Ref. Ares(2022)8485700 - 07/12/2022

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

## Project number: *837089*

**Project name:** ***Sustainable Energy Transitions Laboratory***

**Project acronym: SENTINEL**

**Start date: 01/06/2019** **Duration: 42 months**

**Deliverable reference number and title:**
**D7.3: User-oriented evaluation**

**Version: 1.0**

**Due date of deliverable: 11.2022** **Actual submission date: 6.12.2022**

| Dissemination Level | | |
|---|---|---|
| PU | Public | X |
| CO | Confidential, only for members of the consortium (including the Commission Services) | |
| EU-RES | Classified Information: RESTREINT UE (Commission Decision 2005/444/EC) | |
| EU-CON | Classified Information: CONFIDENTIEL UE (Commission Decision 2005/444/EC) | |
| EU-SEC | Classified Information: SECRET UE (Commission Decision 2005/444/EC) | |

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## Note about contributors

This deliverable has been synthesised by the teams of the University of Piraeus Research Centre (UPRC), the Renewable Grid Initiative (RGI), the Institute for Advanced Sustainability Studies (IASS), and the Public Power Corporation (PPC). SENTINEL partners have also contributed with reported results based on their simulations.

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**Please cite as:**

**Kleanthis, N., Schibline, A., Stavrakas, V., Ceglarz, A., & Flamos, A., et. al. (2022).** *User-oriented evaluation. Deliverable 7.3. Sustainable Energy Transitions Laboratory (SENTINEL) project*. European Commission. University of Piraeus Research Center (UPRC), Piraeus, Greece.

## ACKNOWLEDGMENTS/DISCLAIMER

The authors would like to acknowledge the support from the EC. The authors would like to thank SENTINEL colleagues for their contributions to specific sections relevant to their models and modelling themes. The authors would also like to thank the stakeholders that participated to the stakeholder workshop in Athens, the online deep-dive sessions, the online SENTINEL final event, and other bilateral event/meetings. The content of this report is the sole responsibility of its authors and does not necessary reflect the views of the EC.

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SUSTAINABLE ENERGY TRANSITIONS

TEESlab University of Piraeus Research Center

Renewables Grid Initiative

IASS POTSDAM

ΔΕΗ Public Power Corporation

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## Abbreviations & Acronyms

| | |
|---|---|
| ATOM | Agent-based Technology adOption Model |
| BEVPO | Battery Electric Vehicle Potential |
| BSAM | Business Strategy Assessment Model |
| CCS | Carbon Capture and Storage |
| CC-MOD | Competence Centre on Modelling |
| $CO_2$ | Carbon Dioxide |
| DESSTINEE | Demand for Energy Services, Supply and Transmission in EuropE |
| DREEM | Dynamic high-Resolution dEmand-sidE Management |
| EPBD | Energy Performance of Buildings Directive |
| EC | European Commission |
| ECEMP | European Climate and Energy Modelling Platform |
| EEM | Energy Efficiency Measure |
| EMMA | Electricity Market Model |
| ENBIOS | Environmental and Bioeconomic System Analysis |
| ETS | Emissions Trading System |
| EU | European Union |
| EV | Electric Vehicle |
| GDI | Government-directed |
| GHG | Greenhouse Gas |
| GU | Generating Unit |
| GWP | Global Warming Potential |
| HEB | High Efficiency Buildings |
| H2020 | Horizon 2020 |
| IAM(C) | Integrated Assessment Modelling (Consortium) |
| ICTA-UAB | Institute of Environmental Science and Technology, Universitat Autónoma de Barcelona |
| IMAGE | Integrated Model to Assess the Global Environment |
| IPTO | Independent Power Transmission Operator |
| JRC | Joint Research Centre |
| KPI | Key Performance Indicator |
| LCA | Life-Cycle Assessment |
| LCSE | Levelised Cost of Saved Energy |
| MDR | Market-driven |
| MEE | Ministry of Environment and Energy |
| MIDAS | Modelling Inventory and Knowledge Management System |
| (MuSIA)SEM | (Multi-Scale Integrated Assessment of) Socio-Ecosystem Metabolism |
| NECP | National Energy and Climate Plan |
| NRAA | National Resource Adequacy Assessment |
| openENTRANCE | open ENergy TRansition ANalyses for a low-Carbon Economy |
| PPO | People-powered |
| PV | Photovoltaics |
| QTDIAN | Quantification of Technological Diffusion and Social Constraints |
| (V)RES | (Variable) Renewable Energy Sources |
| RQ | Research Question |
| SDEWES | Sustainable Development of Energy, Water and Environment Systems |
| SENTINEL | Sustainable Energy Transitions Laboratory |

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| | |
|---|---|
| SMP | System Marginal Price |
| TEESlab UPRC | University of Piraeus Research Centre's Technoeconomics of Energy Systems laboratory |
| TYNDP | Ten-Year Network Development Plan |
| WEGDYN | Wegener Dynamics |
| WP | Work Package |
| WT | Wind Turbine |

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## Executive summary

Throughout its duration, the European Commission-funded Horizon 2020 Sustainable Energy Transitions Laboratory (SENTINEL) project has applied a participatory approach including three steps: **(i).** investigating how to adjust modelling tools based on user needs and test their applicability in three case studies at three different geographical scales: National (Greece), Regional (Nordic region), and Continental (European Union, Norway, Switzerland, the United Kingdom, and some Balkan countries), **(ii).** engaging experts representing various stakeholder groups to understand the key challenges to reaching climate neutrality and specify the most critical and policy-relevant contextual questions that energy system models should be able to respond to, and **(iii).** involving stakeholders in the model application process to test and evaluate the usefulness of modelling results so that modelling teams can plan and implement further modelling refinements based on stakeholder feedback.

In this deliverable, we focus on the third and final step of the overall SENTINEL stakeholder engagement strategy and we aim **(a).** to present stakeholder feedback on the usefulness of the SENTINEL modelling results for the case studies regarding the improvement of stakeholders' decision-making as well as recommendations for improved integration of model components, and **(ii).** to produce a final set of results and lessons learnt after further model application within the case study framework. To meet these objectives, we applied a four-tier participatory multi-method approach consisting of stakeholder interactions in 10 events (workshops, conferences, focus groups, bilateral meetings, etc.), in which SENTINEL modelling teams and more than 90 stakeholders participated.

We discussed with stakeholders about 12 model applications to the case studies (9 for the Continental and 3 for the National case study) to examine the usefulness of our models and modelling results as well as identify modelling gaps requiring further improvements. During the different stakeholder engagement activities, modellers had the chance to receive various perspectives from multiple stakeholders. Discussion topics spanned from general issues related to energy system modelling, like model integration and intercomparison as well as its added value and complementarity with other approaches, to more specific ones, focusing on learning curves for technology costs and infrastructural needs, crucial environmental criteria to be considered, or the behavioural change importance for achieving decarbonisation. Stakeholders also provided useful advice in terms of disseminating and further exploiting modelling results.

We also present further modelling refinements that SENTINEL modellers have implemented or planned for providing more useful and policy-relevant implications that can be leveraged by policymakers and civil society. Moreover, we elicit key modelling challenges and lessons learnt based on the model application process to the case studies and reflect on further research areas regarding energy system modelling. One important lesson learnt from our work is that modellers need to put more effort into involving non-technical audiences in the energy modelling process by making sophisticated outputs more understandable to them. This can further enable the mainstreaming of energy system modelling, as stakeholders with no background in this area can also provide feedback on the relevance of modelling and their needs.

Furthermore, we also find out that stakeholders with technical background pay close attention to how various models were integrated and how modelling outcomes compare to those of other models when using similar scenario specifications and assumptions. We observe that further research and modelling studies should aim at better capturing the effects of fossil-fuel price uncertainty and eliciting strategic choices about a quicker reduction in the reliance on fossil fuels, particularly Russian oil and gas. In

addition, stakeholders are interested in learning how citizen-led energy transition pathways can be realised and consider that people-powered storylines should be further disseminated in energy scenario specifications. Finally, we find out that behavioural change is a critical challenge towards achieving the climate neutral goal.

Despite the end of the SENTINEL project, formed focus groups on various energy system modelling topics, such as energy demand, environmental implications, and socio-economic transition modelling will continue to exist, and new stakeholders are invited to join the discussion. We invite all the readers to find more information about the SENTINEL modelling suite, publications, and stories on the project's website.

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# 1. Introduction

## 1.1. Background

Over the last few decades, energy system models have been a useful tool for well-informed decision- and policymaking processes in Europe, having been used to simulate multiple energy transition scenarios and pathways and reflected on various possible energy system evolutions (Süsser et al., 2020). However, there has long been concern about the legitimacy of energy and climate modelling tools; for example, it is unclear why and to what extent model users should have confidence in modelling outputs (Iyer & Edmonds, 2018). Moreover, the majority of these models are very complex, and, thus difficult to understand, and to use them properly, one must understand all their elements as well as the interactions between them (Süsser et al., 2021). Given also the increased granularity that has come with designing an energy system based on high shares of renewable energy sources (RES), models became so sophisticated that it is quite challenging to understand why they produce specific outcomes (Welsch et al., 2014). This issue could be exacerbated further if such models continued to be developed and expanded to consider other issues relevant to energy system planning, such as synergies and conflicts associated with the representation of societal objectives and environmental considerations (Süsser et al., 2022).

To increase the usefulness of models and advance their understanding of the energy transition dynamics, the energy and climate modelling community must cooperate closely with numerous stakeholders representing policy, industry, academia, and civil society, and develop transdisciplinary strategies (Pade-Khene et al., 2013). Such collaborations should exist through the entire modelling process: starting from defining the Research Questions (RQs), the theoretical and empirical underpinnings, and the input parameters to tailoring models and model runs to the specific needs of specific cases and contexts as well as discussing the implications of the modelling results (Krumm et al., 2022; Süsser et al., 2021). Furthermore, open-source models and openly licensed data with clear documentations boost model users' confidence in modelling outputs by providing transparency and the ability to audit and re-do analysis, as well as the capacity to create and analyse scenarios that clearly address stakeholders' questions and concerns, since without open-source modelling and openly licensed data, any analysis performed cannot be repeated or audited (Niet et al., 2022).

Taking into account all the points above, in the European Commission (EC)-funded Horizon 2020 (H2020) Sustainable Energy Transitions Laboratory (SENTINEL)[1] project, we followed a participatory approach that included extensive stakeholder engagement throughout the entire project's duration. In the context of WP7, we established communication channels with stakeholders from the policymaking sphere, the energy industry, the field of science and research, and the civil society. Deliverable 7.1 laid the groundwork for using the SENTINEL modelling framework (Stavrakas et al., 2021). In particular, reference and disruptive energy transition scenarios leading to climate neutrality were specified in a set of case studies at three different geographical contexts, namely: **i. Continental** (European Union (EU), Norway, Switzerland, the United Kingdom, and some Balkan countries), **ii. Regional** (Nordic countries), and **iii. National** (Greece), each with different energy transition issues and challenges that policymakers and other stakeholders will face in the future (Kleanthis, et al., 2022). Furthermore, we co-defined with stakeholders a large number of critical and policy-relevant RQs that energy system

[1] https://sentinel.energy/

models should be able to address, which were compiled and categorised based on their relevance using the "Three types of knowledge" tool (Swiss Academies of Arts and Sciences: Network for Transdisciplinarity Research, 2020).

