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Perspectives on Modeling Energy and Mobility Transitions for Stakeholders: A Dutch Case

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Abstract: We address the value of engaging stakeholders in energy and mobility transitions by using models. As a communication medium, models can facilitate the collaborative exploration of a future between modeling researchers and stakeholders. Developing models to engage stakeholders requires an understanding of state-of-the-art models and the usability of models from the stakeholder perspective. We employ mixed methods in our research. We present the overview of models that have been proposed to make sense of the transitions in the scientific literature through a systematic literature mapping (n = 105). We interviewed 10 stakeholders based in The Netherlands to elaborate on use cases in which models can benefit stakeholders in practice and the characteristics of usable models. We conclude our research by elaborating on two challenges of model design that modeling research can consider to engage stakeholders. First, we argue that understanding the epistemic requirements of both modeling researchers and stakeholders that models can simultaneously meet is crucial (e.g., questions addressed using models and assumptions). Second, we seek technical solutions for producing models in a time-wise manner and developing interfaces that allow models distant in formalism and represented phenomena to communicate in tandem. Our research creates awareness of the model design aspect by considering its usability.

Keywords: energy transition; sustainable mobility; modeling; transition models; stakeholder engagement; learning; usability of transition models; epistemic requirement; model integration

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1. Introduction

Achieving sustainable energy and mobility systems requires stakeholder decisions to be made and actions to be taken over time [1–4]. Accordingly, various models with different formalisms and represented phenomena have been introduced to support these heterogeneous decision-making processes. These include policymaking frameworks that articulate relationships between policies and their environmental impacts [5], energy audit models that explore industrial measures for improving energy efficiency [6–8], and quantitative models that simulate future scenarios to enhance policymaking consistency and validate underlying theories [9,10].

1.1. Engaging Stakeholders in the Transitions by Using Models

Engaging stakeholders is recognized as a crucial element for achieving societal transformation [11–13]. Models can serve as a valuable medium for collaborative research between stakeholders and researchers about systems transitions. However, it is vital to investigate how adaptable models are for engagement [9].

Researchers working on energy or mobility system modeling have focused on enhancing modeling practices by better representing transitioning systems. This involves understanding modeling methodologies [14–17], the characteristics of systems (e.g., techno-economic details, heterogeneity of actors, emergent behaviors, dynamics of transition scenarios) [17–20], and geographic, temporal, and sectoral resolutions [19,20]. Despite this progress, research on the usability aspect of models from the stakeholder perspective is still in its early stages.

Recent studies have addressed concerns regarding the usability of models from the stakeholder perspective. First, the studies highlighted the need for models to better represent human behavioral aspects (e.g., cultural dimensions) and balance price policies (e.g., regulatory policies) with non-price policies (e.g., public awareness) [21,22]. Second, the studies revealed that improving the comprehensibility of models through visual aids and instructions could enhance their usability [22,23]. Third, they showed that transparent communication regarding involved assumptions, databases, and modeling frameworks could also improve model usage [21–24]. Last, the articles emphasized the applicability of models in specific use cases, such as integrating energy models into transport planning and using them for policymaking and collaboration between municipalities [22,23].

Modeling is an epistemic activity that helps us understand complex phenomena [25,26]. In energy and mobility transitions, engaging stakeholders through modeling can support decision-making and facilitate collaborative learning between researchers and stakeholders [27–29]. However, we must broaden our understanding of two aspects. First, we must understand models that are diverse in formalism in the represented phenomena relevant to the transitions. By understanding the diversity of models and each modeling approach's strength(s), researchers can employ suitable modeling methods by balancing the use context in practice and the research environment. Second, we need to consider characteristics that can ensure the usability and effective use of models in practice.

Muratori et al. [30] reviewed approximately 30 models that were developed to project the future of integrated energy and mobility systems and categorized the models by specific purposes (e.g., models for estimating vehicle choices). However, as stakeholders' needs may exceed these categories, we expanded our exploration of models in our research. While the usability of models from a stakeholder perspective has mainly been discussed for energy system models, we incorporated user perspective knowledge to identify common stakeholder perspectives for future research. We consider that doing so would help researchers to better understand the needs and viewpoints of stakeholders and thereby develop more valuable and relevant models for exploring integrated energy and mobility systems.

1.2. Research Questions

To address the knowledge gap, we investigated the following research question:

> *"What are the key considerations and approaches for effectively engaging stakeholders in energy and mobility transitions using models?"*

To this end, we answered three sub-research questions. The sub-research questions and the associated research aims and objectives are presented in Table 1.

Demarcation

Our research aims to support energy and mobility system transitions in The Netherlands. Therefore, we focused our interviews on practitioners working in the Dutch energy and mobility sectors.

Table 1. Research questions, objectives, and methods.

	RsQ1	RsQ2	RsQ3
Research question	*"What models have been proposed in the scientific literature to understand energy and mobility transitions?"*	*"What traits of models are supportive of stakeholder engagement?"*	*"How can models be designed to engage stakeholders in the transitions effectively?"*
Aim	Providing state-of-the-art models used for understanding the transitions, which can support modeling researchers to employ models and modeling approaches that are suitable for engaging stakeholders	Providing knowledge about model usability, which can enhance the effectiveness of stakeholder engagement by using models	Providing insights to bridge the gap between available models and stakeholders' needs, which can support modeling researchers to design models for effective engagements
Research objective	Identifying state-of-the-art models presented in scientific literature considering forms, represented phenomena, and utilities	Identifying traits of models that can enhance their usability from the stakeholder perspective	Identifying approaches for the model design
Method	Systematic literature mapping	Stakeholder interview	Synthesis
Section	Section 2	Section 3	Section 4

1.3. Research Methodology

This paper utilized a three-step methodology (Table 1). First, a systematic literature mapping was conducted to review models in the scientific literature that pertained to energy and mobility transitions, thereby addressing RsQ1 in Section 2. Second, stakeholders from the local and regional government, businesses, and innovation management involved in energy and mobility transitions were interviewed to gather ideas for use cases of models in practice and the traits of usable models necessary to answer RsQ2 in Section 3. Third, the reviewed models were evaluated from the stakeholder perspective to determine how to design models that better engage stakeholders. Finally, the evaluation and reflection results were synthesized to answer RsQ3 in Sections 3 and 4.

