SENTINEL

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Topic: LC-SC3-CC-2-2018 of the Horizon 2020 work program: Modelling in support to the transition to a Low-Carbon Energy System in Europe

BUILDING A LOW-CARBON, CLIMATE RESILIENT FUTURE:

SECURE, CLEAN AND EFFICIENT ENERGY

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Contents

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Executive summary

Although energy models advance rapidly in terms of technical and techno-economic details, social and political aspects and environmental burdens beyond greenhouse gas emissions are currently underrepresented. However, in light of the European Green Deal and the EU Energy Union Strategy, models must advance in terms of social and environmental considerations to support decision- and policymakers in adequately addressing that environmental burden and to put "citizens at its core" of the energy transition. In this deliverable, we present key user-needs for environmental and social aspects that need to be better represented in energy system models (Section 2), and how we have developed and adapted the modelling tools ENVIRO, QTDIAN, and ATOM in response to the identified user needs. We show three main user needs regarding social aspects, specifically (i) social impacts on energy politics and policies, (ii) the social acceptance of energy technologies and infrastructure, and (iii) consumers' behavior in energy models. We furthermore show that users consider relevant the following factors within the environmental aspects of energy scenarios: (iv) demand of raw materials/ circularity, (v) the implications on nature and biodiversity, as well as (vi) full life-cycle impacts and externalization. ENVIRO and QTDIAN are being developed within SENTINEL in a participatory process by engaging with stakeholders in the information and development stages of the model implementation. In contrast, ATOM is adapted by considering user-needs especially in the implementation stage. We conclude that we have benefited from the insights of model users and other stakeholders, and that this will allow us to make our modelling tools fit-for-purpose. All three modelling tools will support decision-makers by answering the most important of the questions users have risen within the SENTINEL stakeholder engagement process. Model-linking within the WP2 and other WPs will ensure that the understanding of environmental and social aspects is strengthened in energy system models and will be embedded in the overall SENTINEL platform.

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1 Introduction

Energy system modelling plays an increasingly important role in providing insights about energy policies, and has increasingly done so for the last 50 years. As Pfenninger et al. (2014) put it, energy system models are not only a tool for the definition of scenarios and long-term planning strategies, but also the expression of the semantics used to formalize the "*scattered knowledge about the complex interactions of the energy sector*" (page 75). The field of energy systems modeling is prolific and many models have been and are currently developed using different semantics. For example, whereas most of them differentiate between primary energy sources and final end-uses of energy, many ignore other differences like the energy needed by the very energy system to maintain its functioning (Sorman et al., 2009).

These semantic differences in modelling result from the different narratives (Kovacic, 2017) that influence the modeler, who, in return, implicitly include their perceptions and beliefs in the modelling semiotic process (Ellenbeck & Lilliestam, 2019; Sebeok & Danesi, 2012; Silvast et al., 2020). This plurality of views must not only be acknowledged, but also embraced in the modelling process. Indeed, scholars have pointed out that there is a risk of erroneous decision-making if energy planners rely too much on one [one-semantic] model and take decisions with only partial information available (A. Nikas et al., 2021). Also, in line with the voices that call for data and code 'openness' in energy modelling (Pfenninger et al., 2018), we propose that the process of designing a model must include further narratives and needs beyond modelers' own views.

Social aspects and environmental implications beyond greenhouse gas (GHG) emissions are currently underrepresented in energy system models. In terms of social aspects, most models take a technical-economic approach (e.g., Koppelaar et al., 2016; Lopion et al., 2018, etc.), which limits their capacity for including social developments and dynamics, such as social acceptance and policy preferences. These aspects are relevant for the semiotic process of energy models, because societies have important impacts on driving or constraining the energy transition: for example, citizens develop community energy projects on the one hand, and oppose local energy infrastructure developments, on the other hand. Current models tend to treat the social dimension of the energy transition as an exogenous narrative, meaning that they consider the society as wider social context (Hirt et al., 2020; O'Neill et al., 2017), and, thus, they neglect interactions among societal factors and of these with other factors like technology, economy or even environment. Linking social science to computer-based modeling is a hot topic, because it can broaden the perspective on and understanding of energy transitions (Geels et al., 2016; Trutnevyte et al., 2019; Turnheim et al., 2015). Beyond the social perspective, increasing awareness on the trade-offs between GHG emissions and other environmental impacts are also important for the success of the energy transition. For example, electrification of the energy systems comes with an increasing demand for technologies that require critical raw materials like germanium. In the EU, these materials are fully supplied from China (2020 CRM list JRC).

In light of the European Green Deal and the EU Energy Union Strategy (COM/2015/080)[1] models must advance in terms of social and environmental considerations to support policymaking. The Energy Union Strategy stresses that environmental impacts must be adequately addressed, even though it does not mention words like "water", "biodiversity" and "raw materials". Furthermore, the Energy Union claims to

[1] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2015%3A80%3AFIN

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put "*citizens at its core*" and envisions a Union "*where citizens take ownership of the energy transition, benefit from new technologies to reduce their bills, participate actively in the market, and where vulnerable consumers are protected*". It is important that the EU ensures that these environmental and social aims are fulfilled by considering *how* the transition is designed and *by* and *for whom*.

In the SENTINEL Work Package (WP) 2 we contribute to the above debate with three tools to overcome the current limitations of energy models to represent social and environmental aspects. More specifically, ATOM is an agent-based technology adoption model that simulates the expected effectiveness of the adoption/ diffusion of technological (social) innovations under policy schemes of interest. The model allows to consider and explicitly quantify uncertainties that are related to agents' preferences and decision-making criteria (i.e., behavioral uncertainty of consumers/ citizens). In addition, QTDIAN is a social model plug-in toolbox that develops user need-based social storylines and quantitative inputs for a better representation of social drivers and constraints in energy system models. Finally, ENVIRO is a python-packaged model based on the strengths of Life-Cycle Assessment (LCA) and integrated assessment of social metabolism (IASM) that assesses GHG emissions, water use and pollution, and raw material demands related to energy system scenarios.

In this deliverable, our research questions are: "*Which social and environmental aspects must be reflected in energy system models according to model users' perspective needs?", and "how can ENVIRO, QTDIAN, and ATOM be developed to ensure that they can address these user- needs?"* We divide users in two groups: users of the WP2 tools (energy modelers), and users of SENTINEL energy model results, including decision-makers (users).

User-needs have been assessed in the SENTINEL Deliverable 1.2 (Gaschnig et al., 2020) and included in each of the 'modeling' WPs (2-6) at different stages of the model development process. The case of WP2 is different in the sense that user-needs and related stakeholder engagement activities have defined the roots of two of the tools developed, leading, thus, to a participatory process than to one of adaptation. Whereas ATOM was designed in a previous EC-funded H2020 research project (TRANSrisk[2]), QTDIAN and ENVIRO have been fully designed within the SENTINEL project, from the definition of their internal semantics to the formalization of its application. However, all the three development processes have included the participation of agents other than modelers with the objective to make the modelling tools fit-for-purpose. In this deliverable we explain the participatory process of the model developments and adaptation: We (1) introduce social and environmental aspects to be integrated in energy system models in Section 2, and we (2) present how three different modeling tools have been developed/ adapted according to knowledge gaps and user-needs identified to better represent social and environmental aspects in modelling in Section 3. Finally, in **section 4** we elaborate on how our modeling framework can contribute to analyzing different socio-environmental aspects that are currently neglected by existing energy system models, while we reflect on technical limitations and constraints that need to be further explored and considered by future interdisciplinary modeling tools and ensembles.

[2] http://transrisk-project.eu/

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2 Socio-environmental knowledge gaps and user-needs in energy systems modeling

To understand and identify the different socio-environmental knowledge gaps, user-needs, and research priorities, we used a multi-methods approach based on a literature review, online interviews with key stakeholders, an online survey, and three stakeholder workshops (**Figure 1**).

In the first tier of our approach, we conducted a focused literature review of scientific articles and position papers to identify knowledge gaps related to socio-environmental modelling trends under the SENTINEL Deliverables 2.1 & 1.2. The literature review was followed by interviews in five different European jurisdictions– the EU, Germany (GER), Greece (GRE), Poland (PL), and Sweden (SWE)− in order to understand how models are used in policymaking, and what users demand from future energy system models. Building on insights from the literature reviews and the online interviews, we designed and performed an online survey to get more insights on specific user-needs from a larger sample. Lastly, in the third tier of our approach, we have participated in 3 thematic workshops where the SENTINEL consortium directly interacted with various stakeholders to understand and identify different socio-environmental aspects that should be considered in the modeling work under WP2.

In all stakeholder-related activities, we engaged with policymakers (abbr. **policy**), scientists (abbr. **science**), experts from the energy industry (abbr. **industry**) and non-governmental organization (abbr. **NGO**). Details on all the 3 different tiers our multi-methods approach are provided in Deliverable 1.2 (Gaschnig et al., 2020), Deliverable 2.1 (Martin et al., 2020) and Deliverable 7.1 (V. Stavrakas et al., 2021) .