To ensure the clarity of modelling algorithms and assumptions, SENTINEL created an open-source modelling suite (**Table 1**) with accompanying model documentations. Different models in this suite can be modularly combined to answer stakeholders' pressing questions about critical issues of the European energy transition and its pathway to climate neutrality. The case studies were used to test the applicability of the SENTINEL modelling suite. Deliverable 7.2 contains information on input data, model linkages, and results. It specifies model applications in the context of policy-relevant scenarios and energy and climate targets and provides an opportunity for stakeholders to assess the value added from the SENTINEL models, by answering critical RQs. Several linkages between the SENTINEL models were established to answer the RQs identified in Deliverable 7.1. Model interlinkages enabled us to answer questions that individual models would be unable to answer or that would require a significant amount of input parameter assumptions in order to be answered. Modelling results provided several implications for the power sector's transformation, demand-side interventions, sector coupling, and the environmental and socioeconomic impacts of the energy transition in all three case studies (Michas et al., 2022).

**Table 1.** The SENTINEL modelling suite.

| Work Package (WP) | Model | Description |
|---|---|---|
| **WP2: Social and environmental transition constraints** | Quantification of Technological Diffusion and Social Constraints (**QTDIAN**) | **QTDIAN** includes qualitative and quantitative descriptions of social and political drivers and constrains of the energy transition. The main objective of this toolbox is to provide socio-political storylines and empirical data to improve the representation of social and political aspects in existing energy system models. |
| | Environmental and Bioeconomic System Analysis (**ENBIOS**) | **ENBIOS** helps energy modellers to include environmental concerns in their models. It combines the ability of life-cycle assessment (LCA) processes to provide detailed environmental impacts and resource-use indicators with the ability of the multi-scale integrated analysis of societal and ecosystem metabolism approach to analyse the metabolism of a system. |
| | Agent-based Technology adOption Model (**ATOM**) | **ATOM** simulates the expected effectiveness of technology adoption under policy schemes and allows to quantify uncertainties related to agents' (e.g., consumers/citizens, households, etc.) preferences. The novelty of the model lies in obtaining realistic uncertainty bounds and splitting the total model output uncertainty in its major contributing sources, while accounting for structural uncertainty. |
| **WP3: Energy demand** | Demand for Energy Services, Supply and Transmission in EuropE (**DESSTINEE**) | **DESSTINEE** investigates the effects of demographic, economic, and technological changes on future final energy demand and power supply, both at a yearly and an hourly dimension. It has a country-level geographical resolution, which can easily be expanded to cover sub-regions within a country. The model has been used for simulating load curves under different decarbonisation scenarios. |
| | High Efficiency Buildings (**HEB**) | **HEB** calculates energy demand of the residential and tertiary building sector under four different scenarios until 2060, based on |

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| | | |
|---|---|---|
| | | macroeconomic indicators and technological development. It includes detailed technological information for the building sector and benefits from certain macroeconomic and sociodemographic data, i.e., population, urbanisation rate, and floor area per capita. |
| | Dynamic high-Resolution dEmand-sidE Management (**DREEM**) | **DREEM** serves as an entry point in demand-side management modelling in the building sector by expanding the computational capabilities of existing Building Energy System models, by not only calculating energy demand, but also by assessing the benefits and limitations of demand-flexibility, primarily for consumers as well as for other power actors involved. |
| | Battery Electric Vehicle Potential (**BEVPO**) | **BEVPO** creates car traffic and parking density maps given the time that vehicles need to travel between different city zones throughout an entire day. The resolution of the model depends on the granularity of travel-time measurements, deriving from Origin-Destination matrices. Its accuracy in space is dependent on the arbitrary granularity with which the modeller divides a city into different zones. |
| **WP4: System design** | **Euro-Calliope** | **Euro-Calliope** models the greenfield deployment of components of the energy system at a sub-national level, in 98 regions across 35 countries in Europe, as a linear programming problem. Its objective function is to minimise total system costs. The model is set up at an hourly resolution for a full year, and it deploys technologies overnight to fulfil hourly demand in each modelled region. |
| | Advanced Energy Systems Analysis Computer Model **(EnergyPLAN)** | **EnergyPLAN** simulates the operation of national energy systems on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors. The key objective is to model a palette of options for the energy system so that they can be compared with one another, rather than model one 'optimum' solution based on defined pre-conditions. |
| | Integrated Model to Assess the Global Environment (**IMAGE**) | **IMAGE** is suited to large scale and long-term assessments of interactions between human development and the natural environment, and integrates a range of sectors, ecosystems and indicators. The model identifies socioeconomic pathways and projects the implications for energy, land, water and other natural resources, subject to resource availability and quality. |
| **WP5: Economic impacts** | Electricity Market Model (**EMMA**) | **EMMA** is a technoeconomic model that models the dispatching of, and the investment in power plants, minimising total costs with respect to investment, production, and trade decisions, subject to a large set of technical constraints. In economic terms, it is a partial equilibrium model of the wholesale electricity market with a focus on the supply side. |
| | Business Strategy Assessment Model (**BSAM**) | **BSAM** is an agent-based model which simulates the day-ahead scheduling of wholesale electricity markets. It consists of three main modules that model: **(i).** the bidding strategy of generating units (GUs), **(ii).** market operations, e.g., spinning reserves, residual demand, price caps, curtailment, etc., and **(iii).** the cost-optimal dispatching of GUs. |
| | WEGener DYNamics computable general | **WEGDYN** is a global multi-region, multi-sector, multi-agent economic impacts model built to analyse economy-wide effects from local system intervention and to isolate corresponding feedback |

| | | |
|---|---|---|
| | equilibrium model **(WEGDYN)** | effects. The main modelling mechanism concerns changes in relative prices across input and factor markets leading to changes in the structure of production, consumption patterns, and international trade relations. |

## 1.2. Objectives and scope of this deliverable

The overarching objective of this deliverable is to present stakeholder feedback on the strengths, weaknesses, and limitations of the SENTINEL modelling suite as applied to each of the three case studies (Michas et al., 2022), including the usefulness of the modelling results in different decision-making processes and other activities, and recommendations for improved integration of model components. Based on the received feedback, some of the models were run again to produce a final set of results and lessons learnt. Its scope can be broken down in the following areas (**Figure 1**): **(i). Model content**, particularly applied model refinements and improvements for addressing additional RQs, assumptions used for simulations, and modelling results for the case studies; **(ii). Model design and data**, namely usefulness of the chosen input/output format of data and improvements of model documentations according to specific user group needs; **(iii). Modelling process**, which mainly refers to the integration of model components as used in the case studies, i.e., interlinkages between models and model intercomparisons; **(iv).** the development of the **SENTINEL modelling platform**; and **(v).** the **identification of further RQs** that are needed to be answered by the SENTINEL models.

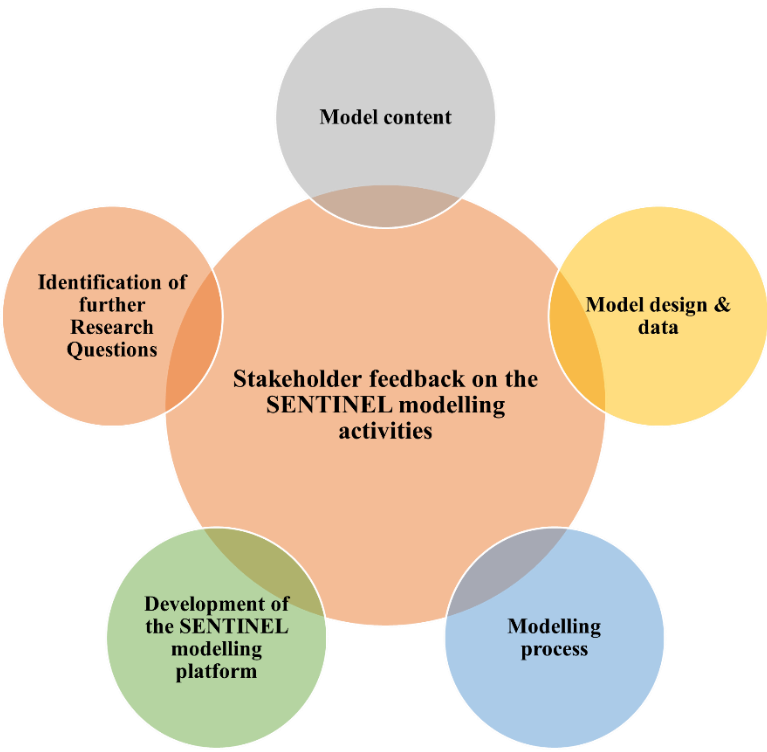


**Figure 1.** Key objectives of this deliverable: Towards further modelling refinements of the SENTINEL modelling suite.

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### 1.3. Structure of this deliverable

The remainder of this deliverable is structured as follows: **Section 2** presents our participatory multi-method approach to engage with stakeholders based on the results of the application of the models to the three SENTINEL case studies. **Section 3** presents stakeholder feedback on the usefulness of the SENTINEL modelling results and further RQs that need to be answered by the models, also considering the latest developments around Europe with the Russia's invasion of Ukraine. **Section 4** includes further model refinements that have been or are planned to be implemented based on the stakeholder feedback. **Section 5** discusses key stakeholder insights concerning specific aspects of modelling, highlights the main limitations of our work, and provides suggestions for further research in the field of energy system modelling.

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## 2. A participatory multi-method approach

To collect stakeholder feedback on the usefulness of the SENTINEL modelling results as well as further model refinements that have been or are planned to be implemented, as well as further RQs that need to be answered by the models, we applied a four-tier participatory multi-method approach, which combined different formats of stakeholder engagement (**Figure 2**). All activities were conducted during the period June-November 2022. Overall, we reached out to more than 90 stakeholders from the different SENTINEL target groups, either in a physical or in an online format. **Table 2** presents a breakdown of participating stakeholders based on the stakeholder groups they belong to.

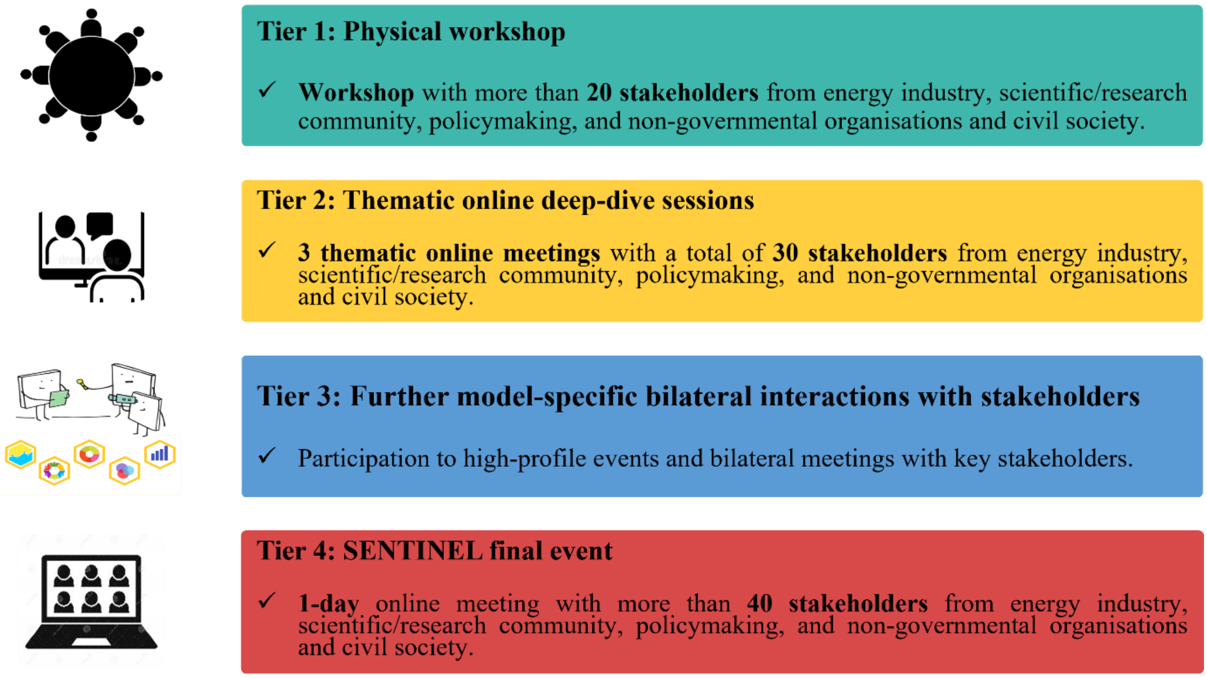


**Figure 2.** A four-tier participatory multi-method approach to collect stakeholder feedback.

**Table 2.** Number of stakeholders engaged per stakeholder group for each one of the different tiers of the approach applied.

| Stakeholder groups | Physical workshop | Deep-dive online sessions | Further bilateral interactions with stakeholders* | SENTINEL final event |
|---|---|---|---|---|
| Policy | 1 | 2 | - | 2 |
| Industry | 9 | 4 | - | 2 |
| Science | 10 | 13 | - | 37 |
| Civil society | 1 | 11 | - | 2 |

* For Tier 3, it was not possible to specify the accurate number of stakeholders engaged during the respective activities, since most activities took place during high-profile events. We refer the reader to the websites of the events in order to find more about attendance and participation.

