***	10/35†; 29%	23/35†; 66%‡	33/35†; 94%‡
	Examples of reported outcomes	*"The scenarios [from the RTP project] require an assumption that significant volumes of bioenergy will be imported to the UK in future in order for them to be compatible with achieving the UK's national climate policy targets for 2050. The use of bioenergy with carbon capture and storage features strongly in the model solutions, often outside of the power sector for end-use fuel production."* (Li et al., 2016: 27) *"Lifestyle changes are most effective in the end-use sectors, leading to a CO_2 emission reduction potential of about 15% in the residential and 35% in the transport sector compared to baseline emissions."* (van Sluisveld et al., 2016: 317) *"[T]he Market Rules pathway would require annual build rates for carbon capture and storage (CCS) of 1900 MW/year from 2025 to 2035. This would now seem to be at the limit of technical feasibility, given that the UK Government abandoned its £1 billion support for a CCS demonstration plant in 2015."* (Barton et al., 2018: 2788) *"The main strategic insight for governments and communities that arises from this analysis is that the sub-national distribution of energy transition costs can vary significantly depending on the choice of decarbonisation pathway taken. Future technology choices in the power sector bring with them strong regional implications for future investment targeting, suggesting the possibility of there being regional winners and losers under different transitions."* (Li et al., 2016: 27)	*"The most critical features are the representation of qualitatively different states and of the normative aspects of change, i.e. that of representing profound or qualitative changes in societal systems including actors, practices, institutions and technologies."* (Köhler et al., 2018a: 16) *"The results show that the dynamics of multiple actors, making non-optimal micro-economic investment decisions, has the potential to derail strategies for deep decarbonisation that assume cost optimal choice behaviour and render ambitious GHG reduction targets extremely difficult to achieve."* (Li, 2017: 68) *"It is, therefore, suggested to link this transitions model to an energy performance model with more technical details to present a more balanced picture of energy transitions and to attain a deeper understanding of their dynamics."* (Moallemi et al., 2017a: 1223) *"By operationalising conceptual interaction between MLP [multi-level perspective] and IAM, we have introduced a new analytical method to bridge the gap in qualitative and quantitative assessment of low-carbon transitions and propagated a new way to study and include more realistic emerging trends in futures studies."* (van Sluisveld et al., 2018: 9)	*"[W]e have demonstrated the innovative nature of the mobility transition model, in particular its capacity to consider many alternative innovations together, to reflect the complex interactions between regime and niches, and to represent social and institutional factors along with technologies in a simulation of radical socio-technical change."* (Köhler et al., 2009: 2994) *"While the storyline is important for transmitting information about governance and the choices of key actors, many targets aspired in it are inconsistent with modelling results."* (Trutnevyte et al., 2014: 26) *"This dialogue between modelers and transition scholars improved the latter's awareness of 'whole system' challenges and the need to go beyond purely critical discussions of models (which characterizes many environmental social scientists). The dialogue also increased awareness of the high plasticity of computer models and the degree to which parameters can be adjusted (what modelers in meetings called 'kicking the models') to achieve particular pathways."* (Geels et al., 2018: 13) *"A fundamental requirement for identifying and addressing the multiple challenges and opportunities posed by energy policy and climate change necessitates a combination of academic knowledge with that from industry, commerce, regulatory bodies, political and societal communities."* (Chilvers et al., 2017: 473)

† 35 corresponds to the number of papers where the authors addressed one or more of the three aims directly in their findings or conclusions. Therefore, the general or review papers were excluded in this subset of 35. The percentage value corresponds to the share of articles relative to the 35 studies.
* 44 corresponds to the total number of papers in our review. The percentage value corresponds to the share of articles relative to the 44 studies.

This need to find solutions is nicely depicted by Geels et al. (2016) who evoke a shift in the climate change debate, moving on from identifying problems to discussing potential solutions. In other words, there is not only a methodological challenge for tran- sitions studies (i.e. moving towards discussing solutions), but this may also entail a need to define clear and practical technological, political, social and other types of measures to meet the targets like the Paris Agreement's 2 °C target. It is within this background of moving towards identifying solutions that collaborative work appears to be useful and becomes an aim of this integrative research. The combination of modelling and transitions theories or frameworks enables forward-looking perspectives and seeks pragmatic means to foster transitions, embracing the numerous aspects involved in such processes (Auvinen et al., 2015; Hoekstra et al., 2017; Li et al., 2016).

4.1.2. Increasing realism

The second category of arguments that were used by the authors to justify the need to carry out integrative research shows the willingness to increase realism in models and socio-technical transitions theories so that models and theories are better in line with observable real-world dynamics (30/44, 68 % of the subset of papers; Table 2). The arguments of the authors in the analysed papers suggested that in order to increase realism, the complex and uncertain nature of transitions must be addressed by painting a robust and complete picture of the process (Turnheim et al., 2015). By complex nature of transitions, authors understood the need to account for the fact that transitions entail interactions and interrelations between multiple scales and domains (e.g. political, economic, social, technological) (Auvinen et al., 2015; Geels et al., 2016), that the critical features of transitions need to be uncovered (e.g. changes in actors, practices, institutions, etc.; see De Cian et al., 2018; Köhler et al., 2018a; van Sluisveld et al., 2018). By uncertain nature of transitions, authors understood the need to account for the contingency of transitions (Li, 2017; McDowall, 2014; Moallemi and Malekpour, 2018; Robertson et al., 2017; Turnheim et al., 2015).

The realism in models can be described as models being informed by and able to reproduce broad patterns and uncertainties from real-world transitions (Beven, 2002; Millner and McDermott, 2016; Trutnevyte, 2016), instead of models being used in a predictive way (Huntington et al., 1982). The lack of realism in current models is often linked to the models' boundaries, structures and assumptions, e.g. when models are based on assumptions of neoclassical economics for representing actor behaviour (Li et al., 2015; Moallemi and Malekpour, 2018). Naturally, models make a number of simplifying assumptions resulting in a reductionism of reality (Geels et al., 2016; Li et al., 2015; Li and Strachan, 2017; Moallemi and Malekpour, 2018). Although some socio-technical inter- actions can be covered in models and in associated storylines, models only delineate a partial picture of the real-world transitions, potentially over-simplifying political, institutional and social change (van Sluisveld et al., 2018).