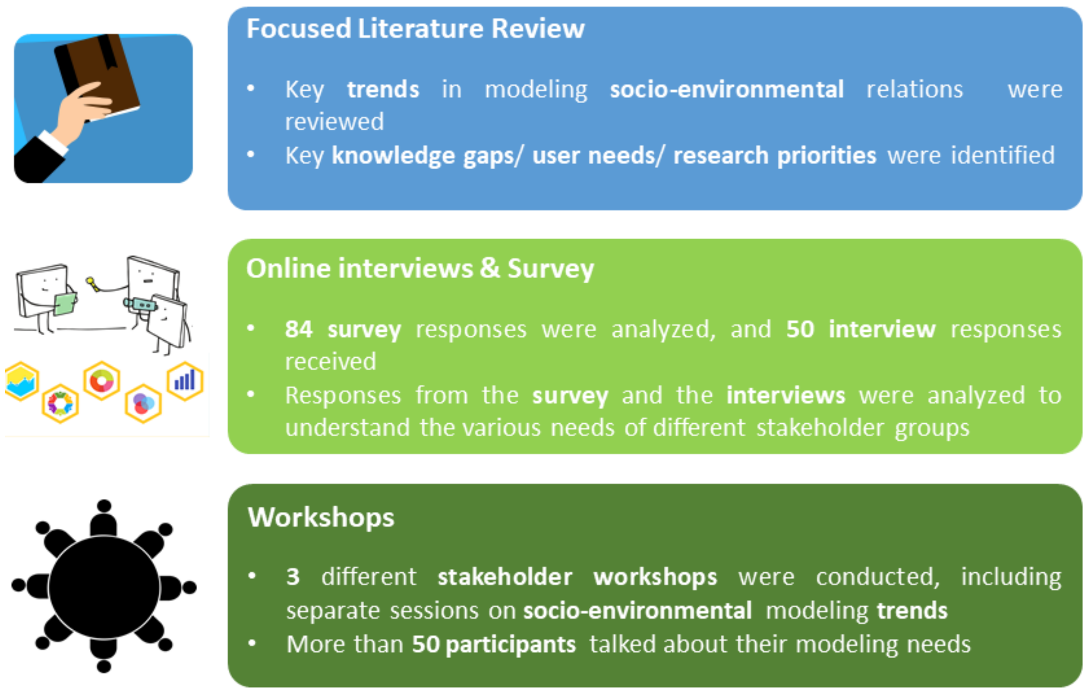

Figure 1. A multi-methods approach to identify socio-environmental gaps and user-needs to be further addressed by the SENTINEL WP2 modeling ensemble

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2.1 Research gaps and modeling trends in social and environmental literature

In Deliverable 2.1, we have reviewed and identified key technologies and social trends of the energy transition, as well as resulting social modeling challenges that must be addressed. We revealed six social trends currently defining energy transitions: **(1)** transition from consumers to prosumers; **(2)** changes in social acceptance of renewables and denial of climate change; **(3)** uneven distribution of winners and losers in the energy transition, incl., employment effects, energy and fuel poverty, as well as community benefits and challenges; **(4)** citizen empowerment by the digitalization of energy generation and usage; **(5)** behavioral change and rising awareness of behavioral rebounds; **(6)** and transition from individual action to policy action. These social trends are relevant when it comes to the question of *how* to design the energy transition. However, many of these social aspects have not been considered in models to date, and those that have, they have mainly treated those aspects as exogenous narratives (Hirt et al., 2020; Krumm et al., under review). Thus, scholars have emphasized on the importance of better incorporating societal transformations in energy modelling (Köhler et al., 2018; Alexandros Nikas et al., 2020; Trutnevyte et al., 2019).

In terms of social aspects, we drew the conclusion that modelers should consider how and to what extent the following aspects could be qualitatively and quantitatively integrated into energy system models: **(1)** social technology preferences and acceptance; **(2)** fields and attitudes regarding social justice; **(3)** preparedness/ upscaling of the economy; **(4)** citizen participation in infrastructure developments and ownership, such as investment decisions in small-scale solar photovoltaic systems; **(5)** consumption behavior in term of energy usage and modes of transportation; and **(6)** support of the public for specific policies, and policies supporting public engagement in the energy transition. In order to so, scholars (Hirt et al., 2020; Trutnevyte et al., 2019) have emphasized that social scientists and modelers must work together to better link social science and socio-technical transition insights with energy modelling. There are already approaches to linking the two fields, but the quantification of social aspects in particular remains a key challenge (Pfenninger et al., 2014; van Sluisveld et al., 2020). Thus, ATOM and QTDIAN will be improved and developed, respectively, within SENTINEL to contribute to closing this research gap.

Besides the work in Deliverable 2.1 on current trends in modelling socio-environmental relations we have also explored approaches used to simulate the environmental impacts of energy technologies/scenarios, with mot efforts coming from the areas of IASM and LCA. IASMs are large models that attempt to integrate geophysical stocks and flows with economic flows such that the key features of a system and its economy are assessed in conjunction with its interactions with the environment (see IAMC, 2020 for an overview of the most commonly used examples). Nevertheless, although IASMs have been specifically formulated to simulate interactions between the economy, technosphere and biosphere, they fail to consider environmental emissions and impacts beyond the use of simplified relationships between parameters. They have been criticized, among others, for being opaque (Pfenninger, 2017), and lacking a fine geographical resolution that allows to connect national with local assessments (Gambhir et al., 2019). On the other hand, LCA provides a systematic method for the accounting of inputs and outputs to and from a energy-related process. However, LCA is limited in its ability to assess impacts at wider scales and it is acknowledged that it must be combined with integrated hierarchical modelling frameworks in order to be used for the assessment of energy strategies within a larger network or an entire society (Creutzig et al., 2012). In SENTINEL, we build on the strengths of both approaches in the development of the ENVIRO module to provide insights about environmental impact assessment in energy system models.

2.2. Socio-environmental user-needs from the perspective of stakeholders

The online interviews, the online survey and the thematic workshops conducted under WPs 1 & 7revealed two main categories of user-needs: **i. the integration of environmental sustainability issues beyond GHG emissions**, and **ii. the better representation of social factors and human behavior in modeling**. More specifically, our interviews showed that stakeholders want a more systemic perspective in modeling, which implies considering external costs and costs on individual and macroeconomic levels in all societal areas, such as the overall costs for the environment, resources, biodiversity, health impacts, and welfare/ jobs. Furthermore, our online survey revealed the same need: the two top factors that should receive more attention in modelling across different European stakeholders were "impact on the environment and natural resource use" (51%) and "behavior, lifestyle, and heterogeneity of consumers" (49%). Interestingly, especially policymakers found the impact on the environment and natural resource use most relevant (83%), whereas NGO representatives, as well as the scientific community, behavior, lifestyles, and heterogeneity of consumers (71%/ 54%). In addition, the participating stakeholders of our user- needs workshop ranked environmental and social factors among the top four that should receive more attention from energy system models, as presented in **Figure 2**.

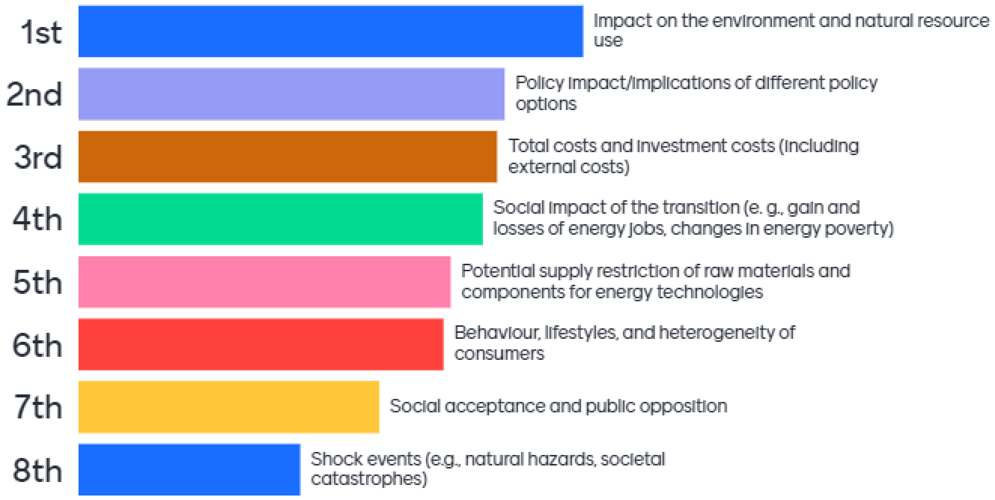

Figure 2. Ranking to the question: Which of the following factors do you think should receive more attention in energy models? (N: 28, live poll). Insights from the online user-needs workshop conducted under WP1.

2.2.1. Key social research gaps and user-needs

We found a high demand for a better representation of social and behavioral aspects in energy system models among various European stakeholder groups. The interviewees raised the issues of social acceptability of the energy transition, implications on employment, technological preferences, engagement of citizens in the transition, as well as social behavior. One industry representative stated: "*It can be in terms of social acceptance, it can be in terms of job creation, it can be in terms of socio-economic impacts that are not all factored in the model that is being run*" (EU_industry#2). **Table 1** summarizes the key user-needs found. In addition, from the online survey, we found that the top three social aspects that should be better-included in energy models are "Co-benefits of prosumerism and community energy" (43% of question´s respondents), the "Social drivers and barriers of innovation diffusion" (43%), and "Dynamics of social acceptance and individual attitudes" (39%) (Error! Reference source not found.).

The user-needs workshop conducted under WP1 confirmed the findings from the interviews and the survey: the workshop participants called for better integration of social impacts on energy politics (e.g., forced by social movements, etc.), the social acceptance of energy technologies and infrastructure, and consumer behavior in energy system models. Nevertheless, all aspects have been ranked relatively high, and no element appeared to be irrelevant (Error! Reference source not found.). The discussion with the participants revealed four main needs: **(i)** to understand the science and to compare it with ongoing policy processes, **(ii)** to understand the social implications of different energy scenarios, **(iii)** to understand how policy changes can trigger behavioral changes, and **(iv)** to measure distributional impacts, like for example local (co-)benefits, but also actual and perceived costs on less wealthy parts of the society.