### 2.1. Tier 1: Physical workshop

During the first tier of our approach, we conducted a physical workshop entitled "*Pathways to climate neutrality in Europe with a spotlight on Greece: Challenges, uncertainties, solutions*", on the 30th of June 2022 in "Oasis" hotel apartments, in Glyfada, Greece, which was held back-to-back with the 3rd SENTINEL annual meeting. The workshop was co-organised with the EC-funded H2020 PARIS

REINFORCE[2] project. The detailed agenda of the workshop can be found in **Section A.** Agenda of the workshop "Pathways to climate neutrality in Europe with a spotlight in Greece: Challenges, uncertainties, solutions in **Appendix**.

Its overarching objective was to gather stakeholders and field experts on the Greek energy system to discuss critical issues of the energy transition in Europe and Greece based on energy modelling insights and to explore potential challenges and solutions moving forward, also considering recent geopolitical and policy developments around Europe. 45 persons participated in the workshop, of which 21 representing different stakeholder groups, namely energy industry, scientific/research community, policymaking, and non-governmental organisations and civil society. The full list of the participating institutions and organisations can be found in **Section A.** Agenda of the workshop "Pathways to climate neutrality in Europe with a spotlight in Greece: Challenges, uncertainties, solutions in **Appendix**.

The workshop consisted of plenary and parallel breakout participation. The plenary participation was divided into three sessions: **(a).** the opening session in which stakeholders were introduced to both the SENTINEL and the PARIS REINFORCE projects, followed by **(b).** the 1st plenary session, and **(c).** the 2nd plenary session. The objective of the two plenary sessions was to present modelling results on low-carbon pathways for Europe and Greece to key stakeholders to receive their feedback regarding their usefulness. During the 1st and 2nd plenary sessions, a total of eight presentations with modelling results from both projects, which were considered important for the participating stakeholders, were made, as these addressed key research RQs identified in the context of previous stakeholder engagement activities with Greek (Stavrakas, et al., 2021) and European (Ceglarz & Schibline, 2021) experts.

During the 1st plenary session, entitled "*Transition pathways to climate neutrality in Europe*", modelling teams from the SENTINEL project made five presentations consisting of their modelling results for different transition pathways to climate neutrality by 2050 in Europe, also considering implications on the Greek energy system. During the 2nd plenary session, entitled "*Decarbonisation pathways and the role of natural gas in Greece*", modelling teams from both projects gave three presentations regarding project results for different decarbonisation pathways in Greece. Both plenary sessions were followed by a 45-minute Q&A session, where modellers were asked questions from stakeholders based on the presented outcomes.

The parallel breakout sessions were implemented in the form of "Climate-neutral World Café" sessions/discussion tables (involve.org, 2018). A total of four parallel breakout sessions were available for stakeholders to attend. Their facilitation was equally distributed between the two projects. The two PARIS REINFORCE "Climate-neutral World Café" sessions aimed at identifying bottlenecks hampering decarbonisation pathways in Greece and co-creating elements of a transformative policy mix that could overcome those bottlenecks, with a particular focus on the Greek power sector[3].

The two SENTINEL "Climate-neutral World Café" sessions aimed at identifying and generating a set of updated RQs to pinpoint what aspects should be answered by energy system models to support policymaking in Greece and how modelling material should be integrated into the SENTINEL platform and disseminated to the different target groups.

[2] https://paris-reinforce.eu/

[3] https://paris-reinforce.eu/news-events/project-news-events/pathways-climate-neutrality-europe-spotlight-greece-stakeholder

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Overall, stakeholders were asked to rotate between the four "Climate-neutral World Café" sessions to ensure equal participation across discussion topics. After the completion of the parallel breakout sessions, each session's facilitator wrapped up the feedback received from stakeholders and presented it to the plenary ("Climate-neutral World Café" gallery).

### 2.2. Tier 2: Thematic online deep-dive sessions

Since it was not possible to present all SENTINEL results during the first tier of our approach, we decided to tailor the framework of stakeholder engagement to correspond with the specific needs of the modelling teams. In the second tier of our approach, we decided to design a concise engagement format -**a deep dive**- that would ensure stakeholders' commitment to participate. Adapting the stakeholder engagement approach allowed us to capture the right structure of interaction between modellers and participants and develop the sequence of questions that should be asked to stakeholders to receive the intended feedback for modellers.

The customisable framework of the deep-dive sessions enabled an individualisation of feedback, but it also demanded a thorough planning process. It was integral to set up a communication channel with each modelling team to better understand what the objective of the deep dive would be and which thematic topics they wanted feedback on, as shown in **Table 3**, **Table 4**, and **Table 5**. Additionally, once the objective and content of the deep dives were clear, it was also imperative to know which stakeholders to invite, how many, and which structure would work best for each session. We carefully selected the participants to ensure that the thematic scope of the deep dives corresponded with the area of their expertise and that their feedback was relevant for SENTINEL modellers, as summarised in **Figure 3**. Stakeholders represented different groups and had backgrounds in policy, energy industry, civil society, and energy modelling.

**Table 3.** Deep-dive preferences concerning the WEGDYN model.

| **Model** | | **WEGDYN** |
|---|---|---|
| **RQs & case study**<br>(With regards to Deliverable 7.1 (Stavrakas, et al., 2021)) | | **Continental** case study<br>**RQs:** 22, 84, 87, 90, 100 |
| **Objective** | Show & consult on intermediate results. | x |
| | Show & communicate (final) results. | |
| | Discuss results (underlying assumptions and data). | x |
| | Check relevance of results. | x |
| | Validate feasibility of results. | x |
| | Reflect on models and scenarios. | x |
| | Anything else? Please elaborate. | |
| **Content** | Model content: Applied refinements and improvements; modelling results. | x |
| | Model design and data: Usefulness of the chosen input/output format of data; documentation improvements. | x |
| | Modelling process: Improved integration of model components; creating interlinkages with other models. | x |
| | Anything else? Please elaborate! | |
| **Experts** | Would you like to meet with stakeholders outside of SENTINEL case studies? If yes, which exactly (e.g., US, Australia, etc.)? | |
| | Stakeholders from what background(s): Research & academia; industry; policymakers; consulting; NGO/Civil society. | No preferences, everyone interested |
| | How many stakeholders would you like to meet? | 3 to 5 |

| | | |
|---|---|---|
| | Are there specific stakeholders (projects or persons) you are interested in inviting to the deep dive? If so, please include name, title, e-mail address. | |
| | Anything else? Please elaborate. | |
| **Format** | One-on-one meetings. | |
| | Focus groups with 2-4 stakeholders. | x |
| | Meetings involving SENTINEL modelling teams- as the entire WP/thematic group/interlinked groups. | x (QTDIAN-Calliope-WEGDYN-ENBIOS)* |
| | Anything else? Please elaborate. | *RQs are addressed by the soft-linkage of QTDIAN-Calliope-WEGDYN-ENBIOS; hence, if mentioned teams have resources and are interested, a mutual exchange would be preferable. |

**Table 4.** Deep-dive preferences concerning the ENBIOS model.

| **Model** | | **ENBIOS** |
|---|---|---|
| **Case study** | | **Continental case study** |
| **Objective** | Show & consult on intermediate results. | x |
| | Show & communicate (final) results. | |
| | Discuss results (underlying assumptions and data). | |
| | Check relevance of results. | x |
| | Validate feasibility of results. | x |
| | Reflect on models and scenarios. | |
| | Anything else? Please elaborate. | |
| **Content** | Model content: Applied refinements and improvements; modelling results. | |
| | Model design and data: Usefulness of the chosen input/output format of data; documentation of improvements. | Usefulness of the chosen input/output data format |
| | Modelling process: Improved integration of model components; creating interlinkages with other models. | Creating interlinkages with other models |
| | Anything else? Please elaborate! | |
| **Experts** | Would you like to meet with stakeholders outside of SENTINEL case studies? If yes, which exactly (e.g., US, Australia, etc.)? | |
| | Stakeholders from what background(s): Research & academia; industry; policymakers; consulting; NGO/Civil society. | Research & academia; Policymakers. |
| | How many stakeholders would you like to meet? | 2 or 4 of each |
| | Are there specific stakeholders (projects or persons) you are interested in inviting to the deep dive? If so, please include name, title, e-mail address. | |
| | Anything else? Please elaborate. | |
| **Format** | One-on-one meetings. | x |
| | Focus groups with 2-4 stakeholders. | x |
| | Meetings involving SENTINEL modelling teams- as the entire WP/thematic group/interlinked groups. | x |
| | Anything else? Please elaborate. | |

**Table 5.** Deep-dive preferences concerning the DREEM and HEB models.

| **Model** | | **DREEM** | **HEB** |
|---|---|---|---|
| **RQs & case study**<br>(With regards to Deliverable 7.1 (Stavrakas, et al., 2021)) | | **Continental** case study<br>**RQs:** 56, 61, 65 & 92 | **Continental** case study<br>**RQs:** RQ52 |
| **Objective** | Show & consult on intermediate results. | | x |

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| | | | |
|---|---|---|---|
| | Show & communicate (final) results. | x | |
| | Discuss results (underlying assumptions and data). | x | x |
| | Check relevance of results. | x | |
| | Validate feasibility of results. | | |
| | Reflect on models and scenarios. | x | |
| | Anything else? Please elaborate. | Policy implications | |
| **Content** | Model content: Applied refinements and improvements; modelling results. | Modelling results | |
| | Model design and data: Usefulness of the chosen input/output format of data; documentation of improvements. | Usefulness of the chosen input/output format of data | |
| | Modelling process: Improved integration of model components; creating interlinkages with other models. | Improved integration of model components | Improved integration of model components |
| | Anything else? Please elaborate! | | |
| **Experts** | Would you like to meet with stakeholders outside of SENTINEL case studies? If yes, which exactly (e.g., US, Australia, etc.)? | No | |
| | Stakeholders from what background(s): Research & academia; industry; policymakers; consulting; NGO/civil society. | Industry; Policymakers. | Research & academia; Policymakers. |
| | How many stakeholders would you like to meet? | 5 to 10 | 3 to 5 |
| | Are there specific stakeholders (projects or persons) you are interested in inviting to the deep dive? If so, please include name, title, e-mail address. | | TBD |
| | Anything else? Please elaborate. | | |
| **Format** | One-on-one meetings. | x | No |
| | Focus groups with 2-4 stakeholders. | x | Yes |
| | Meetings involving SENTINEL modelling teams- as the entire WP/thematic group/interlinked groups. | | As entire WP3 and WP8 |
| | Anything else? Please elaborate. | | |

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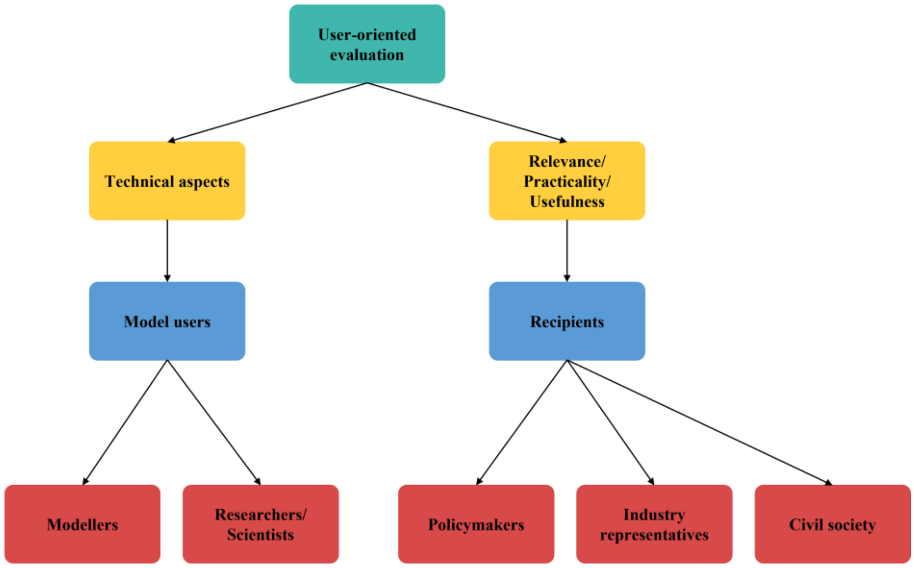


**Figure 3.** A schematic distinction of the different stakeholder groups involved in the online deep-dive sessions based on user needs.