4.1.3. Interdisciplinary learning

The third aim, and thus the third category of arguments that were used by the authors to justify the need for linking models and theories or theoretical frameworks, is to benefit from the opportunities of interdisciplinary learning between scholarly communities of modellers and transitions theorists (31/44; 71 % of the subset of papers; Table 2). Indeed, authors argue that both models and socio-technical transitions theories are potentially mutually informing approaches for the analysis of transition processes (see e.g. Köhler et al., 2018b). Individually, they cannot paint a global picture of the transition and therefore need to be brought together to get a better overall understanding. For example, Geels et al. (2016) describe the potential of linking both approaches as follows: on the one hand, modelling has strong analytical strengths; on the other, important information on transitions can be provided by social science approaches. Combined, any potential over- or underestimation of a particular aspect can be lessened (De Cian et al., 2016; Li and Strachan, 2017; Robertson et al., 2017; Trutnevyte et al., 2014; Turnheim et al., 2015). In other words, these complementary approaches integrate social-related dynamics and technological and environmental constraints of low-carbon pathways (Barton et al., 2018) and thus suggests that both approaches can inform each other to help to circumvent their respective drawbacks (Auvinen et al., 2015; Geels et al., 2016; Holtz et al., 2015; Li et al., 2015; Papachristos, 2018a).

4.2. Reported outcomes of the integrative research and how they compared with the aims

We now turn to the findings and conclusions sections of the analysed papers, where we investigated whether and how the three aforementioned aims were achieved in the actual outcomes. Here, we focus on the subset of 35 papers, where the general and review papers are excluded. As shown in Table 2 and Fig. 3, the papers overwhelmingly delivered benefits in the category of *interdisciplinary learning*, to a lesser extent in the category of *increasing realism*, and much more rarely in the category of *solutions to energy and climate challenges*. We describe and interpret these findings below.

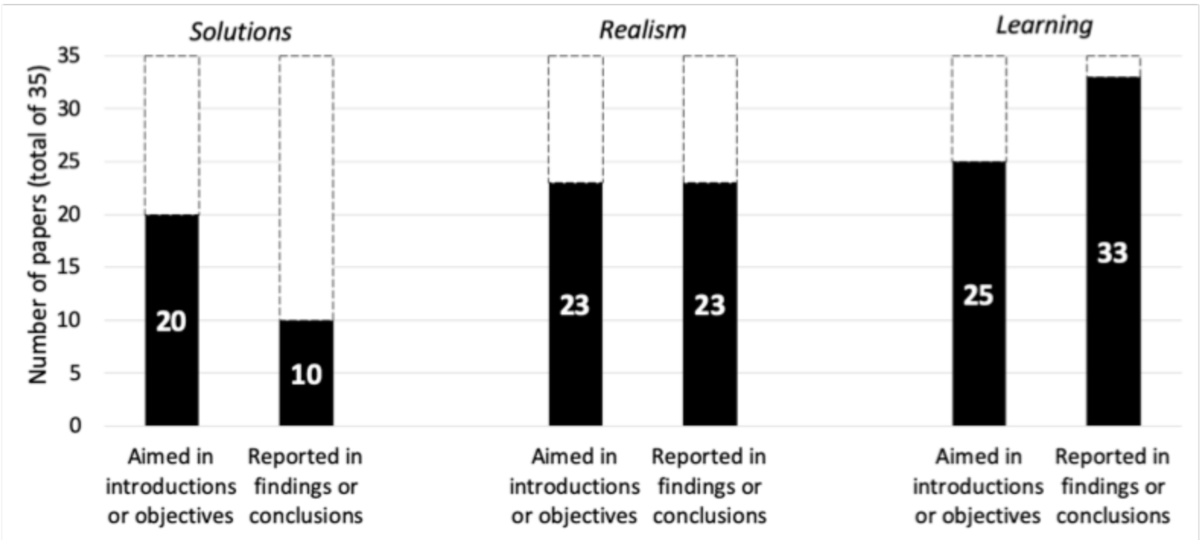

Figure 3. Comparison of the *solutions to energy and climate challenges*, *increasing realism* and *interdisciplinary learning* arguments in the introduction sections of the integrative research versus actually reported findings and outcomes from this research. Note: black areas represent the number of papers, out of the total of 35, where such aims or findings are reported.

4.2.1. Achievements in relation to the solutions to energy and climate challenges category

Despite the aspirations to contribute to the *solutions to energy and climate challenges* category by linking models and transitions theories or theoretical frameworks, only a very limited number of papers (29 %, Table 2 and Fig. 3) actually managed to do so by suggesting concrete recommendations for energy transitions and climate mitigation strategies. This is an intriguing and interesting finding that we wish to underline and highlight in this study: in light of the context of the climate urgency in which transition studies and models are immersed in, there are only few examples of integrative research addressing this need to find solutions in a practical way and demonstrating new insights on how to reach energy and climate targets. In addition to that, most of the conclusions in the reviewed papers focussed on the evolution of technologies with only few studies devoting space to social transitions.

Among the few fruitful examples, van Sluisveld et al. (2018) revealed the high, but limited contribution of behaviour change in the transition towards meeting the European emissions reduction targets. Geels et al. (2018a) identified key transition bottlenecks, e.g. social acceptance or political feasibility, for the UK electricity system transition towards the 2 °C target. Rogge et al. (2018) showed that the German Energiewende in the electricity sector would unfold differently in a new-entrant-friendly pathway or in an incumbent-dominated pathway. Köhler et al. (2009) concluded with the need for hydrogen fuel cell vehicles in the long-term for a realistic shift towards low-carbon mobility. Trutnevyte et al. (2015) investigated the total costs of and investments into the electricity sector for reducing the UK emissions by 2050 under different governance arrangements. They showed that market-led governance would entail the smallest investment costs by 2050, whereas the transition lead by wide societal participation would mean higher investments and total systems costs. Building on the latter study, Li et al. (2016) showed that the choice of UK decarbonisation pathways would lead to substantially different transition costs across the various regions in the UK. Barton et al. (2018) then showed that these aforementioned UK decarbonisation pathways would be consistent with the technology building rates of the UK Government's *Carbon Plan* scenarios (DECC, 2011).

4.2.2. Achievements in relation to the increasing realism category

Many papers intended to *increase realism* in models or theories and about two thirds of them reported related outcomes in their findings or conclusions (66 % and 66 % in both cases; Table 2 and Fig. 3). However, the actual recommendations on how to increase realism remained vague and tentative with only few studies providing concrete suggestions. In the following lines, we present two types of findings to increase realism in models and theories: general and concrete findings. In terms of general findings to improve realism in models and theory, Trutnevyte et al. (2014) argued that more robust energy scenarios could be created by testing qua- litative transition storylines against multiple energy models, each representing an own field of expertise. Other papers made more conceptual and methodological suggestions: Winskel et al. (2014) introduced a learning pathways framework in order to better understand the emergence of innovation niches with regard to so-called technology fields (e.g. how they react to radical or incre- mental innovations). Papachristos (2018a) proposed the concept of retroduction as a methodological approach towards grasping patterns and mechanisms in transitions. Robertson (2016) employed a backcasting perspective in order to identify the necessary steps towards fulfilling a desired energy target.

