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Review

How Can We Design Policy Better? Frameworks and Approaches for Sustainability Transitions

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Abstract: The literature on socio-technical transitions offers a wide range of frameworks and approaches to conceptualise and steer sustainability transitions. However, the complex nature of transition processes, along with the weak correspondence between the transitions literature and policy design, make their joint application rather challenging. In response, this paper proposes a conceptual framework to inform actors managing a system or organisation in a transition process about the steps to follow, from the initial representation of the problem to the formulation of the interventions, and their eventual evaluation for further refinement. This framework is built from an integrative review of the sustainability transitions literature, incorporating state-of-the-art approaches and frameworks to guide policy design. It aims to advance the operationalisation and orientation of policies to accelerate sustainability transitions through a three-phased approach: (i) baseline assessment of systemic challenges, (ii) targets visioning and pathways design, and (iii) implementation and evaluation of policy interventions. The role of the most salient frameworks espoused in the literature is detailed and integrated into the conceptual framework so that transition actors are equipped with the necessary knowledge and tools to design effective policies for the realisation of their sustainability goals.

Keywords: sustainability transitions; socio-technical system; policy design; frameworks; governance

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1. Introduction

A socio-technical system or STS refers to a configuration of resources and capabilities that satisfies specific needs such as food, energy supply, transport, and health. They are the outcomes of activities of economic agents such as users, firms, research institutes, universities, policymakers, special interest groups, media, and civil society [1,2]. The functioning of an STS is shaped by the governance of activities, corporate practices, technological advances, citizen behaviours, as well as the beliefs and attitudes of all actors. STSs generate specific production and consumption patterns as well as externalities vis-à-vis the environment, society, and the economy that shape the state of sustainability of our economic activities.

It is widely acknowledged that STSs in many countries and sectors need to be transformed towards the attainment of the 17 UN Sustainability Development Goals (SDGs) or the global development agenda [3,4]. In other words, sustainability transitions, i.e., processes that lead to a fundamental shift in the state of sub-optimal STS, are necessary to achieve the SDGs [5–7]. For example, transitions are necessary to reduce the CO_2 emissions of the transport and energy STSs (SDGs 7 and 11) [8,9], minimize the dire health consequences of the sanitation STSs in developing countries (SDG 6) [10], and lower the environmental footprint of the STSs associated with food production and consumption (SDG 12) [11]. In a similar vein, the SDGs provide a blueprint or roadmap for directing transitions of STSs to more sustainable outcomes. Exemplar cases include the study of SDG 9 goal of fostering innovation ecosystems to enable sustainability and inclusive growth in the Middle East and North Africa (MENA) region [12], and the monitoring of progress towards SDG 4 targets to determine how the education system manages to provide inclusive, equitable and effective pedagogy [13].

At present, most recent UN reports show little progress in more than half of the SDG targets for 2030, while progress has stalled or gone into reverse for about 30 percent of the targets [14]. This emphasizes the pressing need to intensify endeavours to transform STSs, plan new strategies, and monitor their progress for SDGs attainment [15]. It also highlights the need to produce actionable knowledge, defined as the knowledge "that supports actors' understanding of how to create transformative change towards sustainability" [16].

In this respect, the urgent question is how can we design policies in a better way to steer STS transitions towards multiple economic, social, and environmental goals in a complex and uncertain world? The literature on STS transitions provides multiple frameworks and methods [17–20], which are not yet as much integrated into policy design and public programmes as they could be, perhaps because they are diverse and embedded in a fragmented body of work that spans several literature streams. Moreover, they are dispersed among multiple and complementary schools of thought. They seem to be susceptible to academic marketisation trends rather than policy needs [21]. Some scholars even bemoan that, as certain terms in this field are in fashion, the literature is filled with many articles that make little or no contribution to the scholarly body of knowledge on this field, or to the policy and practice sphere [22]. Therefore, it is necessary to understand the contributions of the existing research and identify where the potential for attainment of our sustainability goals really lies.

Given the above context, the present paper aims to explore the prominent frameworks and methods in the sustainability transitions literature, and their prescriptions to support transition efforts, from the identification of sustainability challenges to be addressed, to the final evaluation of a transition project or intervention. Its central research questions are the following:

- How can the socio-technical transitions literature help trace the origins and magnitude of sustainability problems to be addressed and identify the factors that influence transition processes?
- How can the socio-technical transitions literature help foster innovations towards a specific goal or mission and design pathways for its attainment?
- How can the socio-technical transitions literature highlight the required intervention points and ways to assess their impact towards the desired STS state?

To address these research questions, an integrative review of the literature on approaches, frameworks, and methodological tools in transitions research is carried out. The objective of this review is to collate seminal and representative (rather than comprehensive) theoretical and empirical literature in the field, so that new perspectives on the topic are generated, with the ultimate goal of informing the policy design processes.

The remainder of the paper is organised as follows. Section 2 explains the choice of the literature review method and its details. Section 3 elaborates on the complexity of socio-technical systems transition processes. Section 4 reviews prominent frameworks of the transitions literature that guide the analysis and assessment of transformation processes. Section 5 gives an overview of the approaches and methodologies for the governance of transitions. Section 6 synthesises the findings and discusses the identified gaps. Section 7 concludes.

2. Methodology

The purpose of an integrative literature review is to assess, critique, and synthesise the literature on a research topic in ways that contribute to new thinking about the topic and catalyse new research [23,24]. Thus, an integrative literature review serves the scope of the present study, to guide the review and synthesis of knowledge from diverse sources [25].

It differs from a systematic literature review, which typically aims for a comprehensive compilation of the literature, particularly on well-established topics, and frequently from the standpoint of a single knowledge domain.

A semi-systematic approach was followed to select the literature for study, so as to allow the exploration of topics that have been conceptualised differently by various groups of researchers within diverse disciplines [26]. A three-step methodology was applied to compile the corpus of articles. First, the search terms 'sustainability transition' and 'socio-technical system*' and 'framework* or tool* or approach*' were applied to the Web of Science, Scopus, and Science Direct databases. This was complemented by other sources drawing on the authors' extensive experience in this field. Then, all duplicates were removed. Second, the abstract and keywords were examined to see whether they were pertinent to the three research questions of this paper, namely (i) transition processes, sustainability challenges, systems' performance, (ii) transition dynamics, innovation functions, (iii) governance, pathways, and methods.