A total of three online deep-dive sessions with 30 stakeholders were implemented with regards to **(i).** the socio-economic impacts of the energy transition, **(ii).** the environmental impacts of different energy technologies, and **(iii).** the pathways to decarbonising the building sector. **Table 6** provides an overview of the engagement activities implemented in the three online deep-dive sessions. The agendas of the deep-dive sessions can be found in **Section B.** Agenda of the "Socio-economic Impacts of a Just European Energy Transition" deep-dive session, **Section C.** Agenda of the "Environmental Impacts of Energy Technologies: Introducing the ENBIOS Model" deep-dive session, and **Section D.** Agenda of the "Pathways to Decarbonising the EU Building Sector" deep-dive session in **Appendix**.

**Table 6.** Overview of the engagement activities implemented in the three SENTINEL online deep-dive sessions.

| a/a | Online deep-dive sessions | Date(s) | Number of participating stakeholders |
|---|---|---|---|
| 1 | "Socio-economic Impacts of a Just European Energy Transition" | 19 July 2022 | 9 |
| 2 | "Environmental Impacts of Energy Technologies: Introducing the ENBIOS Model" | 27 July 2022 | 13 |
| 3 | "Pathways to Decarbonising the EU Building Sector" | 13 & 26 October 2022 | 8 |

Every deep-dive session followed the structure of first presenting the SENTINEL models and introducing the stakeholders to the SENTINEL project and the specific modelling results. The second section of the session consisted of interactive focus groups involving the stakeholders. Depending on the number of stakeholders and the stakeholder groups invited, participants were either separated into two parallel focus groups or discussed in the plenary. Discussions prioritised the relevance of the presented results, ensuring that diverse perspectives of stakeholders representing differentiated backgrounds were heard. Depending on the objectives of each session there was a third section of focus groups regarding technical aspects. In this session, stakeholders got to share their feedback about the modelling process, and the assumptions and data used by the SENTINEL partners to get to the modelling results presented. For this more technically focused session, non-technical stakeholders were either free to participate or end the deep-dive session earlier.

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### 2.3. Tier 3: Further model-specific bilateral interactions with stakeholders

In the third tier of our approach, the SENTINEL partners presented **bilaterally** their models and modelling results to different stakeholder groups during relevant high-profile events or meetings to get targeted feedback. During these activities, interactions with stakeholders were implemented either in a semi-structured or an open discussion format and allowed stakeholders to directly express their perspectives on each partner's work. The engagement activities under **Tier 3** were primarily targeted to stakeholder views from the research and the modelling community, and secondarily to representatives from policy and industry, and took place during the period June-November 2022, as summarised in **Table 7**. An overview of this Tier's activities is presented in **Table 8** along with activities of **Tier 1** and **Tier 2**.

**Table 7.** Further bilateral interactions with stakeholders to present modelling results in the context of participating in high-profile events, or bilaterally engaging with key stakeholders.

| a/a | Stakeholder engagement activities | *Where* | Date(s) | Model application |
|---|---|---|---|---|
| 1. | Annual meeting of the SENTINEL sister project open ENergy TRansition ANalyses for a low-Carbon Economy (openENTRANCE)[4] | Online | 27 June 2022 | QTDIAN – Euro-Calliope – WEGDYN |
| 2. | European Climate and Energy Modelling Platform (ECEMP) 2022 conference (former EMP-E)[5]: 3 online parallel sessions & 1 plenary panel | Online | 5-7 October 2022 | |
| 3. | 8th International Conference on Smart Energy Systems (SESAAU2022)[6] | Aalborg, Denmark | 13-14 September 2022 | EnergyPLAN |
| 4. | 17th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES)[7] | Paphos, Cyprus | 6-10 November 2022 | DREEM |
| 5. | Meeting with representatives from the Greek Ministry of Environment and Energy (MEE) | Online | 25 November 2022 | DREEM ATOM |

### 2.4. Tier 4: SENTINEL final event

The final online event of SENTINEL project took place on the 23rd of November 2022. The event was disseminated through partners' social media, while a dedicated event[8] was created in the University of Piraeus Research Centre's Technoeconomics of Energy Systems laboratory's (TEESlab UPRC) LinkedIn page[9]. The overarching objective was to gather not only stakeholders participating in previous SENTINEL events but also newcomers to the project to present and discuss key insights about the options for a transition to climate neutrality in Europe as well as its multiple implications.

62 persons joined the SENTINEL final event, 43 of which were stakeholders that mainly represented the research community. The workshop consisted of plenary participation, divided into two sessions: **(a).** a presentation of the project, its stakeholder engagement process, and the modelling results, and **(b).** a panel debate with modellers. The key objective of the 1st session was to present modelling results on low-carbon pathways for Europe to the participants to receive their feedback regarding models'

[4] https://openentrance.eu/
[5] https://www.energymodellingplatform.eu/conferences/ecemp-2022/
[6] https://smartenergysystems.eu/2022-2/
[7] https://www.paphos2022.sdewes.org/
[8] https://www.linkedin.com/events/sentinelfinalevent6994279103205912577/comments/
[9] https://www.linkedin.com/company/technoeconomics-of-energy-systems-laboratory-teeslab/mycompany/

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usefulness. During the 1st session, a total of four presentations with modelling results were made. The plenary sessions were followed by a one-hour panel debate, where modellers were asked questions from participants based on presented modelling outcomes.

After the implementation of the four-tier stakeholder engagement, modelling teams were requested **(i).** to summarise the received feedback with regards to modelling refinements (e.g., model improvements, assumptions that were used for simulations, modelling results for the case studies, usefulness of the chosen input/output data and respective format, improvements of documentation, improved integration of model components, creation of interlinkages with other models, model intercomparisons, etc.) and **(ii).** provide updated data assumptions, scenario specifications, or modelling results for the case studies, model improvements or intercomparisons, etc. Modellers also discussed lessons learnt and challenges they met based on the conducted refinements. In cases where modelling refinements have not yet been implemented, modellers were asked to include refinements that they intend to implement in the near future (indicated as "Planned" in **Table 8**).

**Table 8.** Overview of the stakeholder interactions implemented with regards to the case study applications of the different SENTINEL models/model linkages.

| Models/Model linkages | Case study | Stakeholder activities | Refinements |
|---|---|---|---|
| **DESSTINEE** | Continental | 1. Workshop (Physical, Athens) | - |
| **HEB** | Continental | 1. Workshop (Physical, Athens)<br>2. Deep-dive session #3 (Online)<br>3. ECEMP parallel session #12 (Online)<br>4. SENTINEL final event (Online) | Planned |
| **IMAGE** | Continental | 1. Physical workshop (Athens) | - |
| **EnergyPLAN** | Continental | 1. Physical workshop (Athens)<br>2. SESAAU2022 conference (Physical, Aalborg) | Implemented |
| **Euro-Calliope** | Continental | 1. Workshop (Physical, Athens)<br>2. ECEMP plenary panel II (Online)<br>3. SENTINEL final event (Online) | Planned |
| **QTDIAN – Euro-Calliope – WEGDYN** | Continental | 1. Deep-dive session #1 (Online)<br>2. ECEMP parallel session #6 (Online)<br>3. openENTRANCE project meeting (Online)<br>4. SENTINEL final event (Online) | Planned |
| **ENBIOS** | Continental | 1. Deep-dive session #2 (Online)<br>2. SENTINEL final event (Online) | Planned |
| **DREEM** | Continental | 1. 17th SDEWES conference (Physical, Paphos)<br>2. Deep-dive session #3 (Online)<br>3. SENTINEL final event (Online) | Planned |
| **ATOM** | Continental | 1. Meeting with Hellenic MEE (Online) | Planned |
| **DREEM** | National | 1. Workshop (Physical, Athens)<br>2. ECEMP parallel session #10 (Online)<br>3. Meeting with Hellenic MEE (Online) | Planned |
| **ATOM** | National | 1. Meeting with Hellenic MEE (Online) | Planned |
| **EMMA – BSAM** | National | 1. Workshop (Physical, Athens)[10] | Implemented |

[10] Even though the EMMA-BSAM application to the National case study was not presented during the physical workshop in Athens, key insights for further modelling refinements were collected from stakeholder interactions during the plenary's Q&A session.

## 3. User-oriented evaluation of the SENTINEL modelling suite

This section presents key stakeholder perspectives with regards to the model application to the case studies, which was gathered throughout the four-tier multi-method approach, and the respective implemented, or planned modelling refinements based on the received feedback.

### 3.1. Physical workshop

Modellers from both the SENTINEL and the PARIS REINFORCE projects presented their results with regards to the Continental and National case studies. A total of eight presentations were made, five focusing on the European and three on the Greek energy system (see also: (Kleanthis, et al., 2022)), which provided:

- Conclusions about the role of electrification of road transport and industrial processes as well as energy-efficiency improvements in buildings in the context of meeting the overall targets at the European level based on results of the **DESSTINEE** model.
- Insights about the reduction potential for energy consumption in the residential and tertiary building sectors based on results of the **HEB** model[11].
- Reflections based on an assessment of the potential of different technologies to reduce carbon emissions in different energy sectors based on results of the **IMAGE** model.
- Takeaways from different energy and total system cost scenarios for Greece along with intercomparisons with other models' results based on the **EnergyPLAN** model[12].
- Findings concerning the variety of cost-effective options and spatial configurations for an energy self-sufficient, carbon-neutral Europe based on results of the **Euro-Calliope** model[13].
- Conclusions about future options for decarbonisation in the residential sector in Greece based on results of the **DREEM** model[14].
- Insights regarding decarbonisation in the Greek power sector based on results of the **PARIS REINFORCE** project[15].

After the presentations, SENTINEL modellers collected insights with regards to their work from the participating stakeholders during the plenary Q&A session and the "Climate-neutral World Café" sessions.

#### 3.1.1. Insights from the plenary Q&A session

After the two plenary sessions, stakeholders had the opportunity to discuss with modellers regarding their modelling outcomes for both the cases of Europe and Greece. The main discussion topics were **(i).** usefulness of, and feedback on, the SENTINEL modelling results, **(ii).** model integration and comparability, and **(iii).** modelling challenges and areas for further research.