In terms of concrete and practical findings, several elements from transitions theories and frameworks were found to need better representation in models to increase realism (Moallemi et al., 2017a; Papachristos, 2014). Li (2017) and Li and Strachan (2017) called for a better representation of actors, as they found that actor inertia could significantly impede on climate mitigation efforts. De Cian et al. (2018) further provided a detailed account of potential avenues to better represent actors, decision making and institutions by refining models. Another customary approach was to adjust the key parameters in models, such as demand as- sumptions that are proxies for behavioural change, in order to increase the realism of models (van Sluisveld et al., 2016; Köhler et al., 2018b).

4.2.3. Achievements in relation to the interdisciplinary learning category

Ninety-four percent of the subset of 35 papers concluded that linking quantitative modelling and transitions theories or frame- works leads to a better understanding of the mechanisms and dynamics that underlie transitions, as well as a better understanding of the functioning of both scholarly communities. Authors reported multiple learning outcomes in terms of empirical, methodological and theoretical findings. Interestingly, more papers concluded that they observed these mutual learning benefits in comparison to the number of papers that aimed for these benefits in the introductions or objectives (Table 2 and Fig. 3).

Linking exercises and thus scientific collaborations in the reviewed papers are also perceived as a way to provide more pertinent information for scientific research, policymaking and action (Cherp et al., 2018; Geels et al., 2018a, 2016; Papachristos, 2014; Rogge et al., 2018; Turnheim et al., 2015). Indeed, many papers began by re-stating the shortcomings of socio-technical theories and models and then argued that both could be an opportunity to improve the overall approach to transitions (Auvinen et al., 2015; Bergman et al., 2008; McDowall, 2014; Moallemi et al., 2017b; Trutnevyte et al., 2014; Turnheim et al., 2015). For example, Trutnevyte et al. (2014) used models to uncover inconsistencies in qualitative storylines lines, thus illustrating the potential complementarity between both approaches (Papachristos, 2018a) and the potential for co-production of knowledge (Auvinen et al., 2015; Chilvers et al., 2017; Geels et al., 2016). Many papers also argued that linking approaches enabled the integration of an increased number of relevant transition elements and increased the knowledge on transitions (Auvinen et al., 2015; Bergman et al., 2008; Geels et al., 2018a; Li, 2017; Li and Strachan, 2017; Mercure, 2015; Papachristos, 2014; Robertson, 2016; Trutnevyte et al., 2015). For example, Robertson (2016) stated that linking approaches allowed placing technology diffusion into a wider social context and thus depicting more thoroughly transitions dynamics (Köhler et al., 2009; Moallemi et al., 2017a) and the causal relationships between different facets of the dynamics in transitions (Papachristos, 2014).

Another interdisciplinary learning outcome in these studies was linked to methodological insights and prospects, as methodological innovations are deemed necessary to favour collaborations between scholarly communities (Geels et al., 2018a; Robertson, 2016; van Sluisveld et al., 2018). One suggestion was to develop “methodological aids”, e.g. transitions bottlenecks in Geels et al. (2018a) and Rogge et al. (2018) or storyline and simulation approaches in Trutnevyte et al. (2014), to act as a form of mediator between models and theory, allowing a form of dialogue between the two (see also Section 5). Another general suggestion was to be more open and transparent regarding a model’s development and use in order to better understand the mechanisms behind models and how specific aspects of transitions are addressed (Köhler et al., 2018a).

Finally, linking both models and theory has theoretical ramifications. Some of the discussion has focussed on the extent to which both approaches may be integrated (see e.g. De Cian et al., 2016; Geels et al., 2018a, 2016; Turnheim et al., 2015). Geels et al. (2016), for example, argued that IAMs and the MLP on socio-technical transitions are ontologically different and consequently a complete integration is unfeasible.

5. Results: methodological strategies for applying models, analytical frameworks, and linking them

We analysed the methodological strategies in the reviewed literature on linking models and transitions theories or frameworks by looking at the application of models (Section 5.1) and frameworks (Section 5.2), and at their linking strategies and their benefits in relation to the categories of *solutions to energy and climate challenges*, *increasing realism*, and *interdisciplinary learning* (Section 5.3). The summary of the review is shown in Table 3.

Table 3: Methodological strategies in the reviewed literature: choice of models, transitions theories and frameworks, and linking strategies (Note: one study could have applied several linking strategies)

Linking approach	Choice of the theories or theoretical frameworks	Model(s)	References; project
Iterating	Storyline with the focus on governance and key actors	5 ESMs, one STET, one economic appraisal, and one environmental appraisal models	Trutnevyte et al. (2014); RTP
	MLP on transitions with the focus on decision making	STET (System dynamics)	Auvinen et al. (2015); other
	Storylines with the focus on governance, key actors and technological and behavioural developments	ESM	Trutnevyte et al. (2015); RTP
	Role of learning in transition dynamics	IAM	De Cian et al. (2016); PATHWAYS
	MLP on transitions and socio-technical scenario tool	Life-cycle assessment	Robertson (2016); other
	Storylines with the focus on transition dynamics	STET (System dynamics)	Moallemi et al. (2017a, 2017b); other
	Storylines with the focus on governance, key actors and technological and behavioural developments	ESM	Robertson et al. (2017); RTP
	Socio-technical storylines	STET (ABM) and ESM	McDowall (2014); other
Bridging	Socio-technical transitions analysis (through the MLP on transitions in particular) and practice-based action research	IAM	Geels et al. (2016); PATHWAYS
	Storylines with the focus on governance, key actors and technological and behavioural developments	ESM	Li et al. (2016); RTP
	Storylines based on MLP and so-called transition bottlenecks	Two IAMs and one ESM	Geels et al. (2018); PATHWAYS
	MLP on transitions with the focus on niche-regime interactions and behavioural change	STET (ABM)	Köhler et al. (2018b); PATHWAYS
	MLP on transitions with the focus on retroduction	-	Papachristos (2018a); other
	MLP on transitions with the focus on business dynamics, business models, technology competition and diffusion, and organisational change	STET (System dynamics)	Papachristos (2018b); other