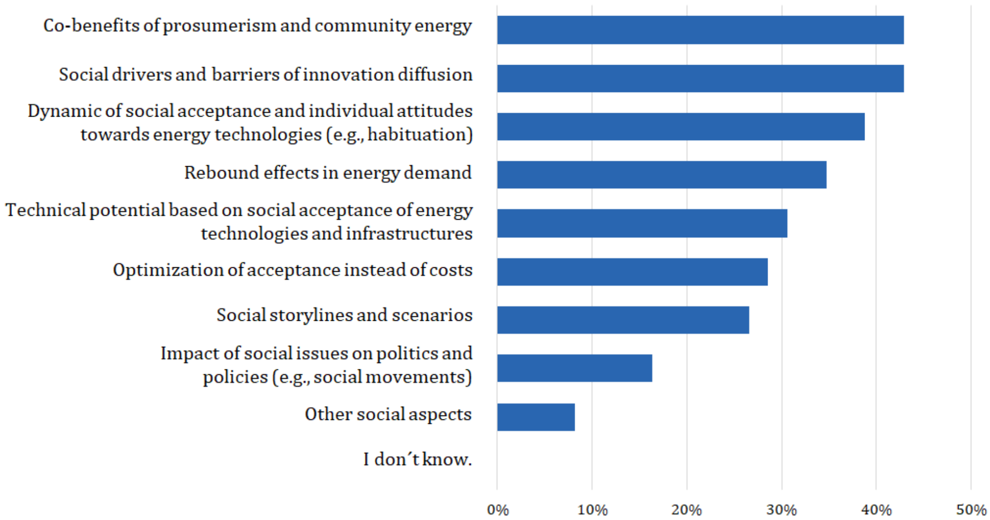

Figure 3. You stated that social aspects should receive more attention in models. What social aspects would you like to see integrated into energy models? (voluntary, multiple choices, up to 3 answers), N: 49.

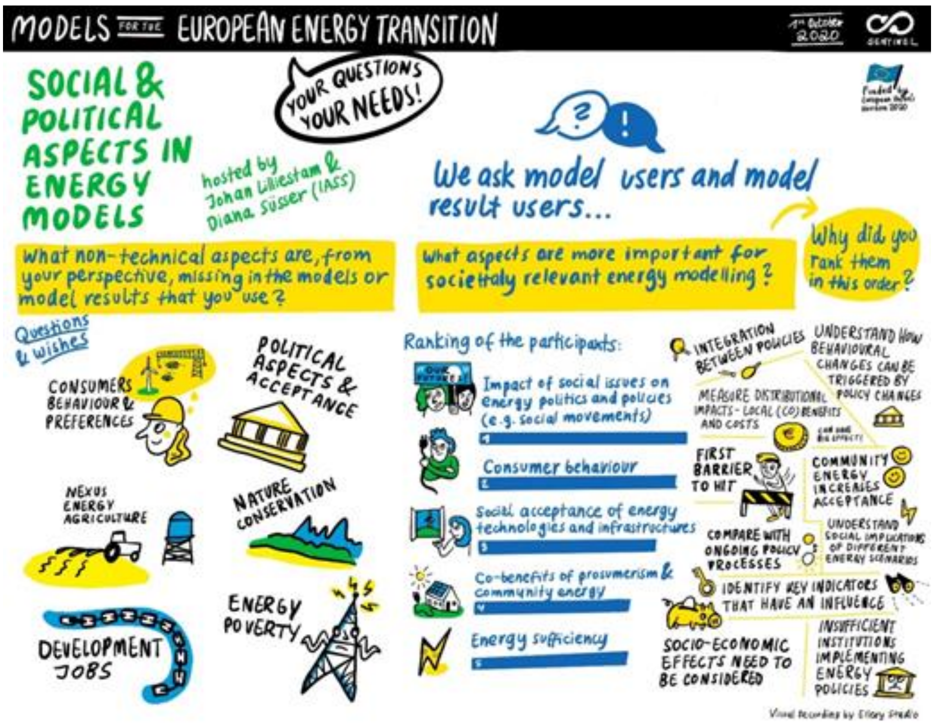

Figure 4. Sketchnote 'Social and policy aspects in energy models'. Insights from the SENTINEL user-needs workshop conducted under WP1 (Breakout Session 1)

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Table 1. User-needs regarding social and behavioral aspects to be better represented by energy system models. Insights from the online interviews conducted under WP1.

Need focus	Example quotes from the interviews
Social acceptability and acceptance	"And then, I think, we have connections to social acceptability, because if we go into more decentralized approach, we can create more value in the regions or in all European places, where you have your own creation of energy and you have your own value chains. You have local jobs, local economy and then, local acceptance." (EU_NGO#1) "The grid extension is fundamental […] but grid extension is dependent on social acceptance. You really need to know, if you need more grids to make it cheaper between North and South of Germany, and you can have fantastic plants of grid extension, and that's good, that says your model. And then you realize that because of socio-economic elements, the TSOs cannot develop the overhead cables, but they need to bury cables underground and that is multiplying by factor 10 the costs of the HDVC, between the North and South of Germany. That is a fundamental thing, but how can you integrate that into the model?" (EU_policy#2) "Social topics are indeed one big hole, a great neglect in most energy and economic analyses in Poland." (PL_science#1) "Plus, one related topic as if from the social side, as if from the other side, but also socially related, that is acceptance, for example, RES development." (PL_science#1)
Citizen participation and citizen energy	"Maybe something like for the actors, I think could be, how they really value an autarky, so whether people really invest in batteries and PVs, for example. Also, regarding the financing aspect and how far it's important for the people in the financing the energy system: if they do so, which technologies and which geographical areas they prefer." (EU_science#1) "[…] maybe including energy communities as investors into the models. So just more analysis about the behavior and acceptance issues that people really have." (EU_science#1)
Employment effects	"It can be in terms of social acceptance, it can be in terms of job creation, it can be in terms of socio-economic impacts that are not all factored in the model that is being run." (EU_industry#2) "It would be very interesting to get some numbers on jobs and those kinds of aspects. I mean, how many jobs there are in the renewable sector and how many jobs there are in the fossil fuels sector. I mean, in the US you have some great numbers on it, showing how exactly many jobs you have in renewable sector and how much in fossil fuels. If the government wants to choose, it should choose the more jobs. In Europe I haven't seen so many numbers around that. That would be interesting. I think jobs is good." (EU_NGO#2) "Social aspects, especially in this crisis, which is beginning to develop, are certainly employment. Well, it is also a question of what we often discuss, as if the level of employment in a given technology." (PL_NGO#3)
Social benefits and costs	"[…] is primarily a model that assesses the overall costs, i.e. includes the overall costs, also assessing the costs related to the development of energy infrastructure, the macroeconomic costs, the social costs related to change, especially in different segments burdened by the costs of energy policy change, such as mining." (PL_policy#1) "It would be desirable to conceptualize and explore alternative (not only technological) pathways that are less bounded by cost-effectiveness considerations and which embody aspects of social inclusion and justice as well as energy-sufficiency aspects." (GRE_policy#1)
Impacts of social and actors behavior	"I would say that modeling of social behavior might be very relevant for modeling potential outcomes." (EU_industry#1) "I also think that there could be an endless story about how different models deal with the fact that the actors are not entirely predictable in their decisions, which is the famous discussion about discount rates, not only those for calculating costs, but those for making decisions." (EU_policy#3) "I think that the second point is behavior of actors that is not included yet, at least in the optimizing models. And you have, of course, the electricity market models, there are some models that have agent-based behavior in them, but somehow it is not very linked at the moment." (EU_science#1) "The improved simulation of 'real-world' decision-making and behavioral aspects are always welcome and offer robust results in the quantitative analysis." (GRE_policy#1)

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In the context of the thematic workshops conducted under WP7, we identified key research questions relevant in the context of the SENTINEL case studies. **Table 2** presents key research questions as discussed with participants during the European case study workshop. Insights from the workshops revealed that many stakeholders need further insights into the societal implications of the energy transitions, and that they see a key limitation of current models is that they cannot provide insights on societal preferences and acceptability of further RES deployment, but also effort sharing, effects of prosumerism and citizen energy, and on local employment effects, among others.

Table 2. Contextualized research questions and critical issues raised by stakeholders during the European case study workshop conducted under WP7– Target and Transformation.

The Target: Where we want to get to?

Dimensions	**Questions**
Policy: climate and energy target	Will the EU and individual countries reach their targets? What would be the societal implications, if not?
Policy: climate and energy target	How will the revised EU target be shared among member states? Which countries will be net-exporters and service providers (e.g., storage) to other countries? [effort sharing]
Policy: energy (in)dependence	Will the EU be energy independent? How strong will it dependent on energy imports?
Economy: employment	Will there be more jobs in the energy sector than today?
Society: public participation	Who will produce the energy? What will be the share of citizen energy?

The Transformation: How to get there?

Dimension	**Key measures**
Policy: policy instruments and measures	What climate policy instruments are the key, and how they need to be designed to ensure a fair distribution of costs and benefits of the transition?
Society: affordability	How can we ensure that the energy transition will be affordable for all (no energy poverty)?
Economy: investments	How can we ensure that investments will be mobilized? What is the role of recovery packages?
Society: behavior, lifestyle, and acceptance	What is the role of individual behavior, lifestyles, and energy source preferences/ acceptance in reaching climate and energy targets? What continued changes should we expect from the Corona pandemic?

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2.2.2. Key environmental knowledge gaps and user-needs

In the interviews, European stakeholders stated that externalization, environmental climate and health impacts, resource efficiency and biodiversity are the more relevant environmental factors that are not sufficiently represented by current energy system models. **Table 3** presents a selection of quotes from the interviews.

Table 3. User needs regarding environmental aspects to be better represented by energy system models. Insights from the online interviews conducted under WP1.