2. Models for Understanding the Transitions

In this section, we explain the methodology used for the literature mapping in Section 2.1 and present six grouped models we reviewed in detail in Section 2.2.

2.1. Method: Systematic Literature Mapping

We utilized systematic literature mapping techniques described in systems engineering, software engineering, and environmental management research papers [31–33].

2.1.1. Literature Acquisition Procedure

To acquire the scientific literature that presented the models in question, we used the PICO search tool to determine keywords and specify a search query [33–36]. Our population of interest was scientific articles, while our intervention involved producing models for decision support and simulation to explain or predict the transition phenomena. We did not make comparisons or aim to favor any one model. Our search string was "(model OR simulation OR 'decision support system') AND (mobility OR transport OR vehicle) AND ('energy transition' OR decarbonization OR sustainab*)," which we applied to Scopus and Web of Science databases for articles published from 2016 to 2021. We only gathered scientific papers whose titles involved the search string. We retrieved 215 articles but only used 105 that met our inclusion criteria of being written in English and having free full-text availability. We excluded papers such as conference summaries and those whose titles merely included homonyms of our search terms (e.g., suspended solids transport).

2.1.2. Literature Mapping Protocol

We used an iterative process to map the retrieved literature due to the diversity of the reviewed models and their potential uses. We initially attempted deductive reasoning using existing frameworks (e.g., the Transition Management framework presented by [3]) by assuming that models would be used for governance activities, such as vision development. The results of this approach were of limited value, as not all models were designed for governance activities. We then tried to develop a new framework, but the deterministic process was unsuitable for identifying the various models. Ultimately, we used inductive reasoning and divided the literature into qualitative and quantitative models based on their primary functions and utilities (e.g., system articulation and sustainable business models) (Figure 1). We further categorized the models based on their representations, as explained in Section 2.2.

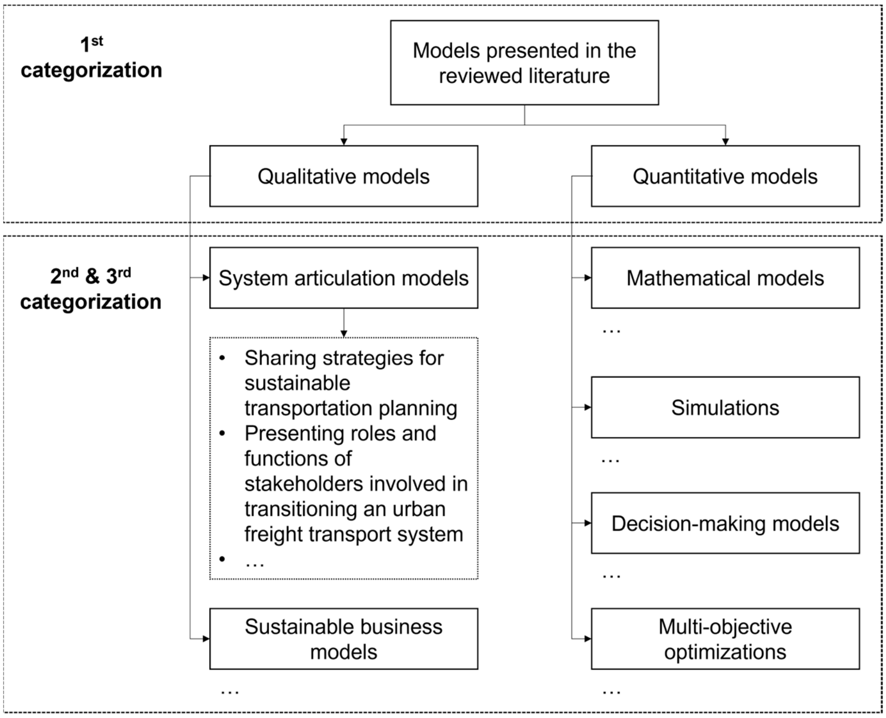

Figure 1. The literature mapping protocol.

2.2. Results

The literature mapping informed the following six types of models:

- Qualitative articulation models (Section 2.2.1);
- Sustainable business models (Section 2.2.2);
- Mathematical models (Section 2.2.3);
- Simulations (Section 2.2.4);
- Decision-making models (Section 2.2.5); and
- Multi-objective optimizations (Section 2.2.6).

Table 2 represents the main functions of six types of models and answerable question(s) by utilizing the models.

Table 2. Categorized models.

Model	Main Function(s)	Answerable Question(s) by Utilizing the Models *
Qualitative articulation models (n = 22)	Sharing both cutting-edge and underexplored knowledge	What are the functions and responsibilities of the stakeholders engaged in transitioning the urban freight transport system?
Sustainable business models (n = 18)	Suggesting viable business models that align with sustainability in the field of mobility	What are the strategies for managing electric vehicles at the end of their lifespan?
Mathematical models (n = 23)	Depicting human attitudes and behaviors	What methods can be used to forecast the adoption behavior of emerging technologies and services?
	Depicting the performance of an organizational activity	How can we evaluate the effectiveness of a policymaking tool?
	Depicting the effects of an organizational activity	What methods can be used to measure the environmental sustainability of an urban mobility design?
Simulations (n = 24)	Anticipating the future of the area by comprehending alterations in human conduct, technological advancement, market trends, and policy execution	How does implementing an international policy target affect a national economy?
	Examining the interaction of a hypothetically designed system with existing systems through analysis	What materials are appropriate for manufacturing batteries for electric vehicles?
	Assessing the influence of decision-making principles employed by practitioners	How can sustainable mobility transition scenarios be effectively generated?
Decision-making models (n = 6)	Developing decision-making criteria for a mobility system maintenance or development project	How are the decision-making criteria shared and applied in regional end-of-life vehicle management?
Multi-objective optimizations (n = 12)	Optimizing the operation of a dynamic system while balancing multiple objectives	How can a logistics company determine the most efficient route for its vehicle?