Third, the articles were read in full by the first author, who applied inclusion and exclusion criteria to arrive at a final selection. The inclusion criteria were purposely kept general. Any selected article had to provide a deep understanding of socio-technical transition processes, governance approaches, and sustainability assessment methods of different transition pathways. The exclusion criteria comprised duplicate papers among the search databases, research with no significant theoretical or conceptual contributions, and research unrelated to the social sciences. The steps of article selection, inclusion, and exclusion were carried out by the first author and meticulously checked by the other two authors. Then each article was read by the authors to identify the ways in which it answered the research queries. These findings were then discussed to arrive at a consensus.

3. Socio-Technical System Transitions: Why Are They So Complex?

The starting point for our paper is the socio-technical system (STS) which is the central unit of analysis in transitions research [2]. Sustainability transitions are change processes of STSs, which reduce the magnitude or impacts of negative systemic outcomes that are widely acknowledged to exacerbate our societal problems and/or improve the impact of positive systemic outcomes that take us closer to achieving the 17 UN SDGs. An STS comprises interlinked components that are distinguished along three analytical dimensions: (i) technical dimension—technologies, infrastructures, material artefacts, supply and distribution chains, and knowledge; (ii) governance dimension—rules and institutions, societal and technical norms, regulations, and standards of good practices; and (iii) social dimension—actors, actor networks and social groups with their specific practices and routines, cultural meanings, preferences, politics and strategies [2,27].

Transitions involve changes across different levels; at the micro-level, concerning individual behaviours and actions; at the meso-level, involving the structuration of regime rules; and at the macro-level, encompassing broader societal and cultural characteristics and trends, such as individualization and globalisation [28]. For example, increasing food packaging is mainly driven by globalisation trends (macro-level), the expansion of supermarkets (meso-level), and the constraints on households' time (micro-level) [29].

Moreover, transitions of socio-technical systems are complex because they are multi-actor and multi-factor [28]. These attributes are discussed next.

3.1. Multi-Actor

The systemic complexity that characterises STS's transitions derives, among others, from the plurality of actors involved, whose actions shape and are shaped by the transition processes. Actor groups come from various institutional backgrounds (e.g., market, government, science, civil society), often with different interests, resources, capabilities, and beliefs about their preferred transition solutions. Actors play an active role in the overall analysis, initiation, and acceleration of STS sustainability transitions. They engage in dialogues about issues and solutions, understand the transition processes, and explore the effects of innovative sustainability solutions in "multi-stakeholder spaces" [30]. For example, drawing from the experiences of an EU project conducted in five European cities involving multiple actors in the transition process, Frantzeskaki and Rok [30] show that transition initiatives necessitate the establishment of trust and transparency among stakeholders. Hence, the success of a sustainability transition depends on the combined efforts and effective involvement of all stakeholders, and their contribution in the creation of "useable" transition knowledge [31].

3.2. Multi-Factor

Transitions are also the outcome of the interplay of many factors and multifaceted interactions within and between systems.

3.2.1. Endogenous Factors

STSs are internally structured by deeply embedded rules, institutionalised practices, vested interests and lateral alignments of actors, thresholds and tipping points, and multi-actor processes [32]. These not only lead to the development of patterns of self-organisation, emergence, and co-evolution, but also to path dependence and system lock-in [33]. For instance, Simoens et al. [34] show that the dominance of single-use over reusable packaging in Germany is not just a matter of inadequate environmental policies or a lack of commitment from businesses or consumers. Rather, it is a case of path dependence of the German packaging sector, which is actively reproducing and reinforcing its existing materiality, institutions, practices, and discursive arrangements through interactions between the various lock-in mechanisms.

3.2.2. Exogenous Factors and Multi-System Interactions

STSs are embedded and constantly interact in a dense network of other STSs [35,36]. These interactions can also shape the internal structure of STSs and, at times, trigger their change [37]. Esfandabadi et al. [38], for example, illustrate through the exploration of different case studies across the world, how the emergence of car-sharing services is highly interconnected with specificities of the car manufacturing sector, regulation and administration, population trends, and the environmental impact of the transportation system.

Socio-technical transitions usually extend well beyond the boundaries of individual STSs [37,39]. They not only involve the alignment of multi-level dynamics within a single system but also the alignment of forces across systems [40]. Therefore, transition analysis requires an examination of multi-system interactions with emphasis on the interconnected and multi-scalar qualities of socio-technical systems [41]. A well-known example of multi-system interactions discussed in the literature is the emergence of functional foods (i.e., products with health-enhancing attributes) as a niche in the food/nutrition socio-technical system. The emergence of functional foods was triggered not only by an increase in people's awareness of the benefits of a healthy diet (food system), but also by demographic developments (e.g., increasing population and changes in age distribution), which raised the demand for healthcare services in pharmaceutical systems and consequently gave rise to campaigns on healthier nutritional habits [42]. Another example of a net-zero transition that illustrates the complementarities across multiple systems is the adoption of electric vehicles (EVs). The diffusion of EVs requires the establishment of corresponding battery recharging infrastructure and consequently new technological connections between the electricity and personal transport systems [39].

Multi-system interactions can generate opportunities to create waves of change that might start from one STS and subsequently affect others. These opportunities must be identified and harnessed for the creation of synergies across systems. For instance, major connectivity innovations—such as IoT (Internet of Things), AI (Artificial Intelligence), and Big Data—continue to promote profound changes in almost every socio-technical system, from communication to health to electricity, and increase their efficiency and productivity in different ways [40].