Need focus	Example quotes from the interviews
Externalization	"There is one issue there that I think should be more widely taken into account when assessing the impact of external policies, and in general I consider it absolutely necessary, because these costs, these are the costs that we all pay. And the state, indirectly with our money and the citizens in the form of, for example, treatment of diseases caused by air pollution. The state, due to sickness absence, etc., these costs are quite enough. And if you take into account different costs, including external costs, when assessing the policy options, the hierarchy of profitability of investing in different energy sources is completely different." (PL_SCI#3) "There is also a lack of such a model that would assess the overall costs for the environment, such ecological costs. So many, many actors have different tools at their disposal, but I don't think there is one available to the public, I don't know if there is one at European level that would take all these components into account." (2261-2265) (PL_POL#1)
Environmental, climate and health impacts	"All the other things that we've been thinking about is this whole concept of cost efficiency. Like cost efficiency means… cost efficiency doesn't take into account climate impacts. Cost efficiency is simply a model looking at… I mean, the whole concept is wrong." (EU_NGO#2) "What are the (environmental) consequences of a large-scale use of renewables?" (SWE_SCI#4) "I think it's important to look at health impacts and climate impacts, to kind of juxtapose costs of acting with costs of inaction. And if you are able to do that, you can clearly show, even if the 65% reduction costs each of us individually and we need to pay 100 euro a month to be able to do that, that's much less than thousands of euros that we all lose, because we will be flooded or our houses will get into fire." (EU_NGO#2)
Resource efficiency	"It is a question of resource efficiency. The resources to reduce climate gases, but also what we need to use the resources we are having as efficient as possible – also if its waste we are using." (SWE_SCI#4)
Biodiversity	"Also, the whole environmental, like the biodiversity aspect of the wind. It's very interesting, I mean, we can't achieve 100% renewables without having hundreds of gigawatts of offshore wind. That is going to be crucial, but you also have to do it in a sustainable way." (EU_NGO#2)

Furthermore, we found that, for the survey respondents, raw material demand (57%), GHG emissions (49%), air pollution (40%), water usage (40%), and loss of diversity (32%) were especially relevant to receive more attention in models (see **Figure 5**). All stakeholder groups ranked raw material demand and GHG emissions relatively high.

The user-needs workshop confirmed the need for energy system models that better consider environmental impacts and constraints. The stakeholders prioritized in particular **(1)** raw materials/ circularity, **(2)** nature and biodiversity, as well as **(3)** full life-cycle impacts (**Figure 6**). These aspects were assessed to be of specific relevance in order to aid decision-making processes, enable links to other models, policies, and strategies, and to facilitate citizen empowerment and stakeholder engagement.

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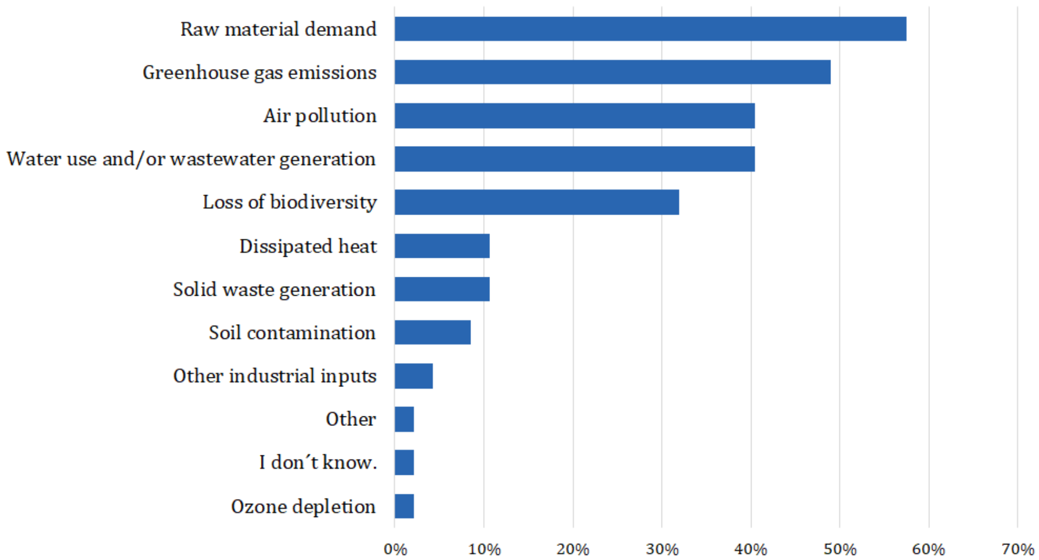

Figure 5. You stated that environmental or resource issues should receive more attention in energy models. What environmental factors would you like to see integrated into energy models more in the future? (voluntary, multiple choices, up to 3 answers), N: 47.

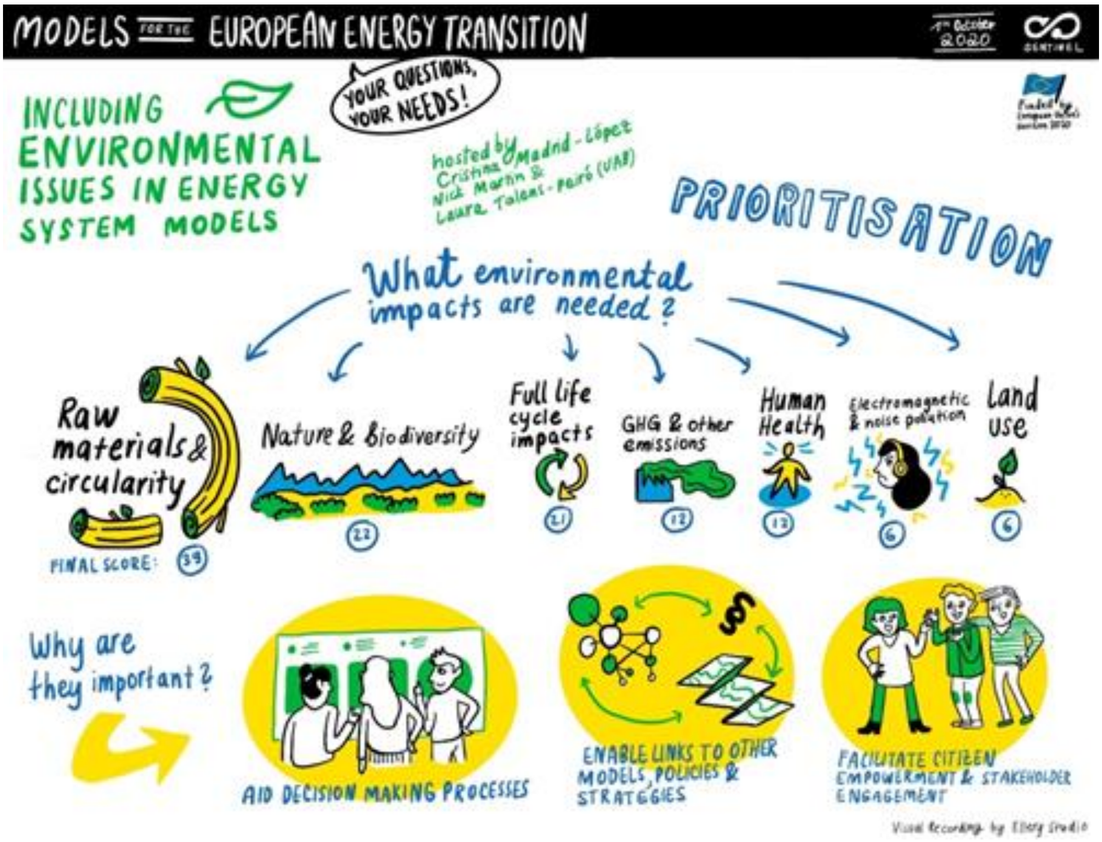

Figure 6. Sketchnote 'Including environmental aspects in energy system models'. Insights from the SENTINEL user-needs workshop conducted under WP1 (Breakout Session 2)

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Discussion during the case study workshops under WP7 confirmed the concerns of participants for **i)** the assessment of GHG emissions, **ii)** the lack of constraints posed by land use and water use, **iii)** the externalization associated with biomass and other energy sources, and **iv)** the lack of supply and the need of recycling raw materials.

Two transversal issues were raised in these workshops: First, the need for system perspectives able to cover trade-offs between different resources. Second, the question about the perception of the general public and policymakers about the worth of protecting nature. The topic of environmental data availability was mentioned during the Nordic case study workshop and corroborated during the European case study workshop, as well as the technical aspects of implementing the results of environmental assessments as constraints in energy system models.

Table 4. Contextualized research questions and critical issues identified in the context of the Nordic and the European case study workshops conducted under WP7– Target and Transformation

The Target: Where we want to get to?	**What will be the key environmental characteristics of a climate neutral energy supply in Europe in 2050?**
Dimensions	**Question Samples**
Assessment of GHG emissions	How to define carbon neutrality? What is the relation between EROI and GHG emissions in this scenario?
Land and water use constraints	What are the incoherencies between energy and environmental policy targets?
Externalization	What are the externalized impacts of different energy configurations?
Raw Materials/Circularity	What is the demand of raw materials of the energy transition?
Systemic approaches	What are the environmental co-benefits resulting from renewable energy systems?
The Transformation: How to get there?	**What do you think are the main opportunities/ challenges for the transition?**
Dimension	**Key measures**
Systemic approaches	How to integrate environmental impacts (land, biodiversity, ecosystem services) with energy systems modelling to better inform policy makers? How do we choose between alternative energy systems?
Externalization	Is it possible to reduce externalized impacts?
Raw Materials	Will the supply of raw materials be an issue for the energy transition?

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3 Model adaptation

3.1 A framework to explain adaptation to user needs

User-needs can be included at different stages of the modeling process. Building on works about the semiotic process in modeling (Sebeok & Danesi, 2012), and the stages of the modeling process to consider uncertainty (Refsgaard et al., 2007), Error! Reference source not found. shows at which stages of the modeling process we have adapted each of the models. The framework includes 3 stages: (i) model definition, (ii) implementation and (iii) feedback. The steps taken within each of them from the forming of a narrative by the modelers to the development of semantics in the model plan, the design and formalization of the relations in the model, data collection and input during the set-up, the calibration and validation of the semantics, the actual simulation performed with the model to its evaluation.