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[11] https://teeslab.unipi.gr/wp-content/uploads/2022/10/Net-zero-building-sector_A-European-Dream.pdf
[12] https://teeslab.unipi.gr/wp-content/uploads/2022/10/Smart-Energy-Europe_A-system-integration-approach-to-renewable-energy-in-Europe.pdf
[13] https://teeslab.unipi.gr/wp-content/uploads/2022/10/Diversity-of-options-to-eliminate-fossil-fuels-and-reach-carbon-neutrality-across-the-entire-European-energy-system.pdf
[14] https://teeslab.unipi.gr/wp-content/uploads/2022/06/Residential-sector-in-Greece_DREEM-modelling-study.pdf
[15] https://paris-reinforce.eu/news-events/project-news-events/pathways-climate-neutrality-europe-spotlight-greece-stakeholder

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#### *3.1.1.1. Feedback on modelling results*

Stakeholders posed specific questions with regards to the SENTINEL modelling results. They were interested to learn more about the decarbonisation potential and the availability of biomass and highlighted that, at the European level, without Carbon Capture and Storage (CCS) technologies, such as bioenergy with CCS, behavioural change is necessary to reach the target of the 1.5°. Stakeholders also mentioned that modelling scenarios usually result in labour markets and supply chains with radically different implications and asked for these aspects to be further taken into consideration by the SENTINEL modelling suite. In addition, they argued that offshore wind will play a critical role in the Greek energy transition but were sceptical about the very large increase in new onshore wind projects required. Finally, another critical issue mentioned by stakeholders is that the grey energy of building materials should be considered while renovating towards a net zero building sector.

#### *3.1.1.2. Model integration and comparability*

Stakeholders were also interested to learn about the extent to which SENTINEL modellers achieved integration of the different models by performing validity checks at the sectoral level, also noting that some of the models have system-wide scope, and, thus, their results can be compared more easily, while this might be more difficult for sectoral models. Modellers noted that sectoral comparisons were conducted between the modelling teams. They also referred to the SENTINEL intercomparison database that has been developed to enable comparisons of modelling results (Oreggioni et al., 2022). A key challenge to this is that models have different definitions of sectors, and thus more clarifications on the models' energy use classifications (e.g., Power-to-X, hydrogen, etc.) are needed in some cases to compare their results. Furthermore, modellers argued that a lot of effort has been made to harmonise input data of the models so that differences in modelling results can be mainly attributed to intrinsic modelling approaches.

#### *3.1.1.3. Modelling challenges and* areas for *further research*

Moreover, stakeholders asked what areas should be further researched to improve the models and modelling insights. According to SENTINEL modellers, key challenges to improving the models are the lack of transparency of data and the difficulty in accessing them, forcing the modellers to go further than the available macro data categories (e.g., by making necessary assumptions). Furthermore, modellers indicated that the aftermaths of the Russia's invasion of Ukraine shows how important it is to quickly achieve the independence from Russian gas and other fossil fuels and given this situation gas cannot be considered as an intermediate solution, thus suggesting looking into other solutions to replace gas, e.g., by lowering energy demand. In this regard, a relevant topic would be identifying the time and investment needed to decarbonise the building sector. Modelling results also showcased that there are various technically and at aggregate level economically achievable pathways toward climate neutrality. The next step is to find out what options and timing are most desirable instead of what is possible.

### 3.1.2. Insights from the "Climate-neutral World Café" session #3: SENTINEL modelling tools to support policymaking in Greece

In this "Climate-neutral World Café" session, the "Idea Tree Exercise" method (Stokols et al., 2019) was followed. According to this method, participants were prompted to write down either a question, topic, or comment regarding the energy transition in Greece that they believe is relevant for energy system models to answer, also considering recent geopolitical developments (i.e., Russia's invasion of Ukraine and energy crisis in Europe). The second step of the process enabled another stakeholder to

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comment, elaborate, or ask follow-up questions to the original stakeholder's input. Finally, the sticky notes were all placed on a board and the participants used dot voting to prioritise the most urgent input to support policymaking.

In two rounds of the "Idea Tree Exercise" method, two separate stakeholder groups contributed their ideas, leading to 18 different insights being generated in total, commented on, and prioritised. Results from this session provided an interesting mix of economic, technical, political, and social RQs about critical issues and challenges towards a decarbonised energy system in Greece. Additionally, stakeholders prioritised different urgencies in all the three stages of the "Idea Tree Exercise" method. As summarised in **Figure 4**, the questions and comments generated by stakeholders concerned mostly the topics relevant to the Greek political context, which were clustered into five categories: **(i).** *Costs of the net-zero transition*, **(ii).** *Energy system needs and considerations*, **(iii).** *Modelling capabilities and user needs*, **(iv).** *Policy implementation realities*, and **(v).** *Citizen-led and prioritised energy transition*.


**Figure 4.** Clustering of stakeholder questions about the critical issues and challenges towards a decarbonised energy system in Greece.

During the first round, stakeholders generally had a more technical background and were much more experienced in the energy system modelling process. Due to this, in the first stage of the "Idea Tree

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Exercise" method, questions and comments they wanted to be answered by energy system models reflected their advanced understanding of what energy system models do, and more importantly, what they are not yet doing well enough for the Greek context. For example, questions focused less on costs and policies, but more on novel innovative solutions and modelling capabilities. Indeed, the second stage of the "Idea Tree Exercise" method, where each individual's sticky notes were rotated to the participating stakeholders, resulted in follow-up questions and comments about the scientific preciseness of the original input from the first step, or they provided more data to agree with the original input. For the prioritisation stage of the "Idea Tree Exercise" method, "technical" stakeholders favoured citizen-led, innovative solutions.

In contrast, the second round included diverse stakeholders from Greece that encompassed more political and economic backgrounds in industry and policy. These stakeholders highlighted that both policies and the energy system requirements of Greece are quickly changing, and energy system models need to keep up with these changes. For example, the topic of security of supply was brought up by several stakeholders that prioritised increased storage capacity and additional liquid natural gas investments. From a policy perspective, stakeholders also wanted models to stay contemporary with the rapidly changing policies, asking about REPowerEU plan's implications on Greece's energy security, RES, and storage. In the second stage of the "Idea Tree Exercise" method, the participating stakeholders mostly agreed with their peer's original comments. Notably, an inquiry about model inputs and assumptions underscored an insightful answer: "Stakeholders need transparency". Therefore, models need to be open-access and modelling assumptions need to be clearly explained. During the final prioritisation round, the stakeholders agreed that transparency is the most relevant modelling aspect to consider for the future, which echoes and confirms previous findings generated in SENTINEL regarding user needs for modelling (Gaschnig et al., 2020).

#### 3.1.3. Insights from the "Climate-neutral World Café" session #4: SENTINEL modelling platform

The main purpose of this session was to gather ideas that could help the consortium to prioritise the most significant issues that should be considered during the development, the operation, and the maintenance of the SENTINEL modelling platform. In this regard, an open discussion format was followed. To solicit the feedback from experts, each participant received a large sticky note and marker to ideate one or more comments relevant to the set objectives. During the two discussion rounds of the session, two separate stakeholder groups contributed their ideas by placing the sticky notes to a board. After grouping together and further analysing the feedback received from the stakeholders, summaries with the key insights based on the discussion topics concerning the platform were developed and are presented in **Figure 5**.

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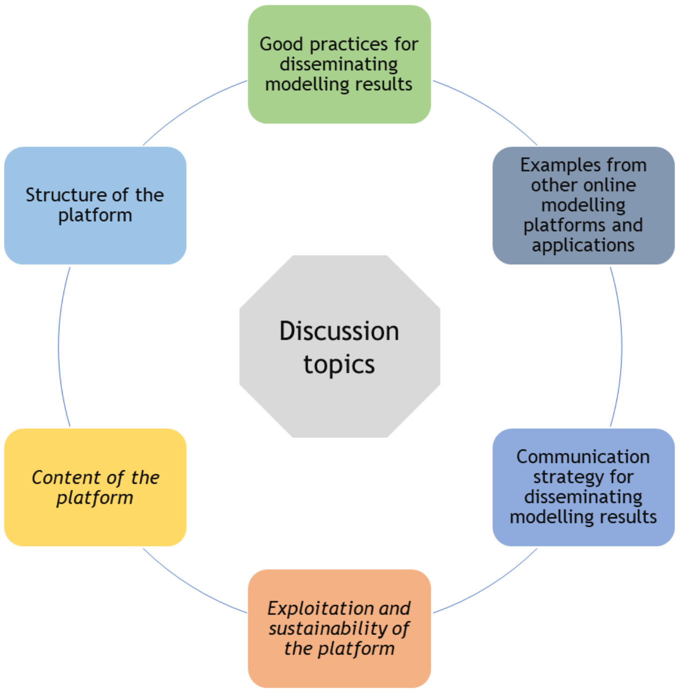


**Figure 5.** Discussion topics with regards to the SENTINEL modelling platform.

### *3.1.3.1. Good practices for disseminating modelling results*

Stakeholders provided useful feedback with regards to the dissemination of key modelling results via the SENTINEL modelling platform, highlighting the need for making the results simple, comprehensible, transparent, and visually appealing. They suggested that technical language should be adapted in a way that promotes user-friendly and digestible dissemination of modelling results to all interested parties, like, for example to policy experts, by translating them into targeted policy recommendations. As they highlighted, policy experts often find it difficult to properly understand the technical specifications provided by modelling teams, which can often lead to misinterpretations and misunderstandings. Stakeholders argued that the presentation of modelling results, as included in the online platform, should be easily understandable to different types of users, i.e., to people who are not familiar with energy modelling, but also for those, who are looking to dive deeper into the data and modelling details.

Moreover, stakeholders exclaimed that the transparent dissemination of the results, including model assumptions, uncertainties, and what model results can say (and what not) is essential. They highlighted the need for assumptions, scenarios, and data used to be clearly explained, and that the presentation of modelling results is executed in a coherent manner, which includes simple and eye-catching visualisations. According to their preferences, modelling results should be presented interactively, i.e., with adjustable key factor inputs in terms of assumptions and policy scenarios and be facilitated by standardised approaches.

### *3.1.3.2. Examples of other online modelling platforms and applications*

Stakeholders encouraged additional research of existing web-based interactive modelling platforms and applications as good practices that could be used as inspiration during the development of the SENTINEL platform. They offered the following examples:

I. **GitHub**[16] and **GitLab**[17], online software development platforms that enable software developers to upload their own code files and to collaborate with fellow developers on open-source projects.
II. The **Open Energy Platform**[18], a web interface to access energy related data with proper documentation (metadata) and links to source code and underlying assumptions.
III. The **Open Energy Mod list/wiki**[19], an initiative fostering open source and open data in energy modelling.
IV. The **Strategic Energy Roadmap Scenario Explorer**[20] that shows selected energy modelling results based on the impact analysis of multiple future paths and policies.
V. The **I²AM PARIS platform**[21] developed under the PARIS REINFORCE project, an open-access, data-exchange platform, hosting detailed documentation, inputs and outputs of energy- and climate-economy modelling.
VI. The **Integrated Assessment Modelling Consortium (IAMC) Wiki**[22] that provides an overview of integrated assessment models using a transparent wiki-based approach that has consistently been used across a range of models, also including a model comparison functionality[23] that allows for direct comparisons between these models.
VII. **The Modelling Inventory and Knowledge Management System (MIDAS)**[24] of the EC's Competence Centre on Modelling (CC-MOD), which documents models that are used to quantify the environmental, economic, and social impacts of policy options and their contributions to the EC's impact assessments.

Stakeholders also mentioned the "Energy Scenarios" website[25] of the Joint Research Centre's (JRC) Digital Media Hub as a means of presenting modelling results in a simplified way. They also added that interactive plots, such as the online application[26] of the Euro-Calliope model, which enables users to identify trade-offs among energy system Key Performance Indicators (KPIs), would be very useful for the visualisation of modelling results.