* We formulated the questions by only reviewing the literature that was presented as examples. Thus, the capability of each type of model is not limited to answering the written questions.

2.2.1. Qualitative Articulation Models

The initial literature group introduced qualitative articulation models that visually and descriptively presented concepts and knowledge relevant to energy and mobility transitions (Table 3). The literature mainly offered these qualitative articulation models to increase stakeholder awareness and understanding of lesser-known expertise and contribute to field-specific academic research practice.

2.2.2. Sustainable Business Models

The second literature group identified the enablers of implementing sustainable business models in the mobility sector through business modeling (Table 4).

Table 3. Knowledge disseminated through qualitative articulation models.

Shared Knowledge through the Qualitative Articulation Models	Reviewed Articles
Strategies for sustainable transportation planning (process), including modeling approaches (n = 9)	[37–45]
The functions and responsibilities of stakeholders involved in transitioning an urban freight transport system (n = 1)	[46]
Urban spatial planning aimed at addressing mobility issues such as traffic congestion (n = 2)	[47,48]
Technical solutions for adapting an urban transportation system to fit the unique characteristics of a city, such as a tourism-based economy (n = 2)	[49,50]
The current state of academic knowledge and practices related to emerging research topics, such as end-of-life vehicle management and modeling techniques for electric vehicle batteries (n = 8)	[51–58]

Table 4. Knowledge disseminated through the sustainable business models.

Shared Knowledge through the Sustainable Business Models	Reviewed Articles
Factors that facilitate sustainable urban mobility, such as the endorsement of celebrities (n = 4)	[59–62]
Ways to promote shared vehicle usage, such as offering user incentives (n = 3)	[63–65]
Ways to facilitate the management of end-of-life electric vehicles and batteries, such as fostering cross-sectoral collaboration (n = 3)	[66–68]
Revising business models to suit local contexts and mobility-related industries, such as biofuel transportation, while ensuring sustainability (n = 8)	[67,69–75]

2.2.3. Mathematical Models

The third literature group consisted of mathematical models representing the critical phenomena relevant to transitioning energy and mobility systems in mathematical equations. These models allowed authors to contribute niche knowledge about the phenomena and communicate with stakeholders such as policymakers, urban and traffic planners, designers, and private businesses. Generally, the models represented human behavior and attitude, organizational activity performance, and the impact of organizational activity (Table 5).

Table 5. Phenomena represented in mathematical models.

Displayed Phenomena		Reviewed Articles
Human attitude and behavior (n = 10)	Phenomena related to the choice of travel mode, such as the influence of social norms, emotions, and expert opinions	[76–79]
	Emerging technology and service adoption by capturing decision-making episodes and consumer knowledge, particularly in the context of electric vehicles	[80–84]
	Developing trust in emerging mobility concepts	[85]
The performance of organizational activity (n = 5)	The effectiveness of a decision support system or a policymaking tool	[86–90]
	Other possible factors that could impact the performance of sectoral mobility practices, including aspects such as organizational innovation, that may not be commonly considered or well-known	
The effects of organizational activity (n = 8)	The environmental sustainability of technological solutions, such as urban mobility designs and electric vehicles	[91–93]
	The economic impact of last-mile delivery and sectoral transportation activities when redesigning logistics chains	[94,95]
	The sustainability of urban mobility through an integrated assessment approach	[96–98]

2.2.4. Simulations

The fourth literature group focused on simulating mathematical models to achieve three objectives: Projecting the future of a locale, analyzing hypothetically designed systems, and testing practitioners' decision-making principles (Table 6). The simulation results were then used to provide recommendations for policymaking and business practices based on changes in human behaviors, technology development, market dynamics, and policy implementation.

Table 6. Objectives of simulation contents.

Objectives of Simulations	Simulation Contents	Reviewed Articles
Anticipating the future of the area by comprehending alterations in human conduct, technological advancement, market trends, and policy execution (n = 11)	The evaluation of the effectiveness of implementing international policies, such as the EU's decarbonization target, concerning future economic and technological mobility advancements	[99,100]
	The effects of applying international policies on the economies of individual nations	[101,102]
	Examining the sustainability of a city through the lens of demographic changes, land use, travel behaviors, and technological advancements	[103–105]
	The influence of social media on public perception of sustainable mobility	[106]
	The evolution of the mobility sector due to drivers such as advances in Information and Communication Technology (ICT) and changes in user behavior	[107–109]
Examining the interaction of a hypothetically designed system with existing systems through analysis (n = 9)	Investigating potential materials for the production of electric vehicle batteries and other vehicle components Examining sustainable practices for operating shared autonomous vehicles and developing charging and swapping stations	[110–115]
	The effectiveness of a connected vehicle system, taking into account factors such as safety, vehicle diversity, and technology market readiness	[116,117]
	The impact of user incentives on the performance of a bike-sharing system	[118]
Assessing the influence of decision-making principles employed by practitioners (n = 4) (e.g., principles applied to vehicle routing problem-solving and sustainable mobility scenario generation)		[119–122]

2.2.5. Decision-Making Models

In transportation projects, stakeholders such as citizens, local governments, and academics may have varying expert knowledge and preferences. Therefore, the authors used modeling techniques to capture stakeholders' priorities. This approach aimed to develop decision-making criteria models that are coherent and reflect the priorities of all stakeholders. The authors applied this modeling technique to transportation development projects and end-of-life vehicle management [123–128].