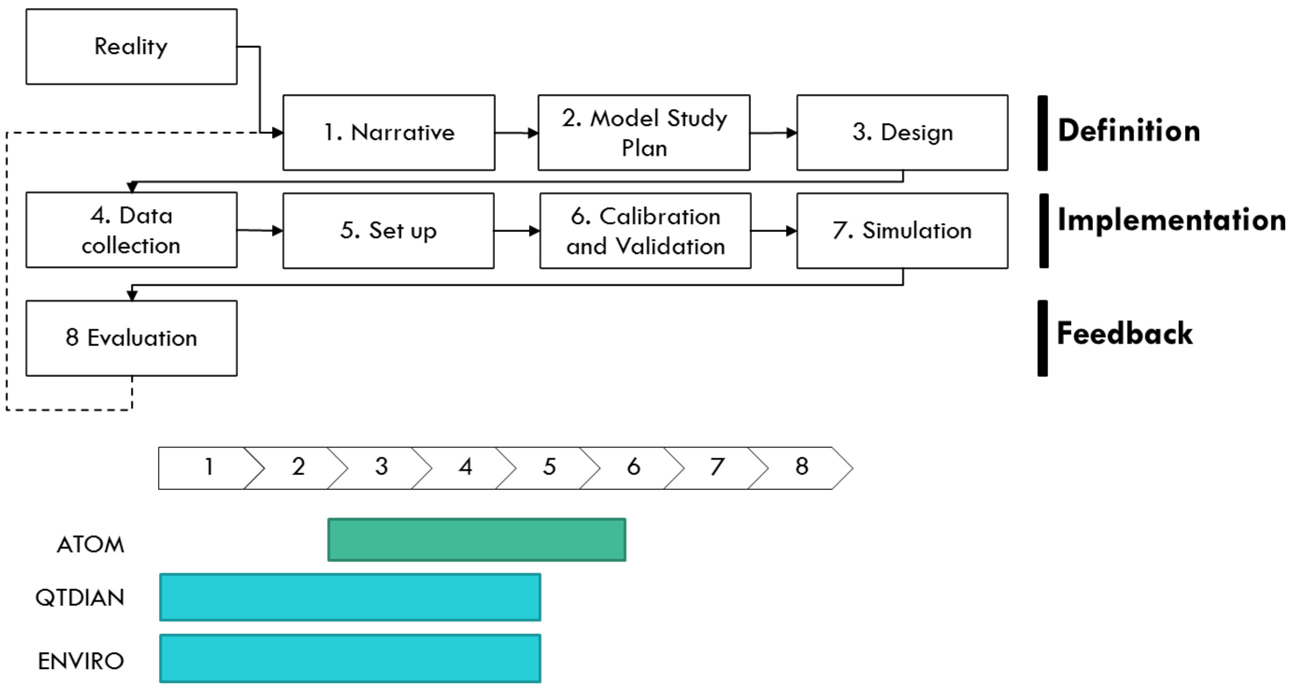

Figure 7. Steps of the modelling process considered in WP2 (above), stages in which user-needs have been included for each modelling tool (below, left) and level of participation (below, right), by February 2021.

Of the three models, QTDIAN and ENVIRO have been developed from scratch within the SENTINEL project, whereas ATOM has been adapted. All three model development processes have made use of literature findings in both WP1 & WP2, and of insights from the SENTINEL stakeholder engagement process in both WP1 and WP7.

Co-creative approaches gained increasing relevance in modeling, to ensure models' fitness-for-purpose, to increase model credibility and legitimacy, and to accelerate modelling impact in policy (McDowall & Geels, 2017; Renn, 2015; van Daalen et al., 2002; Van Ittersum & Sterk, 2015; Voinov & Bousquet, 2010). Models can function as virtual 'laboratories' in which context modelers and decision-makers can explore together potential energy futures. If stakeholders are engaged at different stages of the modeling process, they can enrich diverse steps, such as providing data inputs, discussing scenario runs, interpreting modeling results. Thus, many models are developed by taking user-needs into account, and updates of these needs are required along the way, as environmental, social, and political contexts are constantly changing.

There are different strategies for participatory development, such as open the access to the code behind the modeling tools (Pfenninger et al., 2018), or involving policymakers and stakeholders in the definition of the model semantics (Higgs et al., 2008; Simão & Densham, 2008). The International Association for Public Participation distinguishes five level of participation that defines the public's role in any public participation process. In WP2, participation in the model adaptation has reached so far level three (involve). Collaboration with other modeling teams in the implementation phase is essential particularly for QTDIAN and ENVIRO, as their outputs are to be used by other models. This collaboration will happen in the framework of WP2 Tasks 5-7 as the two tools are used in the case studies and integrated within the SENTINEL platform.

3.2 ATOM

The Agent-based Technology adOption Model (ATOM) is an agent-based model that is supported by a complete framework for parameter estimation and uncertainty quantification based on historical data and observations. Apart from simulating the expected effectiveness of technology adoption under policy schemes of interest, ATOM allows to consider and explicitly quantify uncertainties that are related to agents' preferences and decision-making criteria (i.e., behavioral uncertainty). The novelty of ATOM, compared to existing models, lies in obtaining realistic uncertainty bounds and splitting the total model's output uncertainty in its major contributing sources, based on a variance decomposition framework, and an uncertainty characterization (UC) method, while accounting for structural uncertainty. Thus, ATOM supports the definition of uncertainty ranges, considering the type (i.e., input, parametric and structural), and the nature of uncertainty (i.e., epistemic, or aleatory), and how uncertainty propagates to the model outcomes over the planning time horizon.

ATOM consists of three main modeling modules: **(1)** a calibration module to define the set of the key parameters that govern the agents' behavior and appropriate value ranges based on historical data and observations; **(2)** a sensitivity analysis (SA) module that allows to quantify and consider uncertainties that are related to the characteristics and the decision-making criteria of the agents rather than the more obvious ones (e.g., technology costs, etc.), based on calibration results; and **(3)** a scenario analysis module to explore, given the historical observations, the plausible behavior of the potential adopters, in the geographic and socioeconomic context under study, for policy schemes of interest (i.e., forward-looking simulations).

Variance decomposition takes place for all the three main modules of ATOM. By allowing the user to select preliminary values for the agent-related parameters according to the plausibility of its results, based on historical data and observations, the model captures input uncertainty (i.e., calibration module). By deriving forward-looking simulations for different behavioral profiles (i.e., different set of agent-related parameters), from willing to invest to risk-averse consumers, ATOM captures parametric uncertainty (i.e., scenario analysis module). Both types of uncertainty are then propagated through the model, and their contribution to the total model's output variance is quantified. The rest uncertainty is assumed to be explained by the model's structure. Note that the uncertainty propagation for the agent-related parameters is done for each one of them, allowing calculation of the sensitivity of each parameter to the model output, in the context of a variance-based sensitivity analysis (Sobol method), and calculation of the relative contribution of the variance for each parameter to the total model output variance (i.e., SA module).

Finally, agent-related parameters are represented by mathematical functions and formulae. Users are allowed to specify the values of the agent-related parameters under consideration, according to the plausibility of the model's results compared to historical data-observations (i.e., goodness-of-fit statistics). Also, market-related parameters of the model are set according to past or existing conditions related to the geographic and socioeconomic context of interest. Accordingly, the characteristics of the technology under study and the policy context are specified. For more information about the model's key specifications, assumptions and uncertainties, and a list of the main inputs and outputs see **Appendix 1**.

Mathematical model formulation, detailed description, and indicative applications

Detailed description of the mathematical formulations, mechanics, key assumptions-parameters, and applicability of the model is presented by (Vassilis Stavrakas et al., 2019).

The mathematical framework of the model's calibration module (based on the concept of Gaussian Process emulators) is presented by (Papadelis & Flamos, 2018).

A detailed application of the model for exploring the achievement of the small-scale PV targets towards 2030 in Greece is presented by (Michas et al., 2020).

Many technical innovations and public policies often fail because they do not sufficiently consider what matters to people (i.e., the motivating factors shaping their adoption preferences). People and their social interactions greatly influence the diffusion of technological/ social innovations, and, further, shape overall technological/ social transition dynamics. However, transitions are difficult to understand scientifically because of the influence of a broad range of contextual factors that affect policy processes, society, and agency. Considering the diversity of interests, motivations, and other factors that inform peoples' choices helps to reduce the uncertainty that may lead to policy failure. To this end, upgrading the modelling framework of ATOM and adjusting it to knowledge gaps/ user needs/ research priorities/ social trends, identified through scientific literature and stakeholder engagement, is instrumental as modelling agents' decisions and interactions represents a more "real-world" process which addresses limitations and constraints of monolithic, optimization models, by introducing a layer of control and decision-making, thereby allowing greater understanding of macrophenomena.

Design

The initial modeling framework of ATOM has been expanded to explore the effect of more agent-related parameters in PV adoption. Scientific literature, for example, reports that the attitude of Greek consumers toward installing small-scale PV systems varies according to their income and education level and seems, also, to be correlated with their consumption profiles and demographic characteristics (Tsantopoulos et al., 2014). To this end, the model will explore different behavioral and socio-economic profiles to implement socially-informed modeling exercises.

Considering the United Nations' commitment to guarantee that "no one is left behind" by "reaching the furthest behind first", engaging 'hard to reach' citizens, and understanding how their aspirations and perceptions can be mapped onto the requirements, or opportunities of a low-carbon transition is instrumental according to both literature and stakeholders. Thus, in order to meaningfully design and carry out socio-technically informed modeling exercises, we have reinforced the ATOM modeling framework by reflecting on the decision-making process of different consumers/ citizens' profiles. In particular, a special focus is given so that the initial modeling framework of ATOM is expanded to user profiles that go beyond capturing the mainstream dominant groups, focusing on communities and groups that face social/ economic marginalization, including women and other genders, and/ or demographics that are typically excluded due to racialization, face other discrimination or challenges such as forced migration due to conflicts (e.g., refugees).

In this context, the factors/ parameters that are assumed to moderate human behavior will be used as inputs in the model to explore the impacts of human-centered interventions in different geographical and socioeconomic contexts and levels. This exercise will demonstrate the potential of the model to further evolve, based on user needs and stakeholders' feedback, from a technology adoption stand-alone model, into a diffusion of social innovations model that will scale-up social innovations, from individuals to large social units, like communities. This way the ATOM modeling framework could be used to explore the ways in which both envisaged social innovations and technological infrastructure can be adopted by, and diffused into, households/ communities of different socio-economic profiles.