#### *3.1.3.3. Strategy for effective communication and dissemination of modelling results*

Experts noted that correctly identifying the target audiences of the SENTINEL modelling platform would be the key to adapting content according to their preferences. Web developers should design a platform that provides added value for different user groups, but when designing the platform, the target

[16] https://github.com/
[17] https://about.gitlab.com/
[18] https://openenergy-platform.org/
[19] https://wiki.openmod-initiative.org/wiki/Main_Page
[20] https://www.set-nav.eu/content/set-nav-scenario-explorer
[21] https://www.i2am-paris.eu/
[22] https://www.iamcdocumentation.eu/index.php/IAMC_wiki
[23] https://www.iamcdocumentation.eu/index.php/Model_comparison
[24] https://web.jrc.ec.europa.eu/policy-model-inventory/explore/
[25] https://visitors-centre.jrc.ec.europa.eu/en/media/tools/energy-scenarios-explore-future-european-energy
[26]https://explore.callio.pe/?spore-id::data=None&slider-storage=%5b0.0027201042426852,%201%5d&slider-curtailment=%5b0.0185844496790347,%201%5d&slider-biofuel=%5b0,%201%5d&slider-import=%5b0.0542322709410837,%201%5d&slider-elec-gini=%5b0.7257623221316274,%201%5d&slider-fuel-gini=%5b0.6522944837756298,%201%5d&slider-ev=%5b0.5626366117766397,%201%5d&slider-heat=%5b0.0398350997108831,%201%5d&slider-transport=%5b0.5264832433794119,%201%5d

group that will form the majority of users should be defined. They also suggested that it would be beneficial to receive feedback from the target audiences on whether the content and structure of the platform are understandable to them.

#### *3.1.3.4. Strategy for exploitation and sustainability of the platform*

Stakeholders suggested reaching out to the identified target audiences to highlight the unique selling points of the SENTINEL modelling platform, e.g., user-friendliness, front-end oriented modular platform design to fit various purposes and RQs of different stakeholder groups, etc. They claimed that several similar online modelling hubs have already been created and that it would be useful to develop the SENTINEL platform in a way that it has some competitive advantages compared to other existing online applications. Furthermore, they argued that maintaining the modelling platform, especially after the end of the SENTINEL project, is very important. In this sense, they proposed creating a simple platform that is well structured and easy to manage and will work smoothly after the project end. In this context, they also stressed out the importance of identifying synergies with other projects and initiatives in the field of energy system modelling.

#### *3.1.3.5. Content of the SENTINEL platform*

Stakeholders prioritised model intercomparisons, asking for explanations of model differences by comparing specific model outputs when inputting the same parameters, and applications in case studies, requiring specific information about the functionality and use cases of specific models as well as descriptions of the relation and linkages of different compatible models. They noted that mock-up model testing for the replication of results, accompanied by training material for model application, would be a useful feature to include in the platform. Experts also asked for the incorporation of well described and open-source model overviews and documentations, download options of models and output data, historical, and projected input data, and key model assumptions used, as well as uploading their sources, if available, and a contact point to reach out to in case of technical difficulties. They also asked for a timeline of updated model versions and a track record that will include all reports and publications referring to these versions. Stakeholders also referred to the need for including policy descriptions in cases where specific policies were analysed by the models to derive their outputs. An interesting point of discussion was related to what might happen if we do not reach the targets set by energy policy documents, with some stakeholders asking for the presentation of such cases to be also informed about negative energy system implications.

#### *3.1.3.6. Structure of the SENTINEL platform*

Stakeholders argued that it is important to distinguish the platform's interfaces in two sections; one for visitors that are interested in the key messages and visualisations of results, e.g., policymakers, technical users and another for modellers looking for higher granularity and input data, etc. Moreover, they proposed two different menus within the platform's structure. The first is related to the SENTINEL intercomparison database (Oreggioni et al., 2022), which could include searching functionalities to find variable values for selected energy system KPIs. The second concerns the RQs of the SENTINEL case studies (Stavrakas et al., 2021) that could also incorporate a keyword search to find relevant RQs and read the respective modelling results based on the case study model applications (Michas et al., 2022). For example, users interested in learning more about the use of biomass across different sectors could type "biomass" and navigate themselves through relevant RQs about biomass, where responses based on modelling results could be available.

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

#### *3.1.3.7. Key take-aways*

The main suggestions from the participating stakeholders regarding the development of the SENTINEL modelling platform are summarised below:

- Need for model intercomparisons, well described and open-source model overviews, and documentations of models.
- Clarity on assumptions, scenarios, and data and coherence on the presentation of modelling results.
- Utilisation of user-friendly language and inclusion of policy descriptions in cases where specific policies were analysed by the models to derive their outputs.
- Definition of key target groups and constant communication with them for their feedback on the platform.
- Identification of competitive advantages compared to other existing online applications and synergies with other projects and initiatives in the field of energy system modelling.

## 3.2. Thematic online deep-dive sessions

### 3.2.1. Online deep-dive session #1: "Socio-economic Impacts of a Just European Energy Transition"

SENTINEL modellers presented their energy system models and the interlinkages to show stakeholders how the socio-economic impacts of the energy transition were approached and modelled in the Continental case study. Specifically, QTDIAN developed three different socio-political storylines to determine the feasible European net-zero energy pathways: Market-driven (MDR), Government-directed (GDI), and People-powered (PPO). The QTDIAN storylines are described in more detail in **Figure 6**. In this socio-economic soft-link approach, the MDR, least-cost storyline acted as the reference storyline, though the reference will also achieve climate-neutrality by 2050. From this, the centralised expansion of the GDI storyline and the local-led, decentralised PPO storyline were compared against the market-based reference storyline to see what the distributional economic impacts are of European net-zero energy systems.

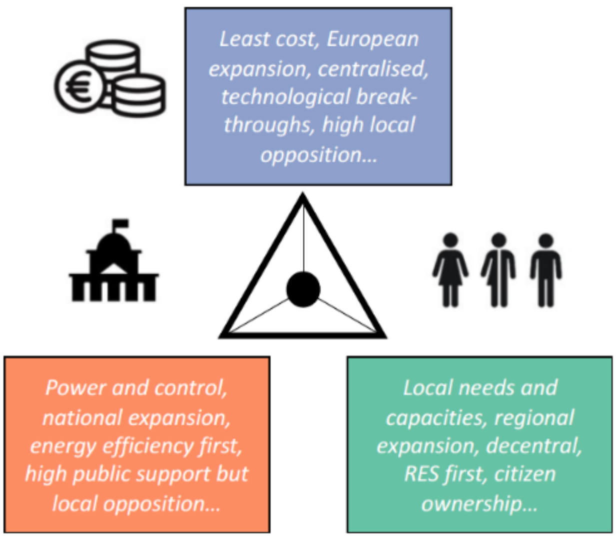


**Figure 6.** QTDIAN social storylines: Market-driven (MDR, top), Government-directed (GDI, left), People-powered (PPO, right).

These storylines are fed into the technical energy system configuration and optimisation model, Euro-Calliope. Finally, these social storylines and technical data are fed into the macro-economic model, economic impact model WEGDYN, to output employment effects, welfare, and public budget. The idea of the linking between the modelling tools was to, first, arrive at possible configurations for the future European energy system based on three distinct storylines based on governance logics, and second, to assess the economic implications coming with the three storylines (**Figure 7**).

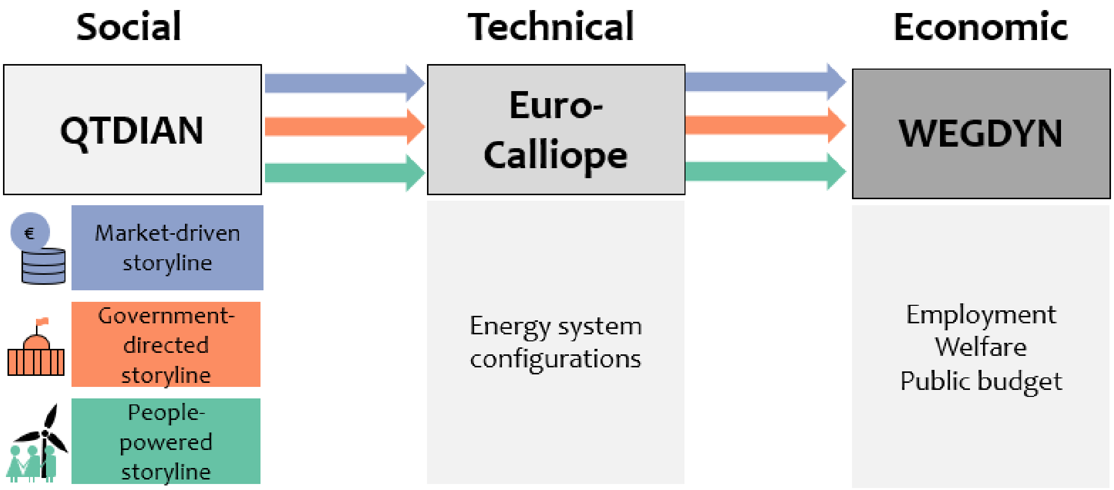


**Figure 7.** Interlinkage framework for modelling the socio-economic impacts of the energy transition.

The interlinkage between social, technical, and economic models and the socioeconomic modelling results presented in this online deep-dive session are summarised in **Figure 8**.

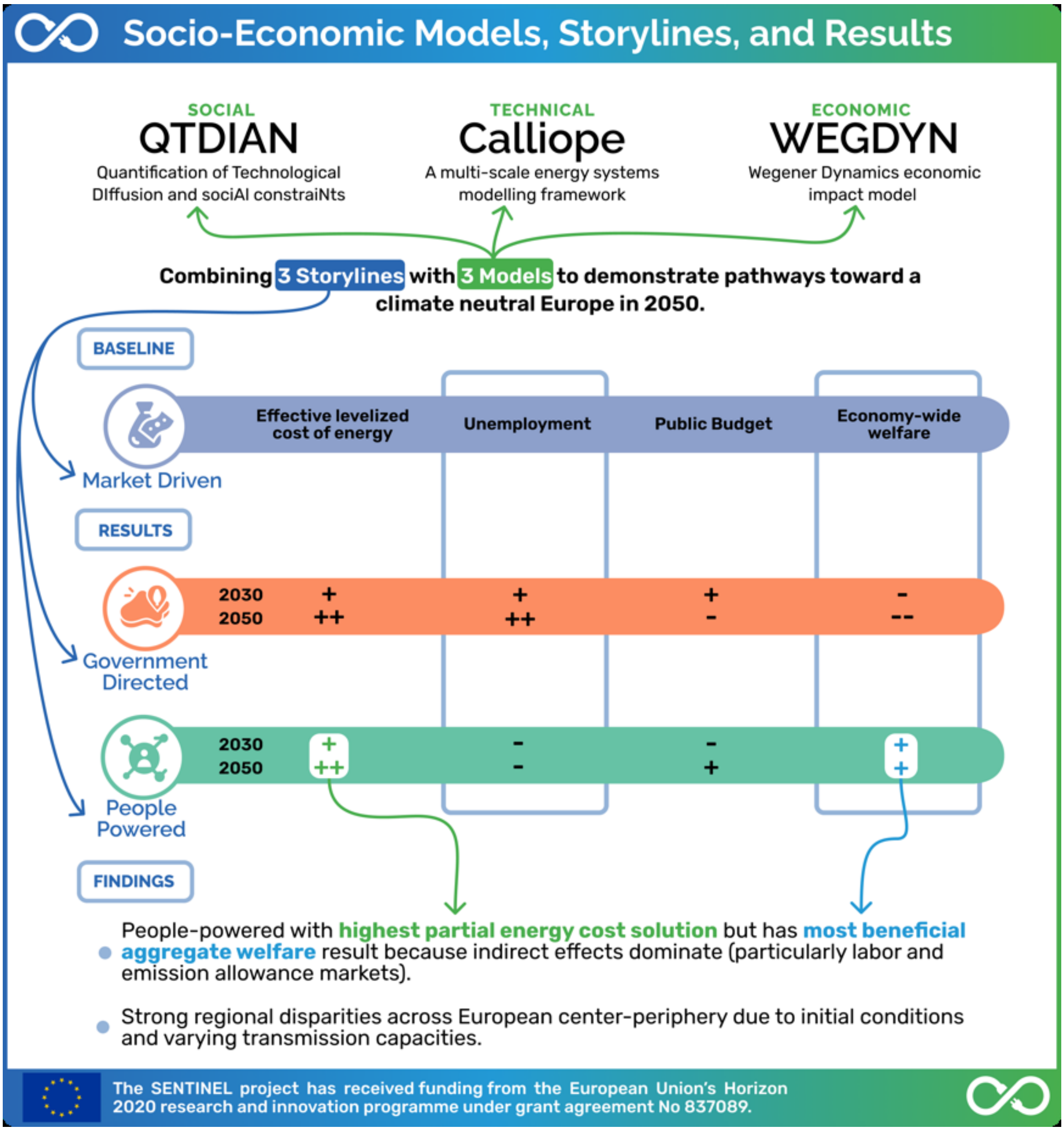


**Figure 8.** Models, storylines, and results presented during the "Socio-economic Impacts of a Just European Energy Transition" online deep-dive session.