2.2.6. Multi-Objective Optimizations

The transportation sector is constantly changing due to the adoption of new technologies, such as electric vehicles, and the integration of electricity and gas systems. As a result, the system performance evaluation model is evolving, emphasizing societal impacts such as greenhouse gas emissions. Stakeholders, including logistics and transport providers, urban planners, supply chain managers, transport infrastructure managers, and policymakers, must decide on the best strategy for operating dynamic systems that address multiple objectives, including cost efficiency and environmental impact. To support multi-objective consideration, the authors formulated mathematical equations to describe operational systems, such as the supply chain, and the operation's objectives, such as profitability, to determine the optimal solution (Table 7).

Table 7. Multi-objective problems addressed by the reviewed operation research.

Stakeholders	Operation Problem	Reviewed Articles
Logistic and transport service providers	Multi-objective vehicle routing objectives are the amount of energy consumed, the quality of a transported good, etc.	[129–134]
Transportation infrastructure managers	Managing a transportation infrastructure considering emergent problems due to rapid urbanization or energy transition and attempting to fulfill objectives such as cost minimization and environmental friendliness	[135–139]

We examined six distinct types of models that varied in their forms, representing phenomena, and utilities. In the next section, we discuss how to design such models to engage stakeholders in the transition process effectively.

3. Stakeholder Perspective on the Usability of Models

This section addresses our second and third research questions: "What traits of models are supportive of stakeholder engagement?" and "How can models be designed to engage stakeholders in the transitions effectively?" We conducted semi-structured interviews with practitioners in the Dutch energy and mobility sectors to gain insight into the stakeholder perspective on model usability. Section 3.1 provides a description of our interview methodology. Section 3.2 examines use cases in which models can be beneficial in practice and discusses the traits of usable models addressed by the interviewees.

3.1. Method

We utilized a qualitative research method involving semi-structured interviews to gain a stakeholder perspective on model usability. The interviews comprised four parts, as shown in Table 8. Our goal was to gain insight into tasks the interviewees perform so that we can understand the circumstances in which energy and mobility transition models can be helpful in practice. We also gained insight into the interviewees' perspectives on the strengths and weaknesses of models.

3.1.1. Data Collection

We used quota sampling to select interviewees with diverse perspectives from provincial and municipal levels of government and industry (Table 9). We invited 10 practitioners who were accessible to the authors and willing to participate in the research using convenience sampling rather than a randomized group of people [140]. The interviewees had diverse types of experience from relevant stakeholder groups in energy and mobility transitions, representing the government, the power grid operation, and the industry that provides energy and mobility solutions. The areas of expertise ranged from energy and electric vehicle charging infrastructure, sustainability, and mobility program management to supporting policymaking. Each interview lasted about one hour, and all sessions took place online from February 2022 to April 2022 due to COVID-19 complications. During the discussions, the practitioners shared their experiences of using models and outputs for policy planning, communicating with stakeholders, and gaining a better understanding of the development of products and business models. In addition, they provided thoughts on improving the utility of energy and mobility transition models. All interviews were conducted in English, recorded, transcribed, and anonymized.

Table 8. Semi-structured interview protocol applied in this research.

Interview Part	Objectives	Asked Questions/Activities per Part
Introduction	Letting interviewees acclimatize to the interviewer's research project and the objectives of interview	A short presentation on the research background and research interest in understanding how to produce models for stakeholders and supportive user scenarios
Understanding interviewees and supportive models to them from multiple perspectives: Working organizations, conducting tasks in the organizations, and individual voices on the transitions	Understanding the tasks conducted by interviewees in their organizations	Q1: "What are your usual tasks in your organization?" Q2: "Can you explain the energy and transport transition projects you are responsible for?"
	Exploring the circumstances in which interviewees make complex decisions wherein energy and mobility transition models can potentially be useful	Q3: "What kinds of decisions do you (have to) make about energy and transport transitions?" Q4: "Do you experience any dilemmas during such decision-making processes?"
Understanding strategies for designing useful models from user experience	Understanding whether interviewees are directly engaged in using models	Q5: "When working on energy and transport transition projects, have you or your organization ever used computer software/tools/games?" Q5-1-1 (if the answer to Q5 was "Yes."): "What software/tools/games did you use?"
	Understanding the effectiveness of using models and/or content generated from models	Q5-1-2: "What support did you receive?" Q5-1-3: "What were the strengths and weaknesses of the software/tools/games?"
Finalization	Concluding interviews	A statement of gratitude for participating into the interview

Table 9. The information on the interviewees based in The Netherlands.

Sector	Job Description	Number of Interviewees
Provincial government	Regional energy network system design Stakeholder communication for regional energy system planning Regional electric vehicle charging infrastructure management	3
Municipal government	Local sustainability program guidance Local sustainable mobility program management	2
Knowledge management	Power grid management	1
Business	Electric vehicle technology development Electric vehicle charging infrastructure Flexibility solution development Sustainability solution development	4

3.1.2. Data Analysis

To analyze the data gathered from the interviews, we utilized the ATLAS.ti tool and adopted the QUAGOL qualitative data analysis approach [141]. We used Vivo coding to gain an overview of the interviews and summarize the main content. Then, we collected the most frequently occurring keywords in each interview and employed keyword searching to obtain the results [142]. Table 10 presents a summary of the interview results.

Table 10. A summary of the interview results.