	MLP on transitions and so-called transition bottlenecks	Two IAMs and one ESM	Rogge et al. (2018); PATHWAYS
	Storylines based on MLP with the focus on lead actors, scope and depth of change, niche momentum, and system inertia	IAM	van Sluisveld et al. (2018); PATHWAYS
Merging	MLP on transitions with the focus on interactions of individual actors and sub-systems, and cumulative effects on system structures.	STET (ABM and system dynamics)	Bergman et al. (2008); MATISSE
	MLP on transitions with the focus on actors	STET (ABM and system dynamics)	Köhler et al. (2009); MATISSE
	Standard demography theory applied to technology and multi-technology competition perspective	Economic modelling	Mercure (2015); other
	Storylines with the focus on governance, key actors and technological and behavioural developments	ESM	Trutnevyte et al. (2015); RTP
	Complexity and behavioural sciences for actor heterogeneity	Economic modelling	Mercure et al. (2016); other
	Assumptions on behavioural and lifestyle changes	IAM	van Sluisveld et al. (2016); PATHWAYS
	Transition management, agent-based economics, and disruptive innovation	STET (transition management)	Hoekstra et al. (2017); other
	MLP on transitions with the focus on actors with differentiated behaviours	STET	Li (2017); other
	MLP on transitions with the focus on actors and institutions	STET	Li and Strachan (2017); RTP
	MLP focussing on government-led and societally-driven pathways	STET	Li and Strachan (2019); other
	MLP on transitions with the focus on causal mechanisms and transition dynamics	Participatory modelling	Ulli-Beer et al. (2017); other
	Storylines, initiative-based learning, applied economics with the focus on actors, decision making and institutions	Two IAMs, one ESM, one STET (ABM)	De Cian et al. (2018); PATHWAY
	Storylines based on the MLP on transitions with the focus on societal needs	Participatory exploratory modelling	Moallemi and Malekpour (2018); other
	MLP on transitions with a focus on policies which could remove barriers in the shipping sector	STET (ABM)	Karslen et al. (2019); other

5.1. Application of models

We identified two main trends regarding the choice and application of models: first, the use of an existing model applied within the context of the study and, second, the development of a new model that is structured and informed by transitions theories or frameworks and that is also built within the context of the study. An overview of the models employed in the identified studies is shown in Table 3.

There are a number of existing models, such as the aforementioned IAMs, ESMs, and STET models, that have been used for energy and climate transition studies. Using an existing model signifies taking into consideration its specific field of quantitative, forward- looking expertise and applying this expertise for understanding future transitions (Geels et al., 2016; Holtz et al., 2015; Köhler et al., 2018a). Specifically, in the case of ESMs and STET models, Trutnevyte et al. (2014) showed that models have so-called different fields of expertise in terms of spatial, temporal and disciplinary foci. As one model is rarely sufficient to understand and quantify all the relevant aspects of transitions, multiple models can be used and compared. This type of understanding of models allows identifying the appropriate models or families of models regarding the research question and objectives of the particular study, and then clarifies the way the model may be linked with a socio-technical framework.

Developing new models within the context of the analysed study mainly meant that these new models were inspired and structured by transitions theories and frameworks and were mostly STET models, including ABM (Moallemi et al., 2017a, 2017b). The STET models were reviewed in depth by Li et al. (2015) and the authors then developed the Behaviour, Lifestyles and Uncertainty Energy (BLUE) model for the UK low-carbon transition with the simultaneous coverage of techno-economic detail, actor hetero- geneity, and transition pathway dynamics (see e.g. contributions from Li, 2017; Li and Strachan, 2017). The ABM approach was used, for example, by Haxeltine et al. (2008), Bergman et al. (2008), and Köhler et al. (2009). The authors developed a model to address transitions in the sustainable mobility sector, combining ABM with a system dynamics structure. Other approaches for building models in the reviewed papers included creating models that build on theoretical frameworks stemming from agent-based economics, disruptive innovation and transition management (Hoekstra et al., 2017), system dynamics simulation (e.g. Moallemi et al., 2017a, 2018b; Papachristos, 2018a, 2018b), participatory modelling with various stakeholders in the model's design process (Moallemi and Malekpour, 2018; Ulli-Beer et al., 2017), and modelling of complexity dynamics and agent heterogeneity (Mercure et al., 2016).

5.2. Choice of socio-technical transitions theories and frameworks

Socio-technical transitions theories encompass a wide range of theoretical frameworks (Köhler et al., 2019; Markard et al., 2012), with the so-called MLP on socio-technical transitions as one of the most popular conceptual frameworks (Köhler et al., 2019). Most studies in the present work analysed and elaborated transition storylines based on the MLP (60 % of the subset of 35 papers, see examples in Table 3). They investigated socio-technical elements that play a role in transitions (e.g. Foxon, 2013; Geels et al., 2018a; Köhler et al., 2018b; Papachristos, 2018a; Ulli-Beer et al., 2017; van Sluisveld et al., 2018), or developed storylines of transitions (e.g. Foxon, 2013; Geels et al., 2018a; Li et al., 2016; Papachristos, 2018a; Rogge et al., 2018). The MLP was employed in this regard in the three main projects in this field: TP and RTP (see e.g. Foxon, 2013; Foxon et al., 2010) and *PATHWAYS* (see e.g. Geels et al., 2018a; Köhler et al., 2018b; Papachristos, 2018a, 2018b). Most studies dealt with storylines based on the MLP in their models, whereas only few papers dealt with the actual conceptual modelling of actor behaviour (20 % of the subset of 35 papers, see some examples in Table 3). We also mention here two approaches other than the MLP presented by Mercure (2015) and Mercure et al. (2016). Mercure (2015) suggested a way of drawing from standard demography theory and applying insights to technology and a unit level. Mercure et al. (2016) drew from complexity and behavioural sciences to investigate uncertainty in climate policies (e.g. technological adoption and diffusion).

Our findings predominantly highlight the MLP as the most popular theoretical framework, which appears to confirm its pro- minence in sustainability transitions studies as noted by Köhler and colleagues (2019). To a small extent, these findings may have been induced by our decision to include the MLP in our set of keywords (Section 2), although any other theories and theoretical frameworks would have been anyway picked up with our broad keywords such as socio-technical transitions or sustainability transitions (Section 2). In our review, we focused on interdisciplinary studies between scholarly communities that have adopted different approaches (e.g. De Cian et al., 2018), but excluded the more disciplinary modelling studies like the work on integrating consumer preferences into models (e.g. McCollum et al., 2018).

5.3. Linking strategies and their benefits

Our analysis showed that authors, first of all, seek to establish a dialogue between quantitative models and socio-technical transitions theories using predominantly the MLP analytical framework, but also other theories and frameworks. We specifically focus here on attempts to link transitions theories and quantitative models. In this respect, we find, as reported also in Trutnevyte et al. (2019), that three main strategies are used in the reviewed papers in order to enable interactions between models and transitions theories, which we term in accordance with Trutnevyte et al. (2019): *iterating*, *merging*, and *bridging*. Such terms have been used extensively – and in heterogenous ways – in the literature; in our case, we attribute a specific meaning to them which we explain below. These strategies differ in particular in terms of the level of integration needed of models and transitions theories or frame- works. An overview of the strategies adopted in the different studies can be found in Table 3 and Fig. 4.