Participants' first impressions mirrored the main ideas of the introductory words from the modelling teams. Several stakeholders in both focus groups agreed that WEGDYN, QTDIAN, and Euro-Calliope's use of interlinkages to capture employment effects was an interesting, innovative approach. Particularly, the stakeholders participating in similar modelling projects to SENTINEL, such as openENTRANCE and the PAC project[27], found the addition of the QTDIAN storylines to be an asset that their projects lacked.

[27] https://www.pac-scenarios.eu/

#### *3.2.1.1. Parallel focus group round 1: Relevance and practicality of results*

Many sagacious discussions occurred during the first parallel focus group discussing the relevance and practicality of the presented modelling results.

*Social storylines as scenarios*

Stakeholders made the connection that the MDR, GDI, and PPO storylines are like the oft-used scenarios: Business-as-Usual, Green- Growth, and De-growth/post-growth. While one of the stakeholders found it interesting to use the QTDIAN socio-technical storylines in place of scenarios, the expert questioned what the advantages were. Another participant asserted that in different countries the energy transition is driven by various actors. Using the storylines and saying only one actor, such as the government, can drive the energy transition, is inaccurate. As a solution, a consideration of a hybrid scenario ensuring greater accuracy was proposed.

Other experts were quite impressed by the detailed, highly granular economic assessment, and observed that the choice to use storylines was compatible with current policy debates around societal drivers of the energy transition. In fact, they admitted that it was more informative than scenarios from the EC or grid operators' Ten-Year Network Development Plan (TYNDP), where artificial scenarios, such as central and decentral, are too abstract. Definitively, the use of QTDIAN's storylines as scenarios in this model interlinkage was perceived as an innovative approach by the stakeholders. Indeed, the differing feedback confirmed to the modelling teams what aspects should be incorporated into future model development, such as the hybridisation of the storylines.

*People-powered storyline implies the highest long-term European-wide welfare: How can policymakers and civil society leverage these results?*

One of the main modelling results concluded that the high-cost PPO storyline resulted in the highest European-wide welfare, due to macroeconomic feedback effects. Stakeholders found this result compelling but wondered how this important finding would be translated to non-technical users, such as policymakers and civil society. From an NGO perspective, stakeholders emphasised the importance of translating results for the layman who do not use it every day. Having country-specific or energy demand sector-specific results available to share with NGO networks, would be helpful so they can compare different trends. When connecting with policymakers, stakeholders stressed the importance of identifying and pairing policy recommendations that best correspond to the socio-economic results presented. In this way, the PPO storyline's positive result when considering employment effects can better be encompassed in future policies.

*Strong regional and demographic disparities remain*

When considering the recent energy crisis related to Russia's invasion of Ukraine, the stakeholders felt that regional, distributional and gender disparities are imperative aspects to address in future socio-economic modelling developments. The future energy transition will require a huge transformation of the economy and a current structural limitation in all storylines is the lack of a skilled workforce. This transformation must also be just, meaning that those regions on the European peripheries or vulnerable households, which are disproportionately women-led, do not get left behind. Stakeholders specifically mentioned the potential distributional effect of the energy price hikes disproportionately harming vulnerable populations the hardest. For future modelling developments, stakeholders agreed it is important to build up the multi-regional framework further and potentially incorporate more country-specific or topical factors into the model.

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#### *3.2.1.2. Parallel focus group round 2: Technical aspects and modelling process*

Unlike round 1, the second round of the parallel focus groups shifted focus from the relevance and practical application of the modelling results to addressing more technical aspects. The discussions encompassed the modelling process, including the data and assumptions used and the study design. This feedback round encouraged expert knowledge exchange between modellers and even facilitated further cooperation possibilities. For example, an energy modeller in a different project mentioned that they integrate an input-output analysis to connect the economy with the energy system to produce input about energy availability, and better understand the constraints to economic growth. In the future, such a collaboration between the projects to address the costs of technologies could provide a positive and fruitful outcome for future model development.

##### *Multiple net-zero storylines: How do we reach the targets?*

Stakeholders expressed several insights when asked about the design of the model interlinkage and its use of multiple net-zero developments. First, some of the stakeholders were not initially aware that even the MDR storyline would meet the 2050 climate decarbonisation goals. This indicated to the stakeholders that even though the MDR storyline was the closest to a traditional baseline scenario, it did not mirror the same typical conclusion that a business-as-usual scenario would not hit the climate targets. Indeed, the modellers consciously intended for their version of the business-as-usual storyline to go beyond the least-cost option.

Technically, stakeholders wondered what data was used that connected all three models. The policy-oriented storylines feed into the technical model, the technical model differentiates supply and demand-side energy mixes for the macro-economic model, leading to economy-wide responses. One of the stakeholders even asked if there was a way to directly link the QTDIAN storylines to WEGDYN, e.g., spending of revenues, etc. The modelling teams considered the possibility of future model developments that could go beyond this linear approach to also investigate the feedback effect. From a policy perspective, some stakeholders feared that having multiple net-zero storylines would confuse policymakers about which option to choose. Another expert declared that externalities, such as the cost of inaction, must be included in the net-zero targets, regardless of how many storylines will achieve the target.

##### *Learning curves for technology costs and infrastructural needs*

Generally, stakeholders were interested in understanding more about the assumptions behind the interlinked models. One issue that a stakeholder brought up concentrated on the assumptions around learning curves for technology costs. These types of learning curves are perceived as always declining, i.e., photovoltaic panel prices, but the costs for some renewables are actually increasing. Therefore, stakeholders wanted to gain more understanding of the data and assumptions for infrastructure needs and the variation of costs that the models used for their results. Social storylines, as used here, represent extreme cases of the spectrum, with either markets, governments or civil society driving the energy transition. Nevertheless, these extreme cases can help contrast the main differences in socio-economic outcomes. The WEGDYN modelling team appreciated receiving this feedback, noting its relevance to future model development. They noted that the interlinkage with the Euro-Calliope model is important in regularly updating assumptions relating to technology progress and both models will continually be developing to ensure that learning curves and infrastructure cost variance are updated.

The major themes of feedback from stakeholders are summarised below and visually in **Figure 9**.


**Figure 9.** Key feedback from stakeholders during the "Socio-economic Impacts of a Just European Energy Transition" online deep-dive session.

### 3.2.2. Online deep-dive session #2: "Environmental Impacts of Energy Technologies: Introducing the ENBIOS Model"

Different environmental aspects are rarely considered in energy system modelling. The most prominent environmental constraint considered by energy system models is the Greenhouse Gas (GHG) emissions, whereas other determinants, such as natural resource depletion or nature degradation, are rarely taken into future account. Because of this, the SENTINEL project's consortium partners at the Institute of Environmental Science and Technology, Universitat Autónoma de Barcelona (ICTA-UAB) developed the ENBIOS open access modelling tool that puts attention to various environmental impacts of energy transition (Martin, et al., 2021). Throughout the SENTINEL project, energy model users and other stakeholders were involved in the selection of parameters that later translated into the ENBIOS indicators of environmental impact and resource use. (For more details see: (Süsser, et al., 2020)). The most prioritised impacts were raw materials and circularity, nature and biodiversity, and life cycle impacts, as summarised in **Figure 10**.

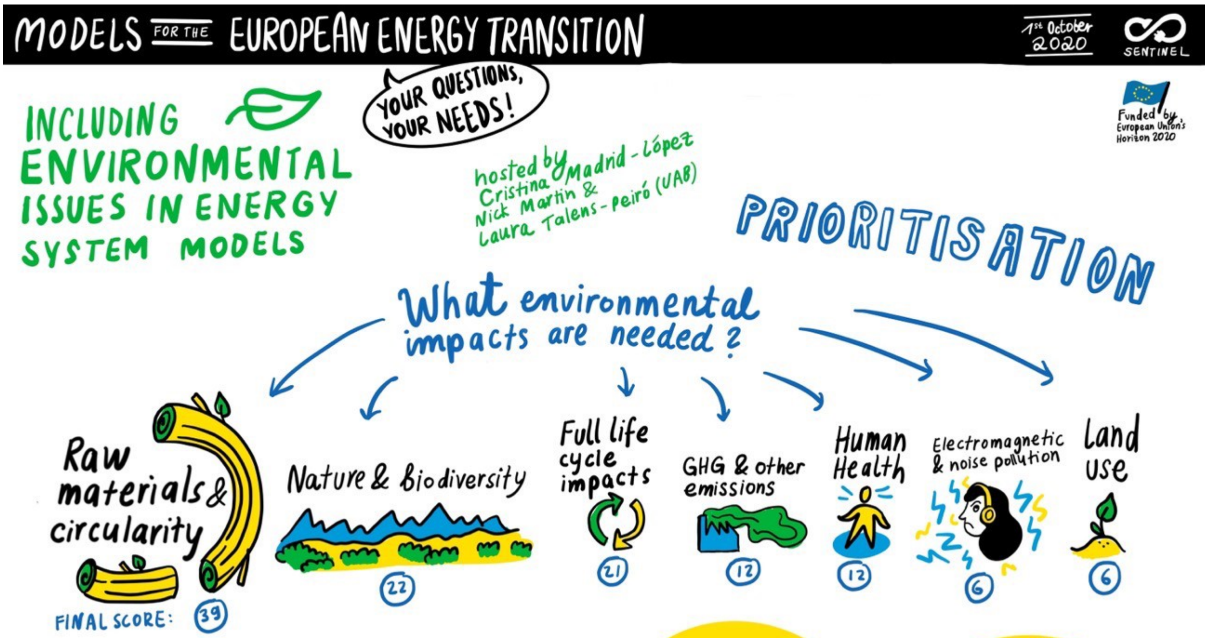


**Figure 10.** User needs prioritisation of environmental impacts, illustrated by Ellery Studios (Gaschnig, et al., 2020).

ENBIOS is a simulation module that, when plugged into an energy system model, factors environmental concerns, like raw materials and circularity (Madrid-López et al., 2021). The modelling process with ENBIOS, as shown in **Figure 11**, starts with the pathways or configurations that energy system models simulate based on policy scenarios. In SENTINEL, ENBIOS was coupled with supply-side and optimisation models, Calliope and EnergyPLAN, to show which pathways are compliant with the scenarios. The energy system configurations modelled by the Euro-Calliope and EnergyPLAN models serve as input to ENBIOS and typically are constrained by the share of renewables, the need to meet the demand and, as previously commented, direct GHG emission targets. ENBIOS calculates for each configuration or pathway a range of 11 indicators including life cycle GHG emissions, impacts over human health, water depletion, raw material use, or labour needs.