<table>
<tr><th>Discussed Content</th><th>Summary</th></tr>
<tr><td rowspan="3">Tasks performed by the interviewees, which could be supported by using models (Q1 to Q4): Section 3.2.1</td><td>Governmental officers:
• Identifying synergies and dilemmas that would be emerged as a result of multiple local initiatives by industry and government sectors (e.g., unexpectedly high cost for acquiring an overarching system, such as the electricity grid and its upkeep)
• Managing regional electric mobility infrastructure to achieve local and national governments objectives simultaneously</td></tr>
<tr><td>Knowledge management (power grid):
• Developing the proof of concept of a technical solution in the context of customer engagement</td></tr>
<tr><td>Businesses
• Supporting product design for the transitions in the context of engineering optimization and communication
• Exploring future circumstances in which products will be sold (e.g., customer preference) and the consequences of introducing products to a future market (e.g., the number of required public charging stations)
• Asset management: Electric charging stations</td></tr>
<tr><td>The interviewees' experience with models (Q5)</td><td>Interacting with models directly or only utilizing the outputs of models: Models were generated by either internal employees (e.g., engineers, data analysts) or external personnel (e.g., universities, consultants)</td></tr>
<tr><td>Functions of the models used (Q5-1-1): Sections 3.2.1 and 3.2.2</td><td>Governmental officers:
• Presenting locations that require existing electric charging stations to be updated.
• Indicating traffic flows and predicting electric charging demands
• Estimating the number of electric charging stations demanded in future
Knowledge management (power grid):
• Estimating the impacts on the power grid and computing the effects of applying diverse smart charging profiles
Businesses:
• Supporting the product design (e.g., optimization)
• Estimating the carbon footprint
• Optimizing flexibility solutions</td></tr>
<tr><td>Strengths of the models used (Q5-1-2): Sections 3.2.1 and 3.2.2</td><td>• Presenting the status of electric charger usage: Supporting the creation of new business opportunities
• Easy-to-change parameters
• Possibility of using in-house data
• Enabling the exploration of the impacts of flexibility solutions by applying diverse scenarios
• Supporting decisions over the number of electric charging stations, which helps communication between stakeholders (e.g., provincial and municipal governments, and charging point operators)</td></tr>
<tr><td>Weaknesses of the models used (Q5-1-3): Section 3.2.2</td><td>• Limited representation of the real world (e.g., a lack of realistic illustration of human behaviors)
• Transparency of models (e.g., codes, assumptions)
• Unnecessarily detailed information (e.g., indicating lots of correlations)
• Extensive development processes
• Less comprehensive definition of a key concept (e.g., mobility)
• Lack of compliance between Dutch and European systems</td></tr>
</table>

3.2. Results

The interviews yielded two types of results. First, in Section 3.2.1, we discuss two use cases where stakeholders can be supported by using models. Second, in Section 3.2.2, we explore the characteristics of models that are essential for effective usage.

3.2.1. Use Cases of Models Supportive to Practitioners

We identified two situations where stakeholders could effectively use models to understand energy and mobility transitions in practice. The first situation is when organizations use models to gain insight into future energy and mobility systems, such as understanding the customer segment of a future mobility market. The second situation is when stakeholders collaboratively design local and regional infrastructure across sectors, such as provinces, municipalities, industries, and civic groups.

Organizational Learning to Understand Future Systems

The interviews revealed three specific examples of organizational learning. First, models that indicate the state of organizational progress in the transitions could offer valuable information. For instance, practitioners in electric vehicle charging innovation development and marketing communications discussed the evaluation of flexibility solutions for preventing grid congestion and ensuring the sustainability of product delivery and employee mobility patterns. A consultant experienced in flexibility solutions stressed the importance of identifying the societal values provided by the solutions, such as energy independence: "If you work on models, the models should also integrate external costs that are indirect effects of benefit".

Second, the governmental officers indicated a preference for models that can support the design of energy and mobility infrastructure. We found that designing models while considering the different responsibilities of local and regional governments is crucial. Models that can simulate the adaptation strategies of local energy and mobility infrastructure in accordance with future projections (e.g., the trend of electric vehicle purchasing) and regulations (e.g., the EU's zero-emission policies) appear to be relevant to the local government level, according to a municipality officer: "As a city, [. . .] we don't have any influences about car manufacturers. [. . .] How are we coping with the grid capacity shortage? How are we combining it with the other mobility transition programs?" On the other hand, models that can present changes in regional energy infrastructure potentially made by such local initiatives and industries would be helpful for regional governments. A regional energy infrastructure planner highlighted the challenge of assessing proposals for developing energy supply systems that could accommodate renewable energy parks and electric vehicles. The proposals submitted by companies responsible for designing and implementing these systems often presented the best-case scenarios from the companies' point of view. However, as a province, it was crucial to consider the values associated with these system development solutions from the public's perspective, including factors such as land use, environmental impact, and potential effects on energy prices resulting from their implementation. Such reflections required a thorough review of alternatives, but generating other options and comparing them to the company's solutions was limited due to the lack of resources, such as a "design tool" as mentioned by the interviewee.

Third, the interviewees highlighted models that allow stakeholders to spot future business opportunities. For example, a government charging infrastructure practitioner noted that models providing the expected demand for electric vehicle charging points, capacity, and installation locations could facilitate tendering between municipalities and charging point operators. An industry practitioner in charging point management emphasized the usefulness of a model that can help identify potential business cases required in the near future. This proactive approach aims to prevent user disappointment resulting from the current lack of available charging poles at charging stations due to limited availability.

Collaborative Infrastructure Design with a Diverse Set of Stakeholders

The interviewees revealed that models could also support the collaborative design of regional energy systems among heterogeneous stakeholder groups. A provincial officer mentioned that planning a regional energy system change was challenging due to inadequate communication between government and industry. To deliver the energy to end-users, the province had to understand the type of energy required by the industry ahead of time. According to the officer in question, there was a different understanding between the types of energy carriers (e.g., hydrogen, green gas, electricity) to be provided to the industrial area and the kind of energy (e.g., electricity, heat) required by the industrial processes such as production. However, communication was hindered due to the confidentiality of future industry plans. To address this, a provincial government officer devised an idea to set up a "task force" that included a diverse range of stakeholders. Using models, stakeholders could test their energy supply and demand plans and receive feedback. Doing so could help to avoid mismatches between supply and demand and identify better energy-sourcing options.