The links and interdependencies among STSs are also potential sources of dynamic conflicts and trade-offs that can hamper transition processes and create unintended negative externalities or trigger search efforts for new transition pathways. Consider the trade-offs between energy, water, and food systems transition pathways. Decarbonization efforts of the energy sector include in many countries the promotion of bioenergy and biofuels, as alternative options to fossil fuels, that can support climate change mitigation [43,44]. However, mass biofuel production or large-scale bioenergy cultivation puts substantial pressure on land and water resources and leaves fewer resources for human and animal food production [43,45–47]. Therefore, emerging trade-offs and synergies between the systems have to be evaluated to inform the adoption of potential nexus solutions (e.g., the introduction of afforestation and deforestation policies, solar-powered water pumping for irrigation, etc.) [46].

4. Frameworks to Analyze Innovation and Transformation Processes

The four prominent strands of thought in the literature on sustainability transitions and their associated frameworks are the following: (Section 4.1) the Multi-level Perspective (MLP), (Section 4.2) the Technological Innovation Systems (TIS), (Section 4.3) the Mission-oriented Innovation Systems (MIS), and (Section 4.4) the Sustainability-oriented Innovation Systems (SoIS) framework.

4.1. The Multi-Level Perspective and Transition Pathways

The Multi-level Perspective (MLP) has been widely applied in transition studies [48–51], for the analysis of systems along three levels. The macro-level, or landscape, is where long-term trends and pressures arise, such as broad macro-economic conditions and shocks, demographics, and climate change. The meso-level comprises economic activities such as production, consumption, and waste generation that flow across STS. The micro level involves the development of novel technologies in niches which are then introduced into the meso-level.

STS are difficult to change because they are structured by dominant regimes [48]. A regime is a set of dominant and existing rules in production and consumption practices that are self-reinforced by socio-economic elements such as knowledge, technology, regulation, markets, supply and demand-side conditions, culture, and social norms [52]. System actors and organisations are embedded in interdependent networks, with organisational commitments and vested interests. STSs also depend on material structures or technical sub-systems for their functioning, with long and deep roots in society and established economies of scale, which make them hard to break. In short, the stability of STS arises from the "deep structure" of a "semi-coherent set of rules that orient and coordinate the activities of the social groups that reproduce the various elements of STSs" [53].

Regimes are constantly re-shaped by four structuring processes via (i) micro-level niche innovations that are accepted by the regimes [48]; (ii) macro-level, exogenous, broader contextual developments within the system that exerts pressure throughout the landscape [48]; (iii) meso-level, internal regime tensions [54]; and (iv) external influences from other systems, regimes or niches [37].

The various kinds of actor alignment(s) within a STS lead to different types of transition processes and, consequently, to the emergence of different transitions pathways [55,56] that lead to new ways of achieving specific societal functions [57]. Geels and Schot [56] distinguish four transition pathways: (1) technological substitution, based on disruptive niche innovations that are sufficiently developed when landscape pressure occurs; (2) regime transformation, in which landscape pressures stimulate incumbent actors to gradually adjust the regime, when niche innovations are not sufficiently developed; (3) reconfiguration, based on symbiotic niche innovations that are incorporated into the regime and trigger further (architectural) adjustments under landscape pressure; and (4) de-alignment and re-alignment, in which major landscape pressures destabilize the regime when niche-innovations are insufficiently developed; the prolonged co-existence of niche innovations is followed by re-creation of a new regime around one of them.

To support efforts to accelerate particular transition pathways, Kanger et al. [58] propose a conceptual framework of six policy intervention points for transformative systems change: (1) stimulate different niches; (2) accelerate the niches; (3) destabilize the regime; (4) address the broader repercussions of regime destabilisation; (5) provide coordination to multi-regime interaction; and (6) tilt the landscape. Policy intervention points can be understood as particular areas in the STS or its environment where appropriate policy strategies would likely facilitate transformative change in the system's directionality [58]. To further advance efforts towards transformative change, Ghosh et al. [59] present twelve transformative outcomes that can guide transformative policies, and their evaluation, towards their envisioned "semi-abstract" goals. Transformative outcomes can be best understood as processes that eventually lead to deeper changes in sets of rules that guide dominant regimes and actors in their behaviour. They can be grouped under three macro-processes that underpin socio-technical change: (1) building and nurturing niches; (2) expanding and mainstreaming niches; and (3) unlocking and opening up of regimes. We summarize and link the notions of intervention points, transformative outcomes, and transition pathways in Section 6.

4.2. The Technological Innovation System

A Technological Innovation System (TIS) is defined as a set of institutions and actor networks that interact in a specific technological field and contribute to the generation, diffusion, and utilisation of variants of a new technology and/or a new product [60–62]. The fundamental TIS components are actors, networks, and institutions [63]. Actors refer to organisations and individuals who work towards the development of the technology in question [64]. These actors then form networks, where interactive learning and the formation of policy networks may occur [61,65]. These actors and networks share institutions which are "sets of common habits, routines, established practices, rules, or laws that regulate the relations and interactions between individuals and groups" [66].

To evaluate and compare the performance of innovation systems, specific TIS functions have been proposed, as emergent properties of the interplay between actors and institutions [67–70]. The functions directly influence the development and diffusion of niche innovations and are also necessary to destabilize existing regimes [71]. Functions can be understood as the integral components and activities of the TIS and are presented by Hekkert et al. [69] as (1) knowledge development and diffusion, (2) entrepreneurial experimentation, (3) influence on the direction of search, (4) market formation, (5) legitimation, (6) resource mobilisation, and (7) development of positive externalities.

4.3. The Mission-Oriented Innovation System (MIS)

The Mission-oriented Innovation System (MIS) framework introduced by Hekkert et al. [72] is defined as "the network of agents and set of institutions that contribute to the development and diffusion of innovative solutions with the aim to define, pursue and complete a societal mission". Candidate innovation missions are plastic-free oceans, affordable energy storage systems, and carbon-free aviation and shipping.

The difference between MIS and other innovation systems frameworks, such as the national, regional, sectoral, and technological, is that MIS emerges around problems rather than solutions. It also deviates in its approach to defining system boundaries, determining the nature of interactions within the system (e.g., demand-pull versus supply-push), and the resulting output (e.g., novel technological and behavioural solutions) [72]. The mission does not comprise a single R&D or innovation project but a portfolio of such projects, each involving actors from multiple sectors and domains with joined-up policy making [73]. In addition, the formation of a MIS requires a broad mix of policy instruments, governance, and coordination mechanisms, and is characterised by a strong effect of directionality.