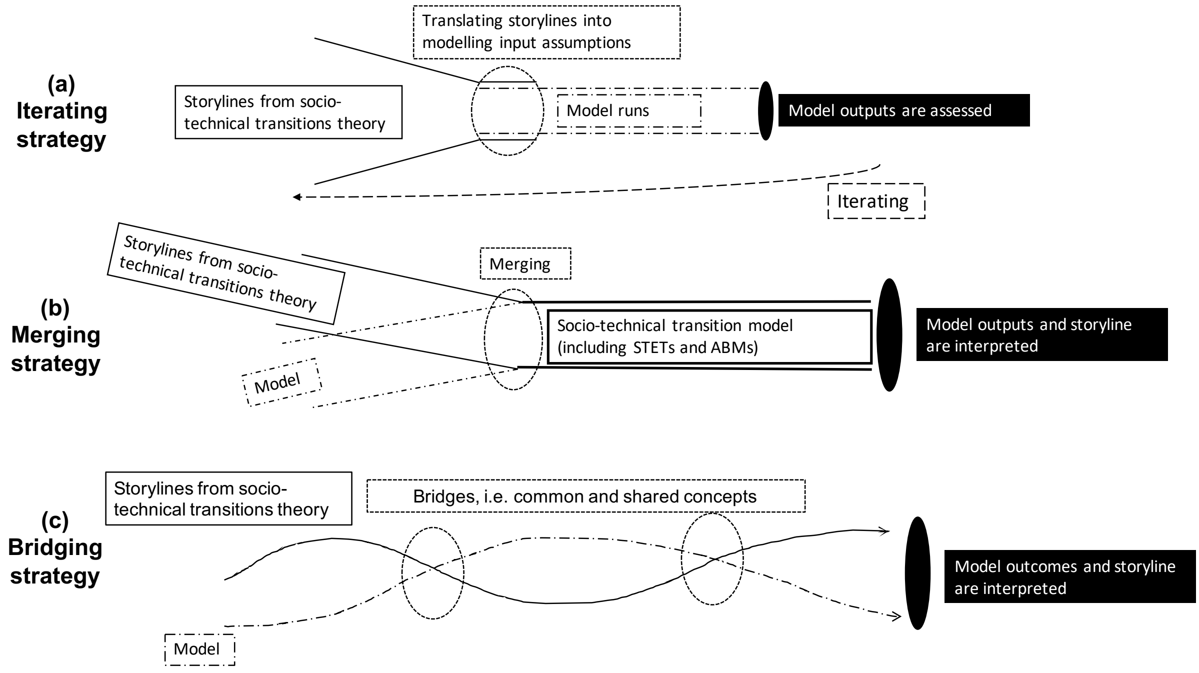

Figure 4. Three methodological strategies for linking models and socio-technical transitions theories and frameworks that were identified in the reviewed literature (a. Iterating, b. Merging, c. Bridging).

5.3.1.Linking strategies: iterating, merging and bridging

The *iterating* strategy consists of transition theory-informed storylines and models that are separate: transitions theories or theoretical frameworks provide broad exogenous storylines, which are used to define quantitative input assumptions to be used by models (Fig. 4a). Model outcomes can then be used to revisit the storylines. This iterating process has been a common approach (McDowall, 2014; Moallemi et al., 2017a, 2017b; Robertson et al., 2017; Trutnevyte et al., 2014) and requires some degree of integration of models and theory. This process emerged from the storyline-and-simulation notion of Alcamo (2008), which occurs in two steps: defining the narrative of a transition and, secondly, translating this narrative into a set of assumptions that serve as inputs for a model. The iterative approach in the literature that we reviewed goes a step further than the conventional storyline-and- simulation. As illustrated for instance in the studies of Trutnevyte et al. (2014) and Auvinen et al. (2015), the outcomes of the quantification strategies and models are used to revise the initial storylines, which in turn can then establish revised assumptions that can again be used in the models.

Through a *merging* strategy (Fig. 4b), storylines and models are brought together to form a model which incorporates socio- technical elements. In other words, there is an implicit assumption that the key transition factors can be modelled. The merging strategy necessitates an in-depth integration of transitions theories and models. We identified two types of merging processes, where insights from socio-technical transitions theories are used either to create new models (e.g. STET models) as we discussed in Section 5.1, or to restructure and reparametrize existing models and substantially improve the representation of socio-technical aspects of transitions in them. The latter process so far focused on an enhanced representation of lifestyle changes (van Sluisveld et al., 2016) or actor dynamics (De Cian et al., 2018; Li and Strachan, 2017), or on identifying parameters within models that could act as proxies (see e.g. De Cian et al., 2018, for a discussion).

In the *bridging* strategy (Fig. 4c), storylines and models are run in parallel and interact only at certain defined moments. For instance, identifying common or shared concepts between models and storylines enables to build so-called bridges between both approaches, allowing them to interact (Geels et al., 2018a; Rogge et al., 2018; van Sluisveld et al., 2018). An implicit assumption here is that some transition factors cannot be modelled. This bridging process was strongly inspired by the studies carried out in the *PATHWAYS* project and in particular the papers of Turnheim et al. (2015) and Geels et al. (2016). This approach necessitates only a limited degree of integration, but leads to an inspection of models and theory to find common grounds where interactions – bridges – can occur and thus requires cross-disciplinary discussions (see e.g. Köhler et al., 2018b). For example, van Sluisveld et al. (2018) identified analytical bridges through shared concepts between the MLP and IAMs on the ways to interpret systemic change (e.g. niche momentum for moving away from the status-quo). Geels et al. (2018a) introduced the concept of transition bottlenecks as a methodological aid, which the authors believe highlights the tensions between modelled and goal-oriented scenarios and MLP analyses. Such analytical tensions, like transition bottlenecks, stem from the fact that models analyse transition pathways that should occur, whereas the MLP analyses why a transition is not occurring and what could be done to overcome transition bottlenecks and provide meaningful and intelligible storylines.

5.3.2.Benefits for solutions to energy and climate challenges

In Table 4, we provide several illustrative examples of which kind of methodological strategy has been used to link modelling with socio-technical transitions insights in order to find solutions to the urgency of climate and energy challenges. Although, as we have shown in Section 4.2.1, only few studies (less than a third) have proposed concrete recommendations in this area, we highlight here the potential benefits of linking both approaches which we believe is an important result.