Models for Organizational Learning and Collaborative Infrastructure Design

Both use cases discussed earlier could be supported using computational simulations. This is because the use cases involve predicting the future of the business environment and regional infrastructure, analyzing the impacts of business solutions on multiple scales, and testing the implications of various choices. These are the primary functions of simulation (Section 2.2.4). In addition, developing sustainable business models is crucial to facilitate changes in business practices.

Collaborative infrastructure design would demand decision-making models and optimizations, as the collaborative process involves multiple stakeholders from different sectors who may not hold homogenous decision-making criteria. Therefore, decision-making modeling can help structure the shared decision-making process (Section 2.2.5). Furthermore, since the collaborative process is participatory, exploring optimum design decisions that meet diverse requirements served by optimizations is an essential activity (Section 2.2.6).

Developing the models discussed above, including sustainable business models, decision-making models, simulations, and optimizations, would ultimately require a detailed articulation of the systems on which the models are founded (Section 2.2.1). Additionally, transforming qualitative expressions into mathematical formulas is critical for computational prediction and optimization (Section 2.2.3). Finally, it follows that applying a range of diverse models while considering their interconnectedness would be crucial to allow modeling researchers to produce models for effective engagement (Figure 2).

In addition, we consider that the term "model" risks creating confusion when engaging stakeholders because some people lack modeling knowledge. We noted that interviewees used atypical terms, such as "digital twin". A municipal officer said: "Working with a model-based [. . .] or an agent-based model is really abstract for me or vague".

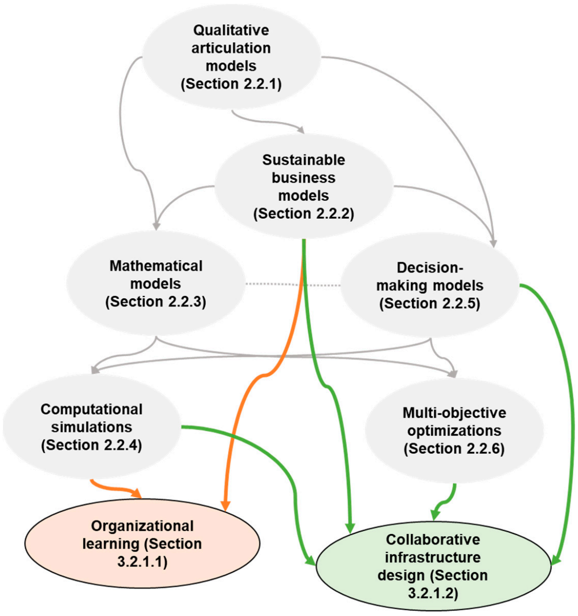

Figure 2. Required models for the two use cases.

3.2.2. Supportive Traits of Models to Engage Stakeholders

Based on the interviews, we found that models with specific characteristics could be better used. These uses include:

- Considering stakeholder perspectives while selecting phenomena to be modeled, including key concepts and assumptions;
- Providing insights into the near future within a short amount of time;
- Conveying balanced information involving reliability and usability;
- Ensuring transparent communication of involved assumptions; and
- Enabling communication between other models.

To evaluate the six grouped models in Section 2.2 in terms of these characteristics, we created Table 11.

Table 11. Assessing the degree to which the reviewed models possess the essential traits to engage stakeholders.

Required Traits of Models	Considering Stakeholder Perspectives While Selecting Phenomena	Providing a Near-Future Projection	Balancing Reliability against Usability, and Communicating Assumptions Transparently	Enabling Real-Time Communication between Models
Qualitative articulation models	-	-	▲	-
Sustainable business models	●●	-	▲	-
Mathematical models	-	○	▲	●
Simulations	-	○	▲	●
Decision-making models	●●	-	▲	-
Multi-objective optimizations	-	-	▲	○
Rating scale	(-) We barely observed models providing the feature. (○) We observed a few models that partially provide the feature. (●) We observed less than half of the models providing the feature. (●●) We observed more than half of the models providing the feature. (▲) The examination required subjective judgment.			

Considering Stakeholder Perspectives While Selecting Phenomena to Be Modeled

Perspectives may differ between the modeling researchers who create the models and the stakeholders who utilize them for energy transitions. This can result in differences in the phenomena the two groups consider and the interpretation of concepts, including their reasoning procedures. To ensure that models are adopted and used appropriately, it is crucial to represent relevant phenomena for researchers and stakeholders. For example, modeled city traffic may be incomplete if pedestrian and passenger behaviors are not considered from the perspective of municipal government officers. Additionally, the interpretation of a concept can vary among researchers and stakeholders. For instance, an energy solution business practitioner found an oversimplified definition of "mobility" in a model for quantifying a carbon footprint that considered an equivalence between commuting via personal vehicles and public transportation.

We examined whether the models reviewed in this study incorporated the perspectives of model users. Sustainable business models were produced by considering stakeholders' interests through qualitative research, such as organizing workshops to co-create locally adapted business models [70,71,73,74] (Section 2.2.2). Decision-making models captured stakeholders' decision-making procedures using customized research methods such as the Fuzzy Analytic Hierarchy and Interval Analytic Hierarchy Processes [125–127] (Section 2.2.5). In some mathematical models, stakeholders appeared to be involved as research subjects whose behaviors were observed and measured rather than direct perspective providers. However, most models did not significantly engage stakeholders in the model production process.

Providing Insights into the near Future within a Short Amount of Time

We determined the importance of quickly producing models that project the near future. For example, an interviewee responsible for electric vehicle charging infrastructure stressed the need for prompt future projections (one to three years) to facilitate electric vehicle charging point tendering. A power grid management practitioner also indicated: "I think 2040, 2050 is far ahead, far in the future. We already, or at least certain areas, need outcome". Thus, the interviewee in question recommended that model producers communicate results iteratively and not wait until the modeling is complete: "I am also open to more or less giving a quicker indication. [...] for five days with an accuracy degree [...] then first you have an indication and [...] then you do some more in-depth analysis [...]".