4.4. The Sustainability-Oriented Innovation System (SoIS)

Innovations that can accelerate sustainability transitions, aiming for economic, environmental, and social value creation, have been variously termed as sustainability-oriented, e.g., [74,75], green innovations, e.g., [76,77], and eco-innovations, e.g., [78,79]. Thus, we refer to sustainability-oriented innovations (SOI) as new or improved products, services, processes or practices that aim at environmental and/or social benefits in addition to economic returns [74,80]. Adams et al. [74] recognize three types of SOI: operational optimisation, organisational transformation, and systems building. It is important to note here that this term highlights our focus on the direction towards sustainability as a normative goal, rather than as a fixed and certain outcome [80,81]. Nevertheless, the development of innovation is always uncertain in terms of its actual outcomes and impacts [82,83].

The system that gives rise to SOI is the Sustainability-oriented Innovation System (SoIS). Altenburg and Pegels [84] define SoIS as a network of institutions that work towards a shared objective: to develop, import, adapt, and disseminate new technologies aimed at reducing environmental impacts and resource intensity to a level that aligns with the earth's carrying capacity. The performance of the SoIS (i.e., the development and diffusion of sustainable innovations) can be explored through the classical seven "functions of innovation systems" of Hekkert et al. [69].

5. Methods and Approaches for Sustainability Transition Governance

The literature on sustainability transitions includes prescriptive methodologies for problem understanding, solution scenario building, implementation, and evaluation—all involving a reflexive element of feedback loops. All these activities are actions taken to study, design, plan, trigger, and manage transitions, and come under the umbrella of transition governance. It is a form of multi-level governance in which state and non-state actors are brought together to co-produce policies with the aim of coordinating science, innovation, and sectoral policy [85–87]. In this context, the notion of transformative governance, as a broader concept, emphasizes the importance of diversity, connectivity, polycentricity, redundancy, and directionality, in triggering regime shifts toward more desirable structures [88,89].

Transition governance calls for continuous learning and adaptation [90]. Sharing and accumulating knowledge for transition governance is the "magic bullet" for effective and successful sustainability transitions. This need for collaborative efforts to steer transitions is also captured by the concept of collaborative governance, which is defined by Ansell and Gash [91] as "a governance arrangement where one or more public agencies directly engage non-state stakeholders in a collective decision-making process that is formal, consensus-oriented, and deliberative and that aims to make or implement public policy or manage public programs or assets" (p. 544).

Below, we discuss four distinct types of frameworks and approaches that have evolved based on the premise of collaborative governance to manage change towards sustainability, namely the (Section 5.1) Transition Management approaches, (Section 5.2) Knowledge Co-production, (Section 5.3) Strategic Niche Management, and (Section 5.4) Modelling Transitions.

5.1. Transition Management Approaches

Transition Management (TM) is a policy-oriented framework, which aims to influence the direction of the search for solutions and enable and encourage transition governance actions [92–94]. A TM process involves problem structuring and establishment of a transition arena; developing sustainability visions, images, and transition pathways; initiating and executing transition experiments; and transition monitoring and evaluation. The TM literature studies how complex adaptive societal systems, such as societal sectors, regions, or cities, can be guided through fundamental nonlinear changes in cultures (for example, attitudes, perceptions, and routines), structures (for example, institutions, ways of organising, and hierarchical orderings), and practices (for example, behaviour, implementation procedures, and daily routines) [19].

In the realm of assessing progress and the effects of transition processes, innovative frameworks supported by indicators are becoming increasingly prominent in the literature. They focus on the evaluation of various transition characteristics, including processes' fairness and inclusivity, as well as their short-, medium-, and long-term impact on social, economic, and environmental dimensions [95–97]. Going beyond mere progress evaluation, indexes are being formulated to gauge the readiness level of a system or country for undertaking sustainability transitions [98,99].

5.2. Knowledge Co-Production through Learning and Experimentation

Evidently, the proactive steering of sustainability transitions is challenged by their high complexity, ambiguity, and distributed control [85]. To address these attributes, transition management requires "societal movement through new coalitions, partnerships, and networks around arenas that allow for building up continuous pressure on the political and market arena to safeguard the long-term orientation and goals of the transition process" [100]. Knowledge co-production is, therefore, a core organising principle in the transition governance literature [90,93,101–103]. It is usually achieved through the collocation of researchers and local stakeholders since the latter are acknowledged to hold a diversity of knowledge and expertise with intersectoral lived experience [104]. Through these processes, participants gain knowledge about tensions and conflicts related to contemporary transition challenges, that empower them to arrive at a consensus for the transition process [30]. The main principles that should characterize knowledge co-production in sustainability research according to Norström et al. [103] are context based, pluralistic, goal oriented, and interactive.

Different types of knowledge are important to the successful governance of sustainability transitions. Rauschmayer et al. [105] distinguish three types of knowledge pertaining to systems, target, and transformative change. The first type refers to the comprehensive understanding of the problem we aim to solve through this transition process and whether to examine it from a micro and/or macro perspective. The second type refers to the future state of the system that actors aim for and why they pursue it, allowing for individual and normative assessment of the impact of the transition initiatives. The third type refers to the ways and means of practically realising the system's desired state in question. Another type of knowledge discussed by van Doren et al. [106] is instrumental knowledge. This type refers to practical skills, strategies, and insights into cause-and-effect relationships between interventions and outcomes related to single-loop learning. This type of knowledge is practical in nature and is related to issues of effectiveness and goal attainment [107]. All these different types of knowledge need to be considered and accompanied by specific sustainability indexes and measurements [108] to better evaluate transformative outcomes.