Overall, our illustrative examples in Table 4 suggest that there is an apparent benefit of linking models and transitions theories and frameworks, as this not only enables a richer assessment of core drivers and barriers in transitions, but also allows capturing their causal relationships. Building on the work of Li and Strachan (2019, 2017), Robertson (2016), and van Sluisveld et al. (2018), the exercise of linking both approaches creates a dynamic web – a structure of interlinked and interrelated elements that influence each other – and hence unveils transition dynamics in practical ways. In line with Li and Strachan (2019), the benefits of the linking approach can be portrayed as a sort of “thought experiment” (Li and Strachan, 2019: 73), where deeply entangled parameters and their dynamics within a model can be compared to real-life political or societal decisions. Conversely, the benefits of linking both approaches are that more tangible associations between transitions drivers and barriers can be established, which provides a wider and more dynamic picture of a transition. For example, Li et al. (2016) found that linking approaches not only directly coupled regional costs and decarbonisation pathway decisions in the UK, but also uncovered the actions that would maximise regional investments and alter the overall costs of the whole system. Li (2017) also showed that behavioural aspects were potentially as important as techno-economic aspects of transitions, concluding that emissions reduction strategies could be significantly affected if behavioural economics and political science insights were better incorporated in models.

Table 4: Illustrative examples of how different factors of transitions are considered in models, socio-technical transitions theories or theoretical frameworks and in the studies that link the two approaches.

Factors that influence transitions	Covered in IAMs	Covered in ESMs	Covered in STET (including ABMs)	Covered in socio-technical transitions theories	Examples of identified benefits from linking models and transition theories	Linking strategy
Technology	Yes	Yes	Yes	Partly	• Helps explain how technologies come to establish themselves by considering multiple socio-technical factors (Köhler et al., 2009, 2018b) • Shows the scale and urgency of deployment needed to fit a particular storyline of transition pathway (Barton et al., 2018) • Puts technology into a context of wider social dynamics (Robertson, 2016)	• *Merging* (Köhler et al., 2009) • *Bridging* (Köhler et al., 2018b) • *Iterating* (Robertson, 2016)
Social acceptance and public controversy	No	No	Partly	Yes	• Provides an explanation why some technologies are not accepted or do not diffuse (Geels et al., 2018)	• *Bridging* (Geels et al., 2018)
Political dynamics	No	No	No	Yes	• Enables to assess potential political resistance that might impede the development of a transition (Köhler et al., 2018b) • Shows the need for radical political commitment to favour transitions (Geels et al., 2018; Rogge et al., 2018)	• *Bridging* (Köhler et al., 2018b; Geels et al., 2018 ; Rogge et al., 2018)
Behaviour, lifestyles and heterogeneity of actors	Partly	Partly	Yes	Yes	• Allows apprehending the role of actors, e.g. governments, and interventions which directly shape transition pathways (Trutnevyte et al., 2015; Köhler et al., 2009; Rogge et al., 2018) • Explains why actor inertia can impede climate action even if there are strong economic incentives (Li and Strachan, 2017) • Shows that, in the short term, lifestyle changes can help avoid partly radical modification of the energy infrastructure (van Sluisveld et al., 2016) • Demonstrates that decarbonisation strategies, based on cost optimal choice, can go wrong in the case of multiple actors making non-optimal micro-economic decisions (Li, 2017)	• *Merging* (Köhler et al., 2009, 2018b; van Sluisveld et al., 2016; Li, 2017; Li and Strachan, 2017) • *Bridging* (Rogge et al., 2018) • *Iterating* (Trutnevyte et al., 2015)
Cultural context	No	No	Partly	Yes	• Accounts for exogenous changes, e.g. growing threats of climate change, which can influence actors' decisions and hence transition pathways (Köhler et al., 2018b; Geels et al., 2018)	• *Merging* (Köhler et al., 2018b)
Governance arrangements	No	No	No	Yes	• Allows apprehending how governance arrangements shape pathway dynamics (Trutnevyte et al., 2015; Köhler et al., 2018b)	• *Bridging* (Köhler et al., 2018b) • *Iterating* (Trutnevyte et al., 2015)
Policies (e.g. feed-in tariffs or carbon prices)	Yes	Yes	Yes	Partly	• Provides an explanation for the positive or negative effects of stability or depreciation of feed-in tariffs (Moallemi et al., 2017a) • Shows that carbon prices alone may not deliver every part of transition, unless coupled with other elements such as behavioural changes (Li and Strachan, 2017)	• *Merging* (Li and Strachan, 2017) • *Iterating* (Moallemi et al., 2017a)
Total and investment costs	Yes	Yes	Yes	Partly	• Assesses in detail the total and investment costs of transition pathways and assess their feasibility (Trutnevyte et al., 2015)	• *Iterating* (Trutnevyte et al., 2015)

Furthermore, the effect of some system elements that play a role during transitions – and that are not necessarily picked up in theories or models alone – are better understood when theories and models are linked, as shown in Table 4. For example, policies, such as carbon price and feed-in tariffs (see Table 4), are often regarded as important drivers of transitions, especially in the model- based analyses. When linking approaches, these elements are placed into a context where it is possible to understand their potential effects or lack of effects (Li and Strachan, 2017; Moallemi et al., 2017a). Li and Strachan (2017) show that even if the UK Government were to increase the carbon price signal to the highest envisaged level by 2050, actor and landscape inertia could nonetheless hinder the efforts towards reaching the carbon emission reduction targets.

According to Table 4, some parameters are better understood or represented when linking models and theory. For example, social acceptance and public controversy (Geels et al., 2018a), political dynamics (Geels et al., 2018a; Köhler et al., 2018b; Rogge et al., 2018), behaviour, lifestyles and the heterogeneity of actors (Köhler et al., 2018b, 2009; Li and Strachan, 2017; Rogge et al., 2018; Trutnevyte et al., 2015; van Sluisveld et al., 2018, 2016) and cultural contexts (Köhler et al., 2018b). The MLP and other analytical frameworks identify these parameters, but use them in rather abstract and theoretical ways. When linked to models and going back to the web analogy, these parameters are placed into a setting with tangible links and the adequate orders of magnitude. For example, van Sluisveld et al. (2016) unveiled tangible links between behaviour changes and mitigation strategies in the context of transition pathways towards meeting the 2 °C target and pinpointed where lifestyle changes could be the most effective (i.e. end-use sectors).

In Table 4, we see that various studies employed different linking strategies (i.e. *merging*, *bridging* and *iterating*), but the benefit from one strategy over another cannot be clearly distinguished, a conclusion also drawn by Hof et al. (2020). We nonetheless observe that all three strategies were employed based on the research question in hand. In other words, in accordance with Trutnevyte et al. (2014), the authors apply a model (whether new or existing) and choose a framework to accompany the model according to the defined research question. The methodological choice, notably, has an important impact on the choice of the linking strategy. For *bridging*, it appears that the process necessitates more clarifications between scholarly communities to identify these so-called bridges (see e.g. Köhler et al., 2018b), but this process may not be as strong when employing *iterating* or *merging* strategies.