The articles reviewed in Sections 2.2.1–2.2.4 showcased various modeling approaches for future predictions. Simulations were primarily utilized for long-term future projections spanning decades, such as exploring the consequences of international policy targets on national economies by specific years such as 2030 and 2050 [99–102]. However, there was a lack of modeling methods that could provide near-future projections in a cost-efficient manner.

Conveying Balanced Information between Reliability and Usability

We noted that models could be designed to better focus on presenting the essential information primarily by balancing reliability and usability rather than providing overly detailed results. For example, a provincial officer warned against getting bogged down in detail by recalling a model that outlined an intensely frequent prediction of the amount of energy generated: "I don't need from all these companies on the minutes [...] but I need to have an idea about what they use on the everyday level. [...] You have to be reliable but not on the very detail".

An objective evaluation concerning whether models succeeded at balancing between reliability and usability was challenging to achieve because the evaluation appeared to rely on the subjective judgment of a stakeholder adopting models depending on the context of model usage, personal preference, etc.

Attaching Transparent Communication of Involved Assumptions

The interviews highlighted the importance of a clear description of the assumptions made when constructing models to increase their credibility. An interviewee working for a new product design research team used metaphorical expressions, namely "white box" and a "grey box", and discussed the transparency of model elements (e.g., codes). In addition, a provincial officer recalled a modeling result in 2019 that projected that the demand for electric vehicle fast charging stations in 2025 would be 5000, but in 2021 the projected demand for 2025 had increased to 6000. The officer emphasized the importance of communicating assumptions such as parameter settings to ensure the reliability of modeling results. However, it was challenging to evaluate objectively whether the communication of assumptions was transparent.

Enabling Communication between Other Models

During stakeholder interviews, it was suggested that artifacts capable of letting distant models at different geographical scales and with different content communicate with each other, preferably in real-time, would be beneficial. For example, a municipal civil servant mentioned integrating models representing electric vehicle charging demand, grid capacity, and traffic into a single, high-level model: "Well, we're combining these models. [. . .] they put it in our heads, and we hope to say wise words. That's how we do it at this moment". Likewise, a practitioner from an energy flexibility solution business preferred a model that could communicate the impacts of intertwined system changes in national and European energy systems (e.g., standardization).

Similar concepts of integrated models were also found in the literature, such as frameworks for assessing the sustainability of urban mobility by involving multiple models [39,43–45]. Mathematical models and simulations were also used to understand the relationships between long-term policy targets and national economic and technological systems [96,98,104,117]. However, the technical measures needed to enable the interfaces were barely discussed.

4. Discussion

Stakeholders' decision-making affects the transitions of energy and mobility systems. Modeling research has developed models to support these decisions. Effective use of models by stakeholders requires access to the models and an understanding of the characteristics of models that could enhance usability. Understanding the various types of models that exist allows us to employ suitable modeling approaches tailored to use contexts. In addition, understanding the essential characteristics of usable models is crucial for effective utilization. We add to the understanding of both aspects by addressing the last sub-research question, "How can models be designed to engage stakeholders in the transitions effectively"?

4.1. Interpretations and Implications

4.1.1. The Models Covering the Transitions in the Representations

The overview of six grouped models representing energy and mobility transitions revealed that authors developed and used them for different epistemic purposes (e.g., disseminating cutting-edge knowledge to stakeholders and translating complex phenomena into mathematical formulas). It may be the case that the models will effectively address specific questions they are designed for. We, therefore, consider understanding the epistemic objectives and requirements of stakeholders to be an essential aspect of a preparation stage. For instance, decision-making models would primarily suit situations where heterogeneous stakeholder groups must make shared decisions. On the other hand, extensive computational simulations might not be the best tool for stakeholders needing only a brief overview of emerging technologies and adoption behavior research.

This epistemology aspect did not appear to be widely addressed in the transition modeling research. To engage stakeholders effectively, it appears to be crucial to diagnose the questions that need to be answered and to design models that meet the requirements for epistemic activities. To achieve this, exploring how to determine the requirements based on an understanding of inquiry in the context of transitions and how to relate the requirements to selecting appropriate modeling approaches can be helpful.

4.1.2. Approaches for Designing the Models for Effective Stakeholder Engagement

To ensure that stakeholders use models effectively, we interviewed Dutch stakeholders who had experience using models to make decisions. We highlighted two issues to be addressed in order to contribute to effective transition model design. The first issue is representing shared phenomena between modeling researchers and stakeholders while simultaneously acknowledging potentially different epistemic requirements (Section 4.1.1). The second issue is implementing technical measures to produce models cost-efficiently and developing interface artifacts that can make models communicate simultaneously. These two problems are distinct yet related.

We regard the first issue in transition model design as needing a mechanism to facilitate the formulation of shared perception about the state of transitions between modeling researchers and stakeholders and the elaboration of epistemic requirements. We saw the diversity of phenomena represented in the models in Section 2.2. The transitions of such diverse phenomena already amplify the complexity of transition modeling. Conceiving the transitions necessitates individuals to make assumptions, hypotheses, etc. (Section 3.2). If modeling researchers are unaware of this heterogeneity, their models may not be easily accepted by stakeholders. The mechanism can be realized as a form of pre-communication in an early stage of model development.

It could involve illustrating explored phenomena by using models and contemplating the epistemic purposes and requirements of both researchers and stakeholders, which can then support the identification of utilizable types of models (Section 2.2). Transparent and credible models may be produced by outlining models that have the potential to be developed and explaining the cognitive processes involved in the analysis of transitions. During this process, modeling researchers may also communicate the scientific theories and methods used for transcribing the phenomena into mathematical formulas and quantification (Section 4.1.2). In addition, we observed the difficulty of examining some factors of model usability (e.g., balanced reliability and usability) (Section 3.2.2). Modeling research may benefit from tools that measure model usability. Nevertheless, we acknowledge that the concepts discussed here must be rigorously examined scientifically and articulated to avoid encouraging speculation.