The success of transition efforts also depends strongly upon the participation of actors at different societal levels [109]. Policymakers who strive to steer societal transformations, need to take action and collaborate with consumers, business organisations, NGOs, and academic institutions [110–112]. Several works study how actors across systems can be engaged. For example, participatory methods bring forward a human-centred approach in the mapping, analysis, design, visioning, and model development supporting the policy decision-making processes [113–117]. Kemp and Ramani [118] propose the "SISTER" framework to facilitate an understanding of how sustainability transitions can be guided in a participatory manner. The framework includes six main action types: (i) S—characterize the system housing the problem; (ii) I—identify the necessary changes, i.e., the innovation and new infrastructure required for transition; (iii) S—build cooperation, or the necessary shared learning or vision for transition; (iv) T—ensure deployment of the required existing technologies and capabilities required for transition; (v) E—invest in the necessary engagements with stakeholders for successful implementation; and (vi) R—truthfully evaluate the output and impact to identify the necessary, sufficient and/or favorable conditions for replication of intervention. The SISTER framework seeks to bring evidence of what works for policymakers and prevent "policy resistance" through stakeholder dialogues to achieve buy-in to solutions.

Overall, building on synergies with various actors enables them to understand problems from multiple perspectives, expands the scope of potential solutions, and contributes to the perceived credibility, salience, and legitimacy of results [119–121]. In particular, under data-scarce conditions, participatory approaches could help to elicit knowledge from actors involved to improve formal and mental models [122,123]. For instance, Indigenous people are recognised as one of the most important knowledge holders [124–126]. Emphasis is also given to engaging diverse actor groups, interests, and epistemologies that extend beyond traditional disciplinary boundaries and merge societal and scientific knowledge. Thus, robust co-created solutions encapsulated in *transdisciplinary knowledge integration* can drive sustainability transitions [127–129].

To facilitate these processes of learning and experimentation, necessary for the implementation, diffusion, and scaling of transition mindsets and actions, transition design serves as a learning tool for action-based transition. Transition design emerges from the integration of sustainability transitions with design theory, education, and practice [130]. It aims to enable a deeper understanding of the social roots of wicked problems and places stakeholder concerns and co-design/collaboration at the heart of the problem-solving process [131]. The objectives of transition design are to enable the visualisation and mapping of complex problems, contextualise them, align the priorities of actors and support them to envision desirable futures collaboratively, and, finally, identify leverage points for change within the system [131]. Within the broader literature, the process of co-design is commonly implemented using collaboration tools, such as "boundary spanning " [132], and decision-making tools for empowering niches [133].

5.3. Strategic Niche Management

A slightly more interventionist action stream that has become very important for policy is Strategic Niche Management (SNM). This concerns the protection of niche innovations with transformative potential. Scholars suggest that governments or other organisations can nurture radical innovations in "protected spaces" (niches) that shield them from mainstream markets [49,134–136]. SNM emphasizes the concentrated efforts undertaken to bring in the knowledge and expertise of users and other actors into technology development processes and generate interactive learning processes and institutional adaptation [137], leading to the development of innovations. Sequences of experiments and demonstration projects enable recursive cycles of these processes, which can aggregate into innovation trajectories [135]. The specific shape and character of the protected niche innovation trajectories are influenced by the quality, specificity, and robustness of expectations, the depth and breadth of social networks, and the relative emphasis on first- or second-order learning [136], with the first-order learning implying a direct accumulation of facts and data, while second-order learning allowing for changes in cognitive frames and assumptions [138].

5.4. Modelling Methods

Several modelling techniques have gained ground in the literature regarding the analysis, governance, and overall management of sustainability transitions. Transition modelling refers to the application of existing modelling methodologies to study and explain the dynamics of transitions and help in choosing the best strategies [139,140]. It involves activities from qualitative exploration of the STS elements and development of potential futures, such as back-casting, and narratives, to quantitative simulations of the dynamics and impact of different scenarios or processes, such as System Dynamics (SD), Agent-based Modelling (ABM), Life Cycle Assessment (LCA), Integrated Assessment Models (IAMs).

Transition modelling can complement the MLP and TM approaches by facilitating the analysis of the causal relations and feedback loops that generate complex system behaviour [141–143]. This coupling also helps overcome policy resistance by mapping out the system structure that produces these obstacles, thereby enabling the identification of high-leverage points that support sustainability transitions [144]. Simulation modelling can help to untangle multi-system interactions and develop causal explanations of past or ongoing system transition processes in support of policymaking efforts [41,145]. It also forces the quantification of transition factors, such as actors' behaviour and landscape pressures [146], makes the assumptions of the analyst more explicit [141], and consequently supports the design of effective policies for sustainable transitions [147].

Particular emphasis is placed on the active involvement of concerned stakeholders and other disciplinary experts in the modelling process, to ensure well-informed and targeted choices. Within this context, participatory SD modelling [148,149] is considered to be a prominent methodology in several fields of transition research, particularly when sustainability issues are at stake [150,151]. Stakeholders' local knowledge enriches the modelling process, while the stakeholders involved also develop a more detailed understanding of how the system works and evolves [152]. In addition, a participatory approach can boost insights into the system to be modelled and is an invaluable mechanism to control possible misjudgements by modellers [150].

6. Synthesis of Transition Frameworks for Policy Design

The previous sections presented a comprehensive overview of the frameworks and methods that can be applied to steer a sustainability transition. This section synthesizes these findings and provides a three-phase structured approach for guiding policy design efforts (Figure 1), that encompasses: (1) Baseline Assessment, (2) Target Visioning and Pathway Design, and (3) Implementation and Evaluation of Policy Interventions. Different frameworks can be beneficial across these three phases, each with its own unique purpose and ability to provide insights and help connect the dots between possible solutions and desired outcomes. Each phase comprises two transition tasks, which are interlinked, as the outcomes of each task are used as input for other tasks. A detailed explanation of each of the three phases and tasks is provided below.