Table 5. User- needs considered in ATOM

User-need/ Research gap	Related research questions	How ATOM will be used to meet this need
Social acceptance/ preferences towards renewable energy technologies	How does the deployment of (regionally, nationally) preferred renewable energy technologies affect potential, overall costs and system design (based on survey data)?	Using historical data for PV adoption to calibrate the model's agent-related parameters, I.e., different variables & value-ranges that determine the behavior/ decision-making process of consumers. These parameters include personal beliefs, social learning, resistance/ opposition towards PV (RES) investments, etc. Forward-looking simulations to explore PV/ storage adoption in the residential sector until 2030 in a set of EU Member States
Local opposition towards energy infrastructures	How does local opposition against renewable energy projects and energy infrastructure projects affect the speed and direction of the overall transition?	ATOM will simulate the adoption behavior of risk-averse/ consumers/ citizens, e.g., ambiguous beliefs towards investing, strong opposition/ resistance towards investing, etc.
Citizen/ community ownership	How does ownership affect the system design?	Assessing the decarbonisation potential of strategic groups of consumers/ citizens: Clustering consumer/ citizen groups (I.e., different behavioral profiles), based on the social storylines derived from QTDIAN, to demonstrate which clusters are more responsive to PV/ storage adoption, across different contexts, for different market-related parameters.
Policy preferences and dynamics	How do policy changes affect the development of renewable energy? How can we represent policy changes in models, and what are the effects?	Apart from different behavioural profiles, the model will simulate the influence/ profitability of different policy schemes (e.g., FiTs, Net-Metering, Self-Consumption, etc.), that aim at boosting a decentralized energy system, towards PV/ storage adoption in the residential sector, for a set of EU Member States. Participatory design of Dynamic Adaptive Policy Pathways, through real time visualizations and interactive stakeholder consultation in the context of the SENTINEL case studies: **(I.)** modelling different policy schemes, **(ii.)** correlating the technology adoption with its value for consumers, and **(iii.)** generating transition pathways, that balance the economic interests of consumers and public authorities, towards the achievement of the 2030 national targets.
Social technological scaling/ scaling of the economy	Does the speed of technology deployment affect the speed and direction of the energy transition?	ATOM could partially contribute to this user-need by simulating the effect of technology costs (I.e., different learning curves) on PV/ storage adoption.

Data collection/ Set up/ Calibration and Validation/ Simulation

In terms of technological innovations, ATOM has been already further developed to explore the effect of different policy schemes (e.g., net-metering, self-consumption with subsidization, etc.) in solar photovoltaics (PV) adoption. In particular, ATOM will be used in the context of the SENTINEL case studies for a set of EU Member States so that it explores scenarios of PV adoption in the residential sector towards the achievement of the respective national 2030 small-scale PV targets. The model has been already calibrated using historical data from the feed-in-tariffs (FiTs) period in Greece, Germany, Italy, and France, while further calibrations will take place for additional EU Member States, given that the respective historical data are publicly available.

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Finally, depending on the availability of historical data, ATOM will be further calibrated/ applied to derive adoption scenarios for other technologies that increase demand flexibility, such as electricity storage or smart-grid devices and technologies related to the digitalisation of energy generation and usage.

Evaluation

Finally, feedback from literature and stakeholders, as well as current circumstances due to the COVID-19 pandemic, dictate that policy measures must adapt to uncertain and continuously changing conditions. A policy design process that utilizes agent-based modelling should be structured around the concept of adaptability. To this end, ATOM has been expanded by including a new plugin module that facilitates decision-making under deep uncertainty, building on the strengths of Exploratory Modelling and Analysis (EMA) (Kwakkel & Pruyt, 2013). In particular, ATOM and this new module will be used to facilitate the participatory design of Dynamic Adaptive Policy Pathways (DAPPs) (Haasnoot et al., 2013), through real time visualizations and interactive stakeholder consultation in the context of the SENTINEL case studies. The implementation of a policy for a time period affects the performance of the alternative policies succeeding it. This new module updates the policy adaptation map showing only the available options from the last timeframe a policy is implemented and forward. As a result, opportunities and dead-ends will be explicitly visualized in a stakeholder-friendly fashion. This exercise will aim at **(I.)** modelling different policy schemes (e.g., net-metering, self-consumption, etc.) that support the diffusion of small-scale PV in the residential sector, **(ii.)** correlating the technology adoption with its value for consumers, and **(iii.)** generating transition pathways, that balance the economic interests of consumers and public authorities, towards the achievement of the 2030 national targets, for a set of EU Member States.

3.3. QTDIAN

The Quantification of Technological DIffusion and sociAl constraiNts (QTDIAN) toolbox

QTDIAN is a social modelling toolbox that deals with social drivers and constraints of technological diffusion. It is newly developed within SENTINEL. QTDIAN is not a stand-alone model, but a 'toolbox' that capture different social, political, and technological aspects to better understand their influence on the renewable energy development and to allow the explicit inclusion of such factors in the models of SENTINEL. These factors are represented qualitatively and, where possible, operationalized quantitatively. QTDIAN consists of three main elements:

(i) Future social scenario storylines of social developments and dynamics that inform and add to the SENTINEL storylines and scenarios,

(ii) Quantitative input assumptions, related to the qualitative storylines, that are operationalized as social drivers and constraints, consisting of a logic and data sets ready to be integrated/plugged into existing energy system models, and

iii) Model output discussion/assessment that interprets model output against social realities, and discusses the social implications of different energy scenarios.

To improve the representation of social aspects of the energy transition in existing energy models, QTDIAN elements are ready to be integrated in other SENTINEL models and beyond (i and ii), or to receive model output (iii).

QTDIAN is developed based on empirically identified user needs in WP1 to ensure that the tool supports decision- and policymakers in answering their questions related to social aspects of the energy transition (Section 2.2.2) (Gaschnig et al., 2020). **Table 6** provides a summary of identified user needs and their consideration in the context of QTDIAN.

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Table 6: User-needs regarding social aspects and their consideration in QTDIAN

User need/Gap	Related research questions	How QTDIAN is designed to meet this need
Local opposition towards energy infrastructures	How does local opposition against renewable energy projects and energy infrastructure projects affect the speed and direction of the overall transition?	Social storylines include opposition against different types of assets (renewable power technologies, infrastructure); quantification as input assumption intended (social constrain effect for potential and development)
Social acceptance/preferences towards renewable energy technologies	How does the deployment of (regionally, nationally) preferred renewable energy technologies affect potential, overall costs and system design (based on survey data)?	Social storylines include acceptance of different technologies, infrastructures; quantification as input assumption intended (social preferences define energy expansion and renewables mix, respectively)
Social citizen/community ownership	How does ownership affect the system design?	Social storylines include ownership and (de)centralized tech system design; consideration as input constraint is intended (defines design of development)
Policy preferences and dynamics	How do policy changes affect the development of renewable energy? How can we represent policy changes in models, and what are the effects?	Social storylines include policies and potential policy changes, as well as address the role of social movement towards policy decisions; quantification as input assumption intended
Social technological scaling / scaling of the economy	Does the speed of technology deployment affect the speed and direction of the energy transition?	Social storylines include energy system characteristics; quantification as input assumption intended

First, user needs have informed the scoping phase of the toolbox development. Key questions we addressed were: What are the key social drivers and constraints of the energy transitions? Which social issues do users believe must be better represented in models? And how do modelers currently represent social and behavioral aspects in their models? The interviews, the survey and the user need workshop allowed us to identify key social aspects and trends of energy transitions.

Second, we developed the QTDIAN toolbox model study plan based on and in direct response to these user needs. QTDIAN's social storylines/narratives of social drivers and constraints capture and materialize social aspects identified as most relevant to our users, including social acceptance and preferences, public opposition, policy preferences and dynamics as well as scaling of the economy.

Third, we will "translate" some of the qualitative storyline features into quantitative modelling input assumptions, which can be used in the framework of other SENTINEL models and beyond. The decision on what features to focus on is based on expressed user needs, but is also constrained by data availability and technical modelling possibilities.

As shown in *Figure 8*, user needs have, so far, supported the definition stage of QTDIAN.

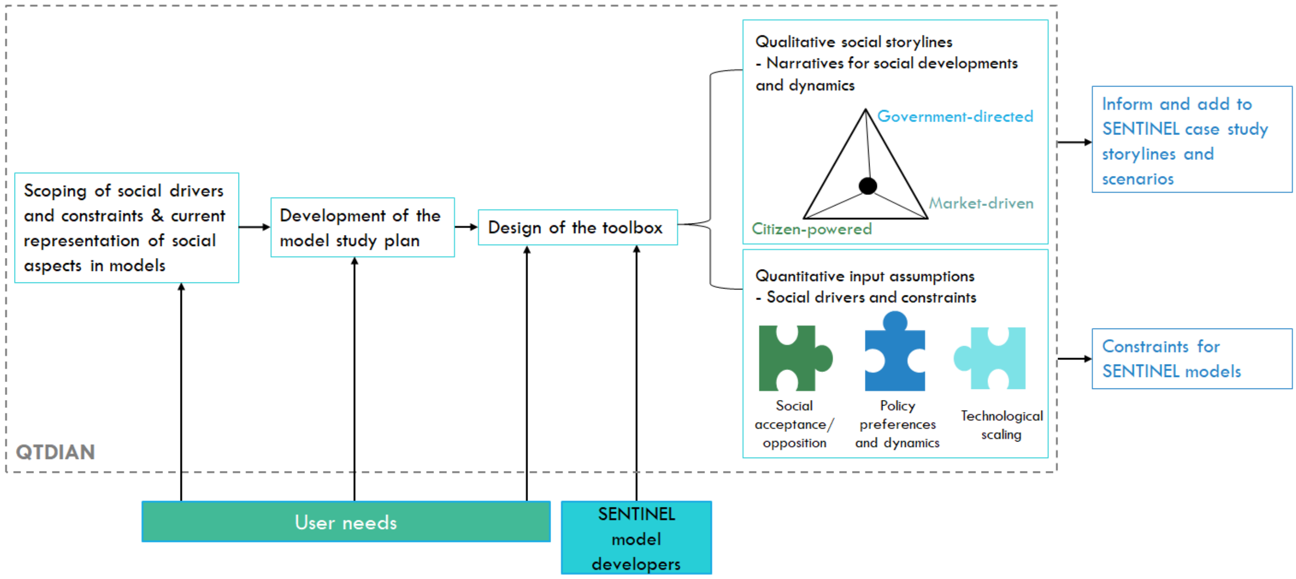

Figure 8: User needs included in the QTDIAN modelling toolbox definition, as of February 2021.