5.3.3. Benefits for interdisciplinary learning and increasing realism

The majority of the papers presented general findings that illustrated *interdisciplinary learning* between scholarly communities and contributed to *increasing realism* in models and theory (Table 2; Fig. 3). Here, we present a number of these recurrent general findings that were mentioned across multiple studies. The first general finding with practical implications for energy transitions and climate change mitigation strategies is that a successful transition requires a form of public support throughout the transition process (e.g. Auvinen et al., 2015; Barton et al., 2018; De Cian et al., 2016; Li, 2017; Li et al., 2016; McDowall, 2014; Rogge et al., 2018; Ulli-Beer et al., 2017). Some elements may favour this support, e.g. high awareness of environmental degradation (Auvinen et al., 2015; De Cian et al., 2016; Köhler et al., 2009; Li, 2017; van Sluisveld et al., 2018), but others may impede it, e.g. high costs (Foxon, 2013; Geels et al., 2018a; Trutnevyte et al., 2014). The second finding is that businesses and industries also shape transitions (Barton et al., 2018) and have the potential to change the structure of the landscape of businesses, markets and industries (Chilvers et al., 2017).

The first general finding with implications for scientific analyses is that there is a need for a better understanding of the un- certainty surrounding transitions. This uncertainty stems in particular from uncertain economic, political and technological devel- opments (Li, 2017; van Sluisveld et al., 2018). For example, the development of a technology is strongly linked to investment costs and energy prices (Chilvers et al., 2017; Li, 2017; Li et al., 2016; Mercure, 2015; Moallemi et al., 2017a; Trutnevyte et al., 2015) and it requires sustained, strong and well-designed policies (Auvinen et al., 2015; Moallemi et al., 2017a; Winskel et al., 2014). The second finding is that there is a diversity of possible futures in terms of technological outcomes and it is therefore paramount to account, throughout a transition process, for the political dimension and actors (Geels et al., 2018b; Köhler et al., 2009; Li and Strachan, 2017; Rogge et al., 2018).

6. Discussion and future research needs

6.1. The need for a stronger focus on solutions to energy and climate challenges and increasing realism

As shown in Table 2 and Fig. 3, we find that the majority of articles that we reviewed contributed successfully to the *inter- disciplinary learnin*g category, where authors concluded that they observed important benefits of mutual learning between the modellers and transitions theorists. Intriguingly, however, we also see that relatively few studies actually spelled out concrete re- commendations for climate and energy solutions (*solutions to energy and climate challenges* category) and for ways to increase the realism in models or theories (*increasing realism* category), even if these studies aimed to do so. There are several possible ex- planations for the results, as we will discuss in the following paragraphs. One explanation could be that the authors may not have consistently reported on the three categories as defined in Fig. 3 due to different writing styles of the authors. Nonetheless, this apparent lack of concrete recommendations for climate and energy solutions, is one of the most important findings from this sys- tematic review and constitutes in our view a limitation of the current integrative research. We will discuss this point in the rest of the section, and in Section 6.2, we will suggest some avenues to foster a more pragmatic approach in integrative research.

The current focus on interdisciplinary learning may be linked to the fact that interdisciplinary collaborations require tedious and strenuous discussions (Trutnevyte et al., 2019) linked to fundamentally different and diverse scholarly backgrounds. Such discussions are a natural part of the early stages of interdisciplinary collaborations and they were essential for this new body of literature to emerge in the last decade. Also, interdisciplinary discussions will rightly remain a fundamental part of the discussion in the future. But for the years to come, in light of our findings, we suggest redirecting this integrative research to focus on finding concrete solutions and steps on how to meet climate and energy targets. More conceptual and especially empirical work is needed to find innovative ways to frame stylised futures and theories in models versus the real-world dynamics in order to increase realism and address the need to find solutions to the energy and climate challenges.

In our view, this stance does not entail a form of reductionism or simplification of the processes in integrative research, but rather sets out a common perspective for all scholarly communities and collaborative efforts, and may encourage a type of practical ap- proach. To explain this point, we suggest a parallel with modern versus antique philosophy as spelled out by Hadot (2001). In Hadot's conception, antique philosophy was a way of life, where a question-answer logic distinguished the written form of this type of philosophy. The culture of questions was thus central to this form of philosophy and the teaching was based on dialogues. The central idea was to inform rather than to form. On the contrary, modern philosophy aspires to elaborate speculative discourses that aim to build systematic theories of reality. Drawing on this, we suggest a parallel with integrative research linking models and transitions theories or frameworks: until recently, most efforts seem to have focussed on understanding and developing models that lay out potential future transition pathways, almost as to create a theory of transition in a modern philosophy sense. However, as we have seen, the need to find energy and climate solutions induces a practical component in research, i.e. the need to take action to meet the targets. The surge towards integrating models and theory – especially the *bridging* approach that we discussed – is interesting as it illustrates, in our view, the antique philosophy conception in which dialogue is established by means of asking questions throughout the process, not to form, but to inform. In this spirit, interdisciplinary learning is of course central, but this conception could open up space for more research on *increasing realism* and *solutions to energy and climate challenges*. Indeed, in such a setting where dialogues are used as a methodological tool, wider collaboration could be favoured which may broaden the spectrum of possibilities to find transformative solutions.

Admittedly, such efforts are already carried out in the current literature to a certain extent, but where the antique philosophy conception may potentially broaden the horizon is through the pragmatic idea to think of a transition as a way of life, or in other words to enact the transition. We would no longer think in terms of a theory of taking action, but rather in actually executing the transition, which pinpoints, in our view, a change in approach. In order to practically enact a transition, research approaches would not only clearly state the target towards which they are working, but also clearly integrate the idea that the path that leads to this target must be thought out in such a way as to be practicable (hence addressing the *solutions to energy and climate challenges* and *increasing realism* claims). This is an area where the MLP and the integrative research investigated in this study showed some lim- itations. Indeed, these methodological approaches are useful heuristics to analyse transitions and have greatly contributed to ad- vancing the field of transitions studies in particular, whereas future research could focus on improving their ability to render practical and concrete measures to enact a transition.

We acknowledge that the discussion carried out up to now raises the fundamental question of the role of science in public discourse and the positionality of a researcher (Wittmayer and Schäpke, 2014). This should, in our view, be one avenue of future research, in particular when it comes to transitions studies and in light of growing calls to find solutions to climate and energy challenges.

Finally, this state of affairs may not only entail a change in approach as we have discussed, but also require dealing with different scales in transitions studies. As we have seen, the national level was mostly studied, but transitions need to take place on different scales – local to global – each having their own specificities.