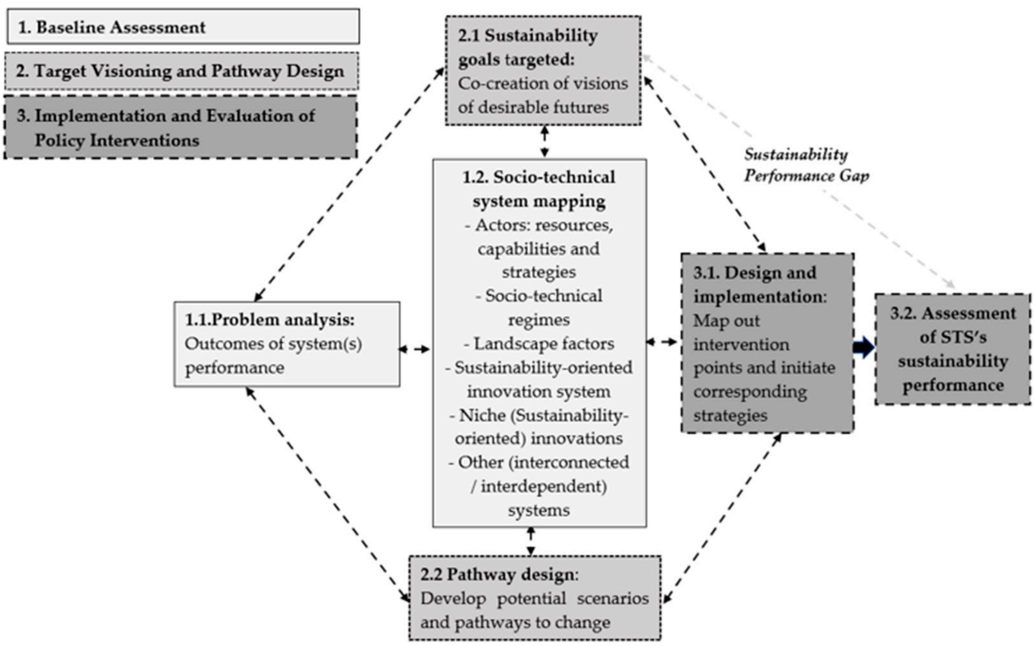

Figure 1. Conceptual framework for the operationalisation of sustainability transitions.

Now, we can also link the developed conceptual framework with policy design. For the purposes of this paper, we define policy design as the development and implementation of policy strategies that transform dominant regimes and/or accommodate strategic niche innovations to achieve a sustainability mission. Policy design in transition management comprises five main components: (i) establishing a transition arena, (ii) developing a vision, (iii) pathway development through back-casting techniques, (iv) experimenting with pathway options, and (v) monitoring, evaluation, and revisions [153], each supported by a variety of actors, with their knowledge, views, competences, and material resources [154]. More specifically, the first component of transition design corresponds to Phase 1 of our framework, the second and third components to Phase 2, and the remaining two components to Phase 3.

The links of these components with our developed framework, along with further details on the tasks and corresponding framework for each of these phases, are presented in Table 1.

Previous studies on guidance and implementation of change for sustainability transitions were based on combinations, parts or alternations of the framework presented below [115,131,155–161]. But, to the best of our knowledge, this is the first attempt to bring these phases together under a comprehensive framework, to support the operationalisation and orientation of policies for sustainability transitions at a systems level.

Details of the Three Phases of the Policy Design and Implementation

1. Baseline Assessment

The first phase departs from a deep understanding of the nature of the societal challenge that needs to be addressed, and the dimensions of the corresponding socio-technical system or systems where it derived from. This phase calls for both an ex post analysis of past system trajectories and a mapping of the system's current dynamics.

(1.1) To understand the societal challenge first requires an analysis and collective understanding of the problem identified, its root causes, long-term, historical, and recent developments that influence its emergence, and its exact definition from the perspective of different stakeholders. Evidence-based narratives and MLP or TIS-based analysis can be followed to disentangle the different dimensions that led to the current challenge.

(1.2) The STS mapping of elements that give rise to the societal challenge is also crucial. The temporary elements and dynamics across landscape, regime, and innovation functions of the STS should be analysed to generate a broader understanding of how these are connected to the societal challenges to be addressed. This step requires the identification of the factors that affect transition processes and the mapping of transition dynamics at different levels, as suggested by frameworks such as the MLP, TIS, MIS, and SNM. A mapping of the stabilising and de-stabilising forces will provide insights into the dynamics that influence the system's present state, and of the functions that affect the performance of an innovation system aiming to accelerate this transition. It is important to acknowledge that transformative change often extends beyond individual socio-technical systems and can have an impact across multiple sectors [40]. The decision on where to place the system boundaries depends on many factors, including resource constraints, the scope of transition, and the origins of root causes, and needs to be carefully decided.

This first phase of the framework clearly links with the establishment of a 'transition arena' for policy design. This allows for knowledge sharing, learning, and discussion among transition actors, which would allow a better grasp of the problem to be resolved, to adjust views, and adapt behaviours [162].

2. Target Visioning and Pathway Design

The second phase aims to identify relevant sustainability goals for the STS and the direction of the potential future pathways that could be prioritised to achieve these goals. This involves building a multi-perspective view of the mechanisms and patterns of possible changes, developing a shared vision, and designing transition pathways and scenarios, while considering possible externalities, risks, trade-offs, etc., to attain the shared sustainability vision.

Table 1. Phases and tasks to operationalise sustainability transitions.

Phases	**1. Baseline Assessment**		**2. Target Visioning and Pathway Identification**		**3. Implementation and Evaluation of Policy Interventions**	
Transition tasks...	1.1 Analyze the problem to be addressed	1.2 Mapping the socio-technical system(s) of focus	2.1 Define sustainability goals targeted	2.2 Design possible transition pathways	3.1 Design and implement transition efforts	3.2 Assess STS's sustainability performance
through...	Ex-post and present analysis of system's trajectories and characteristics		Gaining orientation on stakeholders' objectives, and building a multi-perspective view of the mechanisms and patterns of change		Setting program agenda, developing performance indicators, and continuous performance monitoring and evaluations	
Applicable frameworks and approaches	MLP, TIS, MIS, SNM, Knowledge co-production through learning		MIS, SoIS, and Transition governance methods and approaches		TM, Transition governance methods and approaches	
Policy design components	(i) Establishing a transition arena		(ii) Developing a vision (iii) Pathway development through back-casting techniques		(iv) Experimenting with pathway options (v) Monitoring, evaluation, and revisions	
Deliverables	Analysis of evidence-based narratives on the root causes of contemporary challenges past trajectories of STS	Mapping of STS elements, stabilising and de-stabilising forces corresponding TIS functions emerging technological and social innovations other factors that affect transition processes at different levels	Mapping of multiple perspectives for a shared long-term vision key priorities to catalyze systemic changes that integrate environmental, social, and economic considerations	Plan for scenarios and strategic actions based on leverage points ways to address path dependencies surrounding unsustainable system outcomes	Plan for a broader transformative agenda and potential intervention points systemic dialogue to set practical details and enhance learning	Design protocols for management with participatory methods evaluation troubleshooting integrating new knowledge for programme revision

Note: MLP: Multi-level Perspective, TM: Transition Management, SNM: Strategic Niche Management, TIS: Technological Innovation System, MIS: Mission-oriented Innovation System, SoIS: Sustainability-oriented Innovation System.