3.4. ENVIRO

The ENVIROnmental Asessment Module (ENVIRO).

ENVIRO is a simulation module that helps energy modelers to include environmental concerns that are relevant for decision makers in their models. It combines the ability of LCA processes to provide detailed environmental impact and resource use indicators with the ability of the multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) approach to analyze the metabolism of a system. In its current development stage it tests the raw material, greenhouse gas (GHG) and water-related impacts of energy systems scenarios against the targets set by related environmental policies or social capacity to overcome those.

ENVIRO is designed as a python package with dependencies with the LCA package Brigthway2 and the NIS package developed for the automatization of MuSIASEM assessments.

ENVIRO takes as inputs optimized energy systems in terms of supply and economic costs. The key outputs of the module are:

1) indicators of resource use and environmental impact

2) Identification of hotspots where energy optimization exercises should focus in order to reduce the environmental burden.

ENVIRO is an entirely new module being developed within the current SENTINEL project taking into consideration the needs of decision makers. **Figure 9** shows a scheme of the points in which these user needs are considered in the conceptual implementation on ENVIRO, currently on model development stage 5 as covered in **Figure 7**. The needs are considered in the definition of relevant flows, which will later on translate into indicators and results. For example, if the EU needs to assess the impact of raw material extraction related to electrification, ENVIRO supports models like Calliope and IMAGE in their optimization exercises considering the raw material constraint.

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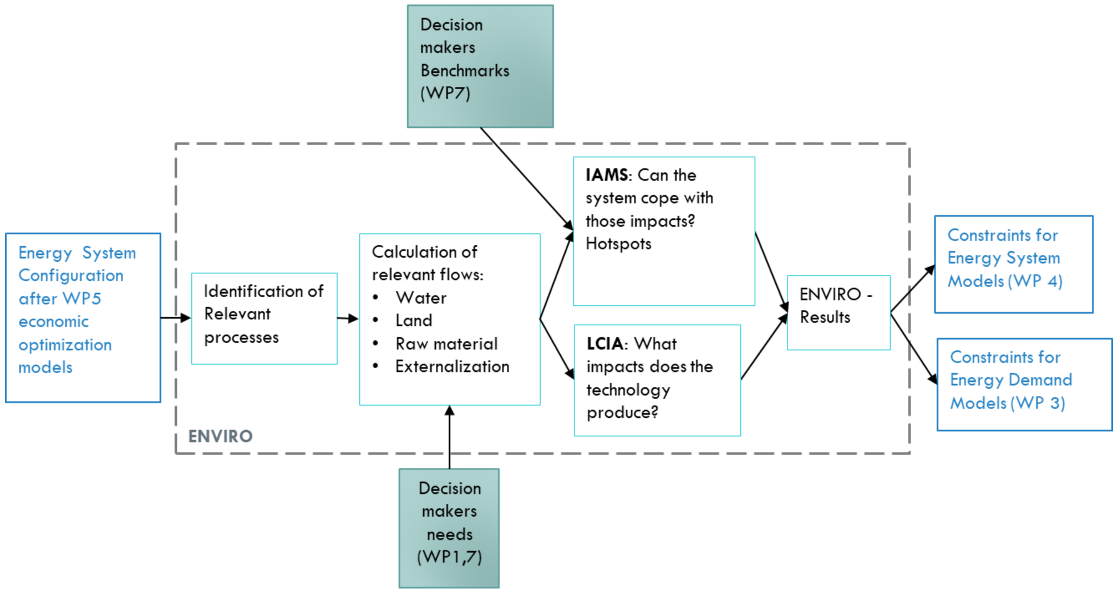

Figure 9: User needs (green boxes) as included in the ENVIRO design (development stage 3)

Table 7. Environmental user needs, their relation to identified research gaps and integration approach used in ENVIRO module

User need/Gap	Related research questions	How ENVIRO has been developed to provide this information
Environmental #1: Inclusion of raw material requirements & circularity	How do raw material requirements and supply constraints affect the deployment of specific renewable energy technologies and overall system designs?	Module includes raw material requirements and possible supply issues (e.g., import reliance), particularly in relation to critical raw materials
	To what extent does increasing the use of recycling and circularity pathways alleviate these constraints?	Module includes recycling and circularity rates as metabolic parameters
Environmental #2: Consideration of impacts over full life cycle	What are the impacts of implementing new renewable energy infrastructure considering their entire life cycle? How do these impacts compare to existing or alternative future scenarios?	Module uses the life cycle assessment (LCA) approach that provides more detailed indications of the environmental impacts of energy generation processes (including infrastructure) throughout their full life cycles
Environmental #3: Inclusion of impacts on biodiversity	How do different sustainable energy transition scenarios and the deployment of renewable energy technologies impact biodiversity?	Module employs the LCA approach which can be customized to provide detailed indicator outputs for biodiversity loss
Environmental #4: Inclusion of more detailed calculations of GHG emissions	How do different sustainable energy transition scenarios impact overall GHG emissions levels?	Module employs the LCA approach which can be customized to provide detailed indications of greenhouse gas emissions. Outputs of this kind provide far more detailed emissions information, beyond the simplified relationships between parameters used in existing IAMs and other approaches
Environmental #5: Inclusion of other forms of pollution	Does a transition to sustainable energy systems with more renewable energy sources affect the occurrence of other forms of pollution?	Module employs the LCA approach which can be customized to provide detailed indicator outputs for various other types of air, land and water pollution (e.g., abiotic depletion, acidification, eutrophication, land and aquatic ecotoxicity)
Environmental #6: Inclusion of other factors influencing human health	What are the other human health benefits of the transition to renewable energy systems?	Module employs the LCA approach which can be customized to provide detailed indicator outputs for human health-related factors (e.g., human toxicity potential, ionizing radiation)
Environmental #7: Inclusion of land & water use outputs	How could different sustainable energy transition scenarios change land and water use regimes?	Module employs the LCA approach which can be customized to provide detailed indicator outputs for land and water use. Metabolic inputs can also be used to provide specific outputs for these categories

In the terms of the framework presented in **Figure 7**, user needs have been considered in the narrative definition, model study plan and model design so far (stages 1-3). The resulting inclusion of user needs into the ENVIRO design is covered in **Figure 9**. Data collection (stage 4) considers user needs in the resolution of

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the data that is being collected and by ensuring that the databases are relevant in resolution and semantics and coherence with the assessment at hand. The further stages (5 onwards) will be implemented during the initial application of ENVIRO to the case studies of the project. **Table 7** expands on how ENVIRO has been adapted to include each of the user needs identified in section **Error! Reference source not found.**. The ways in which ENVIRO was developed to include these needs is also provided. Again, it is assumed that these requirements were integrated from approximately stage 3 of the modelling process onwards.

4 Discussion

4.1 User needs for environmental and social aspects of the energy transition

Findings from WP1 suggest that the users of models and modeling results require a better integration of environmental sustainability issues, one that goes beyond GHG emissions. They also indicate that the social and behavioral aspects of the energy transition should be improved in energy system models. Key social issues include the integration of social impacts on energy politics and policies, the social acceptance of energy technologies and infrastructure, and consumer behavior in energy models. Key environmental aspects include the use of raw materials/ circularity, the implications on nature and biodiversity, as well as full life-cycle impacts.

Whereas model developments add detail, increase resolution and improve technical precision, it is particularly important for modelers to also pay attention to social, political, and environmental aspects, as these non-technical aspects are important for users of modeling results–decision-makers from the field of policy, industry, and NGOs. Because such factors currently determine the development trajectories of new energy technologies across Europe, it is essential to include societal, political and advanced environmental realms in energy system models if they are to generate meaningful and impactful results.

However, many models continue to maintain their techno-economic modelling focus and, thus, they neglect to consider the social and environmental implications of the energy transition. For example, although modelers increasingly recognize social developments as very important drivers or barriers, they persist in omitting them from their models because they are hard to quantify in a robust way (Köhler et al., 2018; Trutnevyte et al., 2019). Thus, it is important to increase the involvement of social scientists in model developments alongside modelers from other areas than energy systems modeling, such as life-cycle assessments. This requires interdisciplinary modeling projects, such as SENTINEL, to expand and complement the current modeling focus.

4.2 Development of ATOM, QTDIAN, and ENVIRO

ATOM, QTDIAN, and ENVIRO are developed and adapted to contribute to meet these user-needs for a better representation of environmental and social implications of the energy transition in energy modeling.

QTDIAN and ENVIRO are both developed by taking user-needs into account from the beginning. Both models benefit from the strong stakeholder engagement process in SENTINEL. By contrast, ATOM is adapted within the SENTINEL project, and user-needs informed this process. Although we, as modelling teams, used different approaches to integrating user-needs in our modeling tools, user-needs are essential for the model developments/improvements and will ensure that the models are fit-for-purpose.