6.2. Methodological and theoretical considerations: towards a more pluralistic approach

The focus on *increasing realism* and *solutions to energy and climate challenges* raises some theoretical and methodological con- siderations. We found three main methodological strategies that were used in the studies that we reviewed for linking models and socio-technical transitions theories or frameworks – *iterating, merging* and *bridging* – and these strategies likely result in uncovering different factors in transitions (Table 4). In light of such complexity and diversity, we agree with other authors that a pluralistic perspective where all kinds of methodological strategies are used and benefit from synergies could be a way forward, albeit the effectiveness of such an approach still needs to be demonstrated (Auvinen et al., 2015; Foxon, 2013; Moallemi et al., 2017a; Rogge et al., 2018; Trutnevyte et al., 2014; Turnheim et al., 2015; Winskel et al., 2014). Yet, a pluralistic approach could likely highlight that no single one-size-fits-all methodological strategy could feasibly be developed. The strategy adopted to choose and link models and theory would be decided within the specific context of each study and according to the research questions raised (Bergman et al., 2008; Chilvers et al., 2017; Köhler et al., 2018a; Trutnevyte et al., 2014). A pluralistic approach would mean that each situation may be unique, despite a common overall perspective (e.g. the 2 °C target and concrete ways of getting there). Finally, a new pluralistic perspective should be steered, in our view, to increase realism of models and theories and to contribute to finding solutions to the energy and climate challenges (Section 6.1).

Accounting for multiple factors and changing settings that occur during low-carbon and energy transitions will require new methodological innovations (Auvinen et al., 2015; Köhler et al., 2018a; Markard et al., 2012; Mekhdiev et al., 2018; Moallemi and Malekpour, 2018; Turnheim et al., 2015; van Sluisveld et al., 2018; Winskel et al., 2014). In terms of methodological innovations in line with the MLP framework, one example is to address the niche level of the MLP by conceptually establishing connections between niches (Köhler et al., 2009), better representing social niche innovations (van Sluisveld et al., 2018), and the dynamics between the niche and the other levels of the MLP (i.e. the regime or meso level and the landscape or macro level). Future advances that address the challenges and limitations of MLP (this however is out of the scope of the present study) would also need to inform the integrative research that includes modelling (Geels et al., 2018b; Geels, 2018b, 2011; McDowall and Geels, 2017; Papachristos, 2018a; Svensson and Nikoleris, 2018). For example, there are questions regarding how the MLP could be linked with other approaches (Geels et al., 2016; Turnheim et al., 2015), considerations of geography (Geels, 2014), power (Geels, 2014), transport studies (Geels, 2012), diverse ontologies (Geels, 2010), and multi-level transitions (Papachristos et al., 2013).

Future research could seek to reach beyond the MLP which was the most popular socio-technical transitions framework for the integrative research that we reviewed. Methodological innovations warrant the need to move towards a more inclusive setting in integrative research. One future research avenue could be to further explore the opportunities that arise from transdisciplinarity or transitions management, especially because we observed a lack of contributions of integrative research to identifying solutions to climate and energy challenges rather than only increasing the realism of models or theories and initiating interdisciplinary learning. It does not represent the only possible approach, but provides content for seeking to increase realism in theory and models to look for solutions to energy and climate challenges.

A first idea to explore could be transdisciplinarity, which may entail integrating various stakeholders, citizens, and experts in order to co-design transition storylines and conceptual models (see e.g. Auvinen et al., 2015; Chilvers et al., 2017; Foxon, 2013; Geels et al., 2018a; Köhler et al., 2009; Robertson et al., 2017; Ulli-Beer et al., 2017) and create conditions for a continuous dialogue between researchers and these actors. Another potential and complementary idea is to incorporate the reflexive principles of tran- sitions management for this field of integrative research (Hoekstra et al., 2017; Kemp et al., 2007; Loorbach, 2010; Rotmans et al., 2001; Rotmans and Loorbach, 2009). The essence of transitions management can be described as an explorative and inclusive process that addresses complex problems and seeks to establish long-term and intermediate goals, short- and long-term policies, and ex- perimentation opportunities to find sustainable solutions (Kemp et al., 2007; Rauschmayer et al., 2015; Rotmans and Loorbach, 2009). Exploring transdisciplinarity and transitions management ideas could be a way of advancing the practical, solutions-oriented dimension that is currently underrepresented in the reviewed studies. Finally, these approaches would enable to develop future scenarios that can be embodied into policies and decision-making processes to effectively trigger energy and low-carbon transitions. Indeed, moving from research to action implies understanding the policy implications and involving policymakers and civil society in the interpretation of results.

7. Summary and conclusions

In the last decade, an emerging body of literature that links computational modelling and transitions theories and frameworks emerged. We carried out a systematic review of 44 papers that linked quantitative modelling (STET, IAMs, ESM) and transitions theories and frameworks (e.g. the MLP) to study energy transitions cases and climate change mitigation strategies. Our results show that there were three main aims mentioned by the authors of this integrative research to justify the need to link models and transition theories (see also Trutnevyte et al., 2019): finding *solutions to the energy and climate challenges*, *increasing realism* in models and theory, and *interdisciplinary learning*.

In the reported outcomes of the reviewed papers, we observed that the vast majority of these papers stated that linking models and transition theories led to *interdisciplinary learning* between modellers and transitions theorists. However, only few papers dis- cussed concrete and practical suggestions towards *increasing realism* in models and theory or towards establishing ways to address the need to find *solutions to climate and energy challenges*. In our view, this is an important finding and we therefore suggest that this integrative research needs to shift its current trajectory in order to focus more on *increasing realism* and finding *solutions to the energy and climate challenges*. One way forward would be to add a practical component to this integrative research, i.e. a need to take action to meet energy and climate targets. In order to practically enact a transition, research should integrate the idea that the path that leads to a target must be thought out in such a way as to be practicable (hence addressing the *solutions to energy and climate challenges* and *increasing realism* claims). In more practical terms, this could entail, for example, involving policymakers and civil society actors in the process for designing models and identifying the key elements to include. It would also require moving beyond currently popular focus on the national level to address local to global scales.

In terms of methodology, our results reveal three main ways that models and transitions theories or frameworks were integrated in the reviewed studies (see also Trutnevyte et al., 2019): *iterating*, *merging*, and *bridging*. These approaches vary notably in terms of the degree of integration of models and theory required. Merging requires the most integration as it assumes that the key transition factors can be modelled. Bridging, on the other side of the spectrum, requires a lower degree of integration and relies more on interactions at different points in time between models and theory on shared concepts. Finally, innovative and practical meth- odologies are required to provide the means to enact transitions. Currently, the field of integrative research does not appear to meet this challenge in a practical sense and thus, in our view, must evolve to rise to these ambitions.

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