Regarding the second problem of model design, providing technical solutions for producing future predictions cost-efficiently and developing interfaces between distant models, the research does not provide sufficient evidence to offer specific recommendations for addressing this problem. However, one suggestion may involve experts from other disciplines collaborating with modeling researchers to improve productivity and streamline the interface development process.

4.2. Limitations of the Research and Suggestions for Future Research

In this section, we discuss research limitations and suggest future research directions accordingly.

4.2.1. Systematic Literature Mapping: The Limited Scope of the Reviewed Scientific Literature and Subjectivity Intervention in the Mapping Mechanism

Our research aimed to offer an impartial survey of existing models by utilizing an iterative mapping approach and reviewing a broad range of scientific literature. Our approach sought to avoid bias toward specific models or scientific disciplines. Nevertheless, we suggest using diverse keywords when formulating search strings to better reflect the diversity of scientific disciplines and associated themes in transition research (e.g., energy justice) (Section 2.1). Additionally, we encountered challenges during the literature mapping process due to our literature categorization approach and taxonomy of models. The associated semantic issues appeared to impact how we identified and analyzed the models (e.g., simulations as design space explorations versus technical system models). As a result, we recommend mapping literature using multiple perspectives more effectively to determine the progress of modeling research and its utility.

4.2.2. Stakeholder Interview: Limited Generalizability

Our exploratory research for understanding model usability from the stakeholder perspective is valuable in raising awareness among the scientific community. Through the interviews, we found that using models can benefit stakeholders' learning about transitions concerning their organizational performance and collaborative infrastructure design. As discussed in Section 3.2.2, our research acknowledges the characteristics of usable models articulated by the previous study (Section 1.1). Nonetheless, our sample size of 10 practitioners from the Dutch energy and mobility sectors may limit the generalizability of our findings (Section 3.1). Moreover, we faced challenges in harmonizing our interviewees' diverse needs and use cases. Thus, we strongly suggest continuing the model user research beyond exploratory research and expanding model usability by employing rigorous scientific approaches.

4.2.3. The need to Validate the Findings with Modeling Researchers

In summary, our research aimed to facilitate stakeholder engagement by using models and support modeling researchers' modeling practices for engagement, as presented in Table 1. However, we recognize that our research findings were not validated by other modeling researchers, limiting our evaluation's objectivity. Therefore, we recommend further research to investigate the perspective of modeling researchers on engaging stakeholders in their modeling practice. We can develop a more balanced and effective engagement practice by considering both parties' viewpoints.

5. Conclusions

This research aimed to understand the key considerations and approaches for effectively engaging stakeholders in energy and mobility transitions using models. We answer our sub-research questions and the main research question as follows.

RsQ1: *"What models have been proposed in the scientific literature to understand energy and mobility transitions?"* In total, we explored six types of models through systematic literature mapping: Qualitative articulation models, sustainable business models, mathematical models, simulations, decision-making models, and multi-objective optimizations. Each type of model held a set of unique forms, functions, and questions to be answered. Moreover, the purpose of presenting each type of model differed (e.g., increasing stakeholder topic awareness by using qualitative articulation models versus providing recommendations to policymaking through simulating futures).

RsQ2: *"What traits of models are supportive of stakeholder engagement?"* From our interviews, we identified two instances in which models can be useful for stakeholders. First, we consider that models can support internal organizational learning. Stakeholders can adjust models to help them understand the progress being made by organizational solutions toward achieving transitions, (re)design local and regional infrastructure adaptable to local transition initiatives and national targets, and find business opportunities (e.g., installing electric charging stations). Second, models can facilitate collaborative infrastructure design across sectors and governments and mediate conversation. The scientific rigor of a model is undoubtedly crucial. To engage stakeholders, the usability of a model also appears to be an essential concern. We thereby identified five strategies: Considering stakeholders' perspectives when selecting phenomena to be modeled, providing near-future projections, balancing the reliability and usability of a model, transparent communication concerning assumptions, and enabling communication between models.

RsQ3: *"How can models be designed to engage stakeholders in the transitions effectively?"* Designing models that engage stakeholders effectively can be initiated by understanding their needs and the use contexts. Stakeholders' needs and use contexts vary, such as the required completeness and forms: Some stakeholders would require models to facilitate complex future scenario simulations, while others would better appreciate the acquisition of straightforward information. Involving stakeholders in the early process of model development and articulating epistemic requirements, as well as suitable forms of models, can be useful in ensuring effective model design.

Regarding the main research question, "What are the key considerations and approaches for effectively engaging stakeholders in energy and mobility transitions using models?", we would first stress the importance of pre-communication with stakeholders at the early stage of model development. Communicating the collaboratively explored phenomena transparently by using models and revealing the associated thought processes of both researchers and stakeholders (e.g., through assumptions or hypotheses) appears to be essential. Furthermore, modeling researchers may cooperate with researchers or practitioners in other disciplines to enhance a model's productivity or develop interface artifacts that enable models to communicate better and generate coherent results.

Future research can increase the understanding of diverse models by reviewing broader scientific disciplines relevant to the transitions and applying multiple modes of observing models. We look forward to continuing the investigation into the model usability aspect by interacting with stakeholders that are more diverse and larger in number. Finally, understanding the perspective of modeling researchers is essential to maintain the viability of stakeholder engagement. Thus, we suggest examining the challenges that the modeling researchers may experience concerning the expansion of modeling research practice toward engagement.

Our essential scientific contribution is to provide the perspective of model design to engage stakeholders in the transitions by using models. Regarding the research outcomes, we will further investigate the pre-communication concept that may facilitate the acquisition of both epistemic requirements of modeling researchers and stakeholders and a shared transition perception mechanism as part of the model design process. First, we should rigorously examine the validity of the concept of pre-communication.

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