Although only a small amount of user-needs information was available at the narrative definition stage of the study, a significant amount of information was able to be gathered from participating stakeholders during the thematic workshops. This information was then incorporated into the model study plan and model design stages, and continues to guide the ongoing development of the module. Perhaps unsurprisingly, the two most significant environmental aspects highlighted in the workshops were raw material demands and GHG emissions; these two issues are perennial concerns in climate and energy modelling narratives. However, air pollution, land and water use, and biodiversity concerns were also raised.

While several existing modeling approaches are capable of addressing these issues is some form, no approach to date has proven capable of producing detailed indicators that address all of these issues at wider spatial scales and high levels of detail. Furthermore, as ENVIRO employs the metabolic framework defined by the MuSIASEM approach, outputs relating to these indicators can be analyzed and compared in relation to each other, and other metabolic inputs, to provide an array of useful secondary indicators that can be used to produce a metabolic profile of each of the scenarios analyzed by the module at a variety of temporal and spatial levels. As such, the resulting module will be capable of addressing the issues identified by stakeholders and providing useful and robust inputs to the ongoing discussions surrounding sustainable energy systems.

User-needs have also supported the development of QTDIAN from the narrative definition stage. The toolbox captures and materializes social drivers and constraints of the energy transition that we identified as most relevant to our users, including social acceptance and preferences, public opposition, policy preferences and dynamics as well as scaling of the economy. The social toolbox supports other modelers that want to improve the representation of social aspects in their model: QTDIAN delivers new social storylines/ narratives, as well as quantified input assumptions to be integrated other models. So far, storylines often don't address social development and dynamics, and social aspects hardly influence the optimization/ simulation process (Krumm et al., in review). QTDIAN provides solutions to advance in that regard. Furthermore, other energy models can use QTDIAN to discuss their results in the context of social realities, and, thus, expand current output discussions. If social aspects are better-represented in energy system models, models will come closer to "real world" phenomena. Nevertheless, QTDIAN will not be able to deal with all social drivers and constraints and further research is needed to examine other social aspects.

4.3 Outlook

Moving forward, the focus with ATOM lies on the application of the model to the SENTINEL case studies to test its usefulness. A critical stage for the successful implementation of a model is data collection. Although the model has been restructured and readjusted to user-needs, and, thus, is set up, data availability is always a major shortcoming. For example, so far, we have been dealing with difficulties to find historical data on storage systems' adoption in the residential sector. To this end, stakeholders insights during the model application part of SENTINEL will be instrumental. As any computational model, ATOM is only as good as the data it uses, and as accurate as the assumptions it makes.

The next focus with QTDIAN lies on the tool implementation. Until now, user needs have informed the definition stage. For the quantification of the qualitative storylines, the data collection is a critical stage.

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"Soft" factors of the energy transition are often difficult to quantify, and if data exist, then it is often highly context-specific and thus valid for a specific region and time period. Nevertheless, we aim to quantify key social drivers/ constraints in order to better understand their influence on the speed of the transition and design of the resulting energy system. Furthermore, the collaboration with other modelling team is pivotal, as QTDIAN can only unfold its usefulness when integrated in other energy models. We acknowledge that interdisciplinary and transdisciplinary modelling is challenging and is time-intensive. However, linking QTDIAN with other energy models can contribute to broaden the perspective on and understanding of the energy transition and increases realism, as Trutnevyte et al. (2019) emphasized for linking social science and modeling in general terms. We encourage more interdisciplinary and transdisciplinary modelling because it can provide explicit, clear and systematic system representations that induce learning and facilitate communication about the target system (Holtz et al., 2015).

Regarding ENVIRO, the two main challenges ahead are i) the selection of the LCA indicators that are robust enough to provide the information needed by the users and ii) the co-development of an integration protocol for other modules to use the ENVIRO outputs. About the selection of indicators, the life cycle impact assessment methods already included in ENVIRO provide a comprehensive environmental profile of the scenarios given. However, as an answer to the interest of the users, we will have to work on specific methods that allow ENVIRO to highlight critical raw material supply risk, biomass externalization and land use. Regarding the integration of the environmental results in energy models, energy modelers are also users of ENVIRO and their needs must also be integrated in the further development of the module. The main challenge lies in the fact that energy models do not include environmental parameters within their semantics and the use of ENVIRO results as constraints for optimization is not a straightforward option for them.

All three modeling tools will contribute to advancing the understanding of social and environmental impacts of the energy transition, and can support decision-makers by answering at least some of the critical issues and questions that users have raised within the stakeholder engagement process. The user-needs we identified are relevant and we encourage models to take up these needs beyond the SENTINEL project.

Finally, social and environmental aspects of the energy transition are sometimes interlinked, which give us an opportunity to explore collaboration between the QTDIAN, ENVIRO and ATOM modeling teams. For example, social storylines as derived from QTDIAN could inform ATOM on different clusters of consumer/ citizen groups. This could allow ATOM to set the necessary agent-related parameters to reflect on citizen profiles and types of behavior. By calibrating to historical data and then simulating, ATOM could assess the decarbonisation potential of strategic groups of consumers/ citizens to demonstrate which clusters are more responsive to PV/ storage adoption, across different contexts and different socioeconomic environments. This indicative soft-linking exercise could shed light on research questions as "*How does local perceptions towards renewable energy technologies and relevant infrastructure affect the speed and direction of the overall transition?*" Additionally, societal preferences for specific renewables technologies, as derived from QTDIAN and ATOM, could be fed into ENVIRO as constraint to benchmark the metabolic profiles of the different scenarios. In contrast, ENVIRO's output on environmental impacts of specific transition pathways could be used to inform social storylines of QTDIAN, which, could be, then, fed into ATOM to inform forward-looking projections of technological diffusion. A linking of the three models would enable us to identify socially preferred and environmentally responsible pathways, in line with current and

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increased decarbonization ambitions, moving away from monolithic modeling approaches which have traditionally dominated energy systems modeling so far, focusing only on least-cost pathways.

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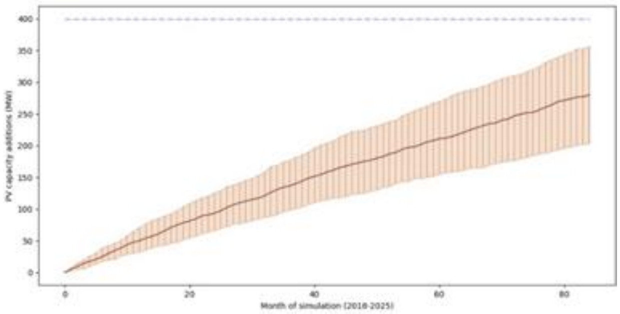
Appendix 1

The Agent-based Technology adOption Model (ATOM)

A1.1. Key model specifications (Status Quo)

Type	Agent-based Simulation Model
Resolution: Spatial	**Country level.**
Resolution: Temporal	**Monthly resolution (e.g., capacity of new PV addition at the end of each simulation month).**
Resolution: Sectoral	**Cross-sectoral technology adoption (e.g., buildings, electricity, etc.).**
Technical implementation	**Written in Python 3, runs on Windows, MacOS, Linux- Command-line tool.**
Availability: Type of licence	To be made available under a free and open license during the project.
Availability: Software download	To be uploaded at https://github.com/ during the project.
Availability: User manual	To be developed during the project.
Screenshot of the model interface	No graphical interface yet. Model is Python source code. Outputs are CSV, txt, Excel files and python figures. **Visualization of indicative results** 

A1.2. Key assumptions and uncertainties

- The applicability of ATOM so far has been demonstrated to extrapolate the dynamics of small-scale PV adoption among Greek consumers, under the current net-metering scheme and a proposed PV self-consumption with storage scheme.
- The model simulates PV adoption among a small number of agents, that is, 1,000 homeowners, who decide to purchase or reject a small-scale PV installation in each simulated time-period.
- It is assumed that the set of key agent-related parameters that govern the agents' behavior are: **(1).** Initial beliefs, **(2).** Social learning, **(3).** Resistance toward PV investment, **(4).** Probability of investing, and **(5).** Inertia.
- It is assumed that all agents are able to use their beliefs regarding the expected cash inflows to estimate the profitability of investing.
- It is assumed that all agents evaluate an investment based on when it will have paid itself back with probability 90%.
- It is assumed that all agents have the same initial budget to spend.
- The model has been calibrated using the historical data for the small-scale PV capacity addition that took place during 2009–2013, which was the period that the Feed-in-Tariffs scheme was operational in Greece.
- It is assumed that when agents decide to invest in a PV system, the final PV size is given by the empirical probability distribution that is derived from the available historical data.
- For the PV panels, it is assumed that the same annual power generation profile was used for all the simulated years.
- Consumption data on the household level for the case of Greece is not available. Only aggregated data is. Thus, to scale down to the household level (i.e., mean daily electricity consumption per household), it is assumed that all agents consume 3,750 kWh per year, which is the mean annual consumption of electrical power per

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household in Greece.

- It is assumed that the mean daily electricity consumption profiles for the "average" household in Greece remain constant.

A1.3. Model inputs and outputs

Key inputs	**Dimensions (Space/Time)**
Historical data on Number and Capacity of grid connection requests	Country/Daily
Small-scale PV investment costs	Country/Yearly
Residential battery storage investment costs	EU/Yearly
Competitive electricity consumption tariffs and other regulated charges	Country/Yearly
Electricity consumption profiles per household	Country/Daily
Solar PV generation profiles	Country/Daily
Compensation schemes for consumers	Policy
Historical data on Number and Capacity of grid connection requests	Country/Daily
Key outputs (decision variables)	
Agent-related parameters governing consumers' behaviour (after calibration).	Country/Constant
Key outputs (derived)	
Projections on new PV capacity addition under the Feed-in-Tariff, the Net-Metering and a PV self-consumption with storage scheme (after simulation).	Country/Monthly
Description of (likely) unclear terms	
Policy: Support scheme assumed by the user - specifications depending on the country of application, e.g., netting period, renumeration of excess electricity, etc. **Constant:** The values of the parameters remain unchanged at each simulation step.	