(2.1) The definition of the sustainability goals targeted requires a multi-perspective view, considering different viewpoints, knowledge systems, and expertise, including those of various stakeholders and affected communities. By understanding the orientation of stakeholders' objectives, decision-makers can develop more informed and inclusive approaches to sustainable transitions, uncover interdependencies, and identify potential barriers or opportunities, as well as key priorities for change, leading to more effective and equitable outcomes. A clear understanding also fosters collaboration, transparency, and shared ownership among stakeholders, ultimately facilitating the successful achievement of sustainability goals. Research frameworks that incorporate participatory design approaches (i.e., [118]) could provide a roadmap on how to accommodate people, agency, and context aspects for a systemic change.

(2.2) The next step involves the design of pathways to achieve the sustainability goals. Designing transition pathways for systemic change involves a strategic and collaborative approach that considers the complexity of the existing systems. Actions under this step involve the identification of leverage points, including policy changes, technological innovations, and behaviour shifts, where interventions can have a significant impact and trigger systemic change. Based on this, strategic actions can be developed, to address the identified barriers and promote transformative outcomes. Considering the complexities of the system, a mixture of short-term, medium-term, and long-term actions should be planned, to target different levels of the system, from individual behaviours to policy and governance structures. Transition frameworks such as the TM and SNM give guidance on the formation of these pathways, together with narratives and scenario-building activities.

This second phase of the framework incorporates the 'development of visions' and 'back-casting of transition pathways' of the policy design components. Problem and system definitions according to the previous phase, are now guiding the formulation of specific visions and strategies to realise them. Different potential pathways are then generated, that link the present state with future outcomes, through back-casting, modelling, and transition narratives [163–165].

3. Implementation and Evaluation of Policy Interventions

The third and final phase of this framework involves the planning and governance actions necessary for the finalisation of transition strategies, their operationalisation, and the evaluation of progress towards the target or mission set. Activities here concern the programme-design-relevant tasks and programme implementation and evaluation of relevant tasks.

(3.1) First, it is necessary to set the practical details of a broader transformative agenda. It should be set with policy intervention points that target specific areas in the STS or its environment where the application of appropriate policy strategies is likely to facilitate transformative change in the system's directionality. These potential intervention points, along with the expected transformative outcomes, as discussed in Section 4.1, are summarised in Table 2. According to the nature of the transition pathways (column 1) that correspond to the sequences of changes, actions, and strategies employed to shift STS from one state or mode to another, a spectrum of different intervention points (column 2) can be targeted and employed, which will then give rise to expected outputs (column 3) and the final transformative outcomes of this transition process (column 4). For example, to achieve the substitution of a dominant regime by mature niches requires policy support to regulate and trigger innovation, through specific interventions such as targeted innovation funding, experimentation, and learning. The expected outputs of these activities will give rise to various alternatives to the existing regime, and ultimately lead to deep changes that underpin socio-technical change, as captured in the three types of transformative outcomes (column 4).

(3.2) The next task involves the establishment of continuous monitoring mechanisms that assess the STS's sustainability performance and monitor the progress of potential programmes or interventions in relation to the intended (desired or acceptable) pathways developed in the previous step. Assessment processes are necessary to indicate whether the system is developing according to the chosen transition focus, and if the 'Sustainability Performance Gap' between the targeted goals and the actual STS's sustainability performance is actually reduced. Quantitative system modelling and practice-based action research can facilitate the process and provide valuable insights [57].

This third phase of the framework indicates the 'experimentation' along with 'monitoring, evaluation, and revisions' elements of policy design. Different options of potential intervention points are explored to inform visions and pathways, as developed in the previous steps. This is accompanied by a continuous monitoring and assessment of the transition processes and revisions of the previous steps when needed. As indicated by the bidirectional links of the framework in Figure 1, this is not a one-way process, but it rather includes several revisions and re-evaluations of each step's outcomes, whenever needed.

The above-developed framework, as illustrated in Figure 1 and further elaborated in Tables 1 and 2, provides a comprehensive approach to guide policymaking that enables socio-technical changes towards more sustainable, less resource-intensive systems. It advances upon previous studies in this field, by incorporating transition frameworks and approaches with policy design elements, to support decision-makers in the operationalisation of transformative actions.

Table 2. Scenarios corresponding to possible policy intervention points. Note: author's adaptation from [56,58,59,71].

<table>
<tr><th>Type of Transition Pathway</th><th>Potential Intervention Points</th><th>Expected Outputs</th><th>Expected/Targeted Transformative Outcomes</th></tr>
<tr><td>1. Regime substitution
(Sudden landscape pressure leads to rapid substitution of the regime by mature niches, e.g., shift from single-use plastic bags to reusable bags, from fossil fuels to renewable energy technologies)</td><td>- Stimulate different niches through support mechanisms, i.e., creation of innovation platforms, policy instruments
- Manage the consequences stemming from the destabilisation of a regime</td><td>Rise of various alternatives for systems change, which break through and replace existing regimes, with minimal negative externalities and trade-offs</td><td rowspan="4">A. Building and nurturing niches:
Shielding
Learning
Networking
Navigating expectations

B. Expanding and mainstreaming niches:
Upscaling
Replicating
Circulating
Institutionalising

C. Opening up and unlocking regimes:
De-aligning and destabilizing
Unlearning and deep learning in regimes
Strengthening regime–niche interactions
Changing perceptions of landscape pressures</td></tr>
<tr><td>2. Transformation, dealignment, and re-alignment
(Disruptive landscape pressure in the context of immature niches leads regime actors to redirect their activities and create competition between niches, e.g., emergence of electric vehicles, plant-based alternatives in food systems)</td><td>Accelerate, stimulate, and/or scale up single niches and align different niches to each other</td><td>Links created between various niches, in a process of strengthening them to enter the markets</td></tr>
<tr><td>3. Reconfiguration
(Disruptive landscape pressures direct the regime to adopt symbiotic niche innovations and change its structure, e.g., from traditional agriculture towards regenerative farming practices, from fast fashion to sustainable and circular fashion practices)</td><td>- Weaken the role of incumbent regime actors hindering transition
- Support symbiotic niches that attempt to enter the regime to solve problems</td><td>Niches gradually trigger change in regime structure, e.g., through the introduction and/or banning of specific technologies, subsidies removal for certain industries, increased participation of niche actors in policy advisory</td></tr>
<tr><td>4. Regime Reproduction
(In the absence of major landscape pressure, niches do not break through, and the regime continues to reproduce itself, e.g., continued reliance on fossil fuel-based energy sources, traditional gasoline-powered vehicles)</td><td>- Coordinate multi-regime interactions, both within and between systems that are interconnected within a societal challenge
- Tilt the landscape by enabling change in the directionality of locally bounded socio-technical systems, incorporating symbiotic niche innovations and/or extending beyond specific niches and regimes</td><td>- Input–output relations between regimes are complementary and jointly address a societal challenge
- Altered broader framework conditions at the landscape level that can trigger change at the regime and niche level</td></tr>
</table>

It must be noted that many frameworks cover different aspects of sustainability transitions and policy design, which address the same or similar policy challenges as ours—without considering socio-technical systems as their unit of analysis. For instance, Lazarevic et al. [166] examine how the transformative outcomes framework introduced by Ghosh et al. [59] can be expanded by incorporating additional consequences of socio-technical change. Haddad and Bergek [161] concentrate on evaluation protocols for transformative innovation programs, combining the literature on sustainability transitions with policy evaluation. Mok and Gaziulusoy [167] centre on strategic design for sustainability transitions by combining three strategic design modes: strategic design positioning, strategic design visualisation, and strategic design innovation. The similarity between these papers and ours is that they try to bring together the transitions literature with the policy design literature for the acceleration of sustainability. However, they are distinct in focusing on only a few elements of the policy design process and just paying limited attention to the socio-technical systems literature. In contrast, our framework provides a more holistic conceptualisation of transition phases with specific steps to operationalize them, and therefore, can be considered as bridging the previously presented approaches.

7. Conclusions

Transition actors, either practitioners or from the policy or research arena, struggle to successfully steer sustainability transitions due to their complex patterns and dynamics. These actors need to be equipped with the necessary knowledge and tools that would allow them to acquire a comprehensive overview of the problem that needs to be addressed, the socio-technical system(s) associated with it and its dimensions, the dynamics that support or hinder change, and, finally, the potential transition pathways that could lead to the envisioned sustainability goals.

Our review shows clearly that despite the enormously rich literature and wide application of the transition frameworks in case studies, the literature provides little guidance on how systemic change could be designed to address particular societal challenges, starting from a systematic chart of the corresponding system to the evaluation of its sustainability performance over time.

In response, this paper takes stock of the most relevant frameworks and methods available to manage change towards sustainability and provides guidance on how they can inform policy design for sustainability transitions. A conceptual framework is built from the integrative review of the literature on sustainability transitions and socio-technical systems analysis to help steer progress towards SDG attainment. Our framework aims to inform policymakers from the initial representation of the problem to the formulation of the intervention and its eventual evaluation for further refinement, through the exploration of answers to three main sets of questions:

- Baseline Assessment: What are the origins and magnitudes of the problems to be addressed? What are their drivers?
- Target Visioning and Pathway Design: What are the feasible targets that will enjoy collective support? Which innovations can foster transition towards the specific goal or mission, and carve out the pathways corresponding to the elimination of the original problem?
- Implementation and Evaluation of Policy Interventions: How should the policy vision be realised? What are the possible intervention points to transition to the target STS state? How can sustainability transition performance be assessed for refinement of policy design?

This is carried out through a discussion of the frameworks and approaches that feature prominently today in the transitions research (Sections 1–5). These are synthesised into a conceptual framework (Section 6) that aims to serve as a practical tool for transition actors, helping them navigate the complexities of sustainability transitions.

In summary, our research enhances our understanding of the dynamics, processes, and pathways that are crucial for the acceleration of transformations to the SDGs. It provides a conceptual framework for policymakers, practitioners, and researchers to navigate the complexities of STS transition, address critical questions, and undertake specific tasks to assess the baseline context of the system, design pathways, and intervene with the right set of strategies to attain them. Our framework offers a valuable tool to operationalize change and achieve progress towards the SDGs, through the transformation of socio-technical systems.

At this juncture, it is noted that the paper is limited to the development of a theoretical framework and does not provide empirical illustrations of its applicability. The scope of the central research question was such that the paper focused on the extensive discussion of existing frameworks in order to propose a refinement. Thus, a comprehensive exploration of empirical illustrations for all presented frameworks and approaches could not be attempted. Furthermore, it was not possible to test existing policies and their implementation for SDG attainment against our framework. Yet, this presents an avenue for future studies. Future research could provide real-world examples to validate, refine, and enhance the practical relevance of the framework. Detailed policy evaluation against the proposed framework can lead to validation and further refinement. Its practical relevance and implications can also be tested and such explorations may reveal new insights for policy development and implementation. For instance, this would be particularly relevant if policy design to attain specific SDG targets were examined against our conceptual framework.

In conclusion, if transition research is to remain relevant now with the ever-increasing urgency to transform all of our human and socio-technical systems that contribute to climate change, it has to continue to integrate its tools to carve out viable future transition pathways.

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