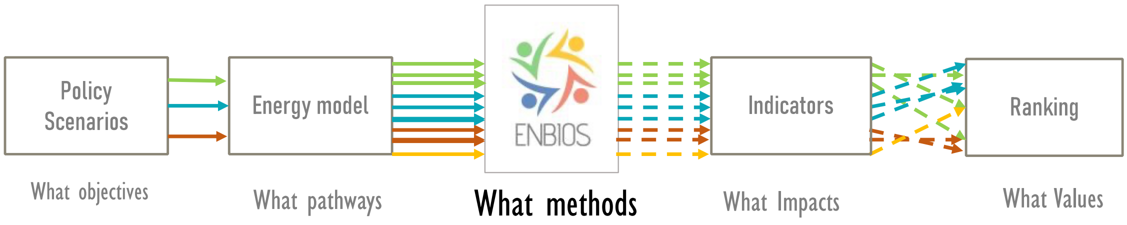


**Figure 11.** ENBIOS application framework.

The ENBIOS methodological framework combines two sustainability impact assessment methods to calculate the necessary environmental indicators. First, ENBIOS uses the LCA, a well-known methodology that can bring a better understanding of the direct and indirect environmental impacts of the energy transition. LCA looks at the whole value chain, thinking beyond the energy system, for example, it includes emissions from manufacturing boilers and not only their GHG emissions. Within SENTINEL, only the supply side assessment was developed. The technologies that use energy, such as washing machines or vehicles, are not yet included in the internal ENBIOS libraries. A key limitation is that LCA does not provide contextualised information, such as the viability of certain raw materials extraction level.

To address this shortcoming, the ENBIOS methodology combines the value-chain and environmental assessment capabilities of LCA with the Multi-Scale Integrated Assessment of Socio-Ecosystem Metabolism (MuSIASEM) (Giampietro et al., 2009). MuSIASEM, or Socio-Ecosystem Metabolism (SEM), is a methodological framework designed for the sustainability assessment of energy system configurations and based on the study of societal metabolic patterns (Giampietro, et al., 2014). Its objective is to characterize metabolic patterns of socio-ecological systems (how and why humans use resources and how this use depends on and affects the stability of the ecosystems embedding the society). A socio-metabolic analysis traces resources as they pass through society (i.e., extraction, processing, distribution, consumption, waste, emissions) (Singh, et al., 2021).

The most integral aspect of MuSIASEM is its ability to integrate quantitative assessments across dimensions and scales for sustainability analyses (i.e., linking energy, water and land uses, waste, urban/rural development, etc.). As a result, ENBIOS can upscale the results from LCA to identify hotspots that make energy pathways defined by energy system models unfeasible. **Table 9** presents the 11 indicators that can be assessed with ENBIOS. A visual representation of the ENBIOS methodological framework is provided in **Figure 12**.

**Table 9.** Impact assessment methods integrated within the ENBIOS module.

| Life Cycle Impacts beyond energy system indicators | Social Ecosystem Metabolism Impacts indicators | Additional indicators not available from LCA or Social Ecosystem Metabolism approaches |
|---|---|---|
| Material, water and fossil depletion | Metabolic rates | Material supply risk |
| Global warming potential (GWP) | Supply/ End use | Material extraction impacts |
| Biodiversity | Land appropriation | End-of-life Recycling |
| Human health | Job dependency | |

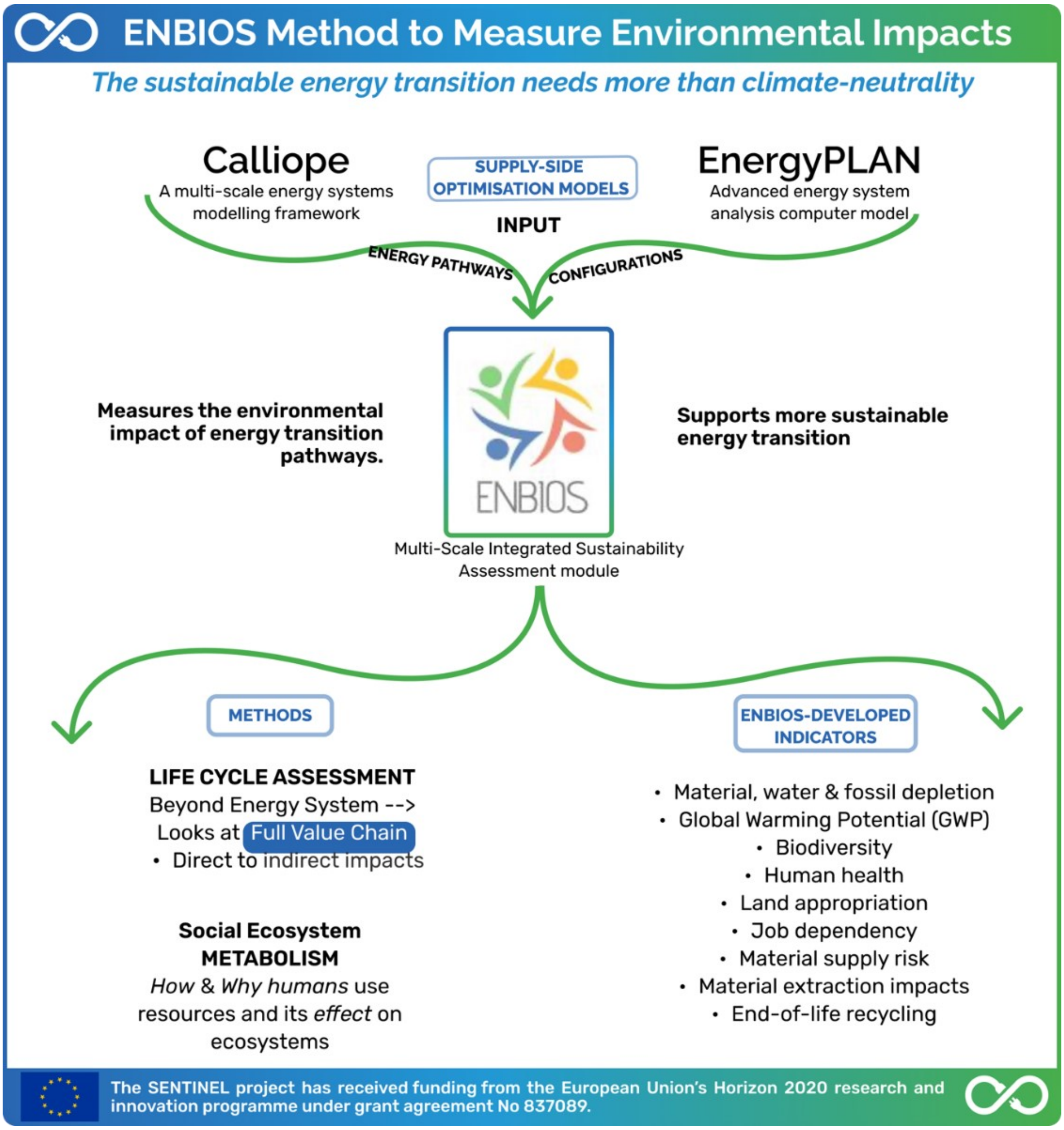


**Figure 12.** ENBIOS methodological framework.

#### *3.2.2.1. Combining LCA and SEM is an innovative approach*

While many stakeholders dealing with the environmental aspects of energy transition were aware of LCA methodologies and LCA's potential integration into energy system models, the addition of the viability assessment provided by SEM analysis was considered innovative and an important integration of environmental constraints, especially since most energy system models do not consider SEM. Stakeholders representing the NGO community and industry associations found this inclusion very useful for their future sustainable planning and analysis applications. From a fellow modeller's perspective, they agreed that ENBIOS would be quite useful as an extension of energy system models for sustainable system planning.

#### *3.2.2.2. Crucial Environmental Criteria should be included in ENBIOS model*

One of the key questions for ENBIOS was to gain insights into identifying new and prioritising the presented environmental indicators. Since the stakeholders represented different backgrounds and, thus, had various prioritisations, the feedback reflected the many environmental criteria that should be included in the future ENBIOS development. Stakeholders agreed that biodiversity loss and GWP are important criteria, as previously indicated in the SENTINEL user needs workshop (Süsser, et al., 2020). Beyond these criteria, stakeholders also emphasised the importance of land use for future development and deployment of renewable energy projects. For example, several stakeholders from the NGOs and industry associations were especially concerned about the sustainability criteria for auctioning offshore wind projects. As this is an important energy technology being implemented and planned for the European energy transition, many stakeholders inquired whether ENBIOS as a tool could be integrated into the auctioning processes to uniformly assess performance indicators. From a renewable energy policy perspective, stakeholders also highlighted the criterion of siting requirements.

#### *3.2.2.3. Regionalisation and country-level approach to compare trade-offs*

Many stakeholders agreed that regionalisation and country-level modelling results are imperative for their work and key to the assessment of environmental impacts and resource use. One participant of the deep dive mentioned the importance of highlighting the balance between different environmental and, consequently, social impacts, so policymakers and other stakeholders can see the bigger picture and trade-offs between different energy options. Most NGO representatives agreed and underlined the importance of showing examples. Based on the regional context, it is easier to identify the trade-offs that are more relevant to an area or energy system.

Considering the example of the offshore wind auctioning process, stakeholders emphasised that since there is no uniform modelling tool to perform environmental assessments, individual actors may utilise different modelling tools. A standardised methodological approach would enable more transparency and ease in comparing tender proposals in the auctioning process. They also agreed that assessments of certain regions would be helpful, especially in terms of impacts and availability of resources, as it would provide more insights and possibilities for models, such as regionalising impact assessments and georeferencing. Other stakeholders retorted that it would be more important to tailor to the national context than regionalising, as the ecosystems differ in various geographical locations. Furthermore, the model could be further improved to compare impacts between onshore and offshore wind technologies.

Finally, stakeholders were highly interested in knowing the implications and trade-offs of excluding protection or unavailable areas in the model, and whether, by doing so, the climate-neutrality targets are met. ENBIOS modellers agreed that this would be a worthwhile analysis, and while there are currently modelling constraints to answer this question, further model development will be implemented in the future.

#### *3.2.2.4. Stakeholder interest for future collaboration and comparison of work*

Several stakeholders were able to identify synergies between their work and ENBIOS. While some, like the stakeholders dealing with offshore wind technology, sought future collaboration to investigate possibility of integrating ENBIOS into the auctioning process, other stakeholders working with energy system models were interested in collaborating with the ENBIOS modellers to better their existing methodology or to utilise the ENBIOS model in their own work. For example, one participant explained that their research project on tailoring the LCA framework to a stationary energy system is looking

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beyond the production phase and includes end-use. After discussions around the limitations and opportunities of a more standard LCA approach and ENBIOS's combined LCA and SEM methodology, both teams were eager to collaborate in future model developments. Interestingly, stakeholders from other modelling backgrounds, including DG ENER, were interested in future collaboration with ENBIOS modellers to compare results of their own modelling.

#### *3.2.2.5. Importance of easily accessible results*

While the attending stakeholders appreciated the presentation, it was difficult for several representatives of NGOs and industry to grasp highly technical aspects. From a practical level, since NGO stakeholder capacities to understand the technical details of the ENBIOS module was limited, it would be most helpful to show high-level examples. Additionally, some stakeholders raised the concern that the findings can be too technical also for policymakers to develop impactful policies from a short-term perspective. This underlines a key lesson learnt for the modelling team, and likely the modelling community in general, that results must be accessible beyond an academic lens, so that other users can share their feedback on the relevance of modelling and their needs.

A summary of the stakeholder feedback received for the case of the ENBIOS module is presented in **Figure 13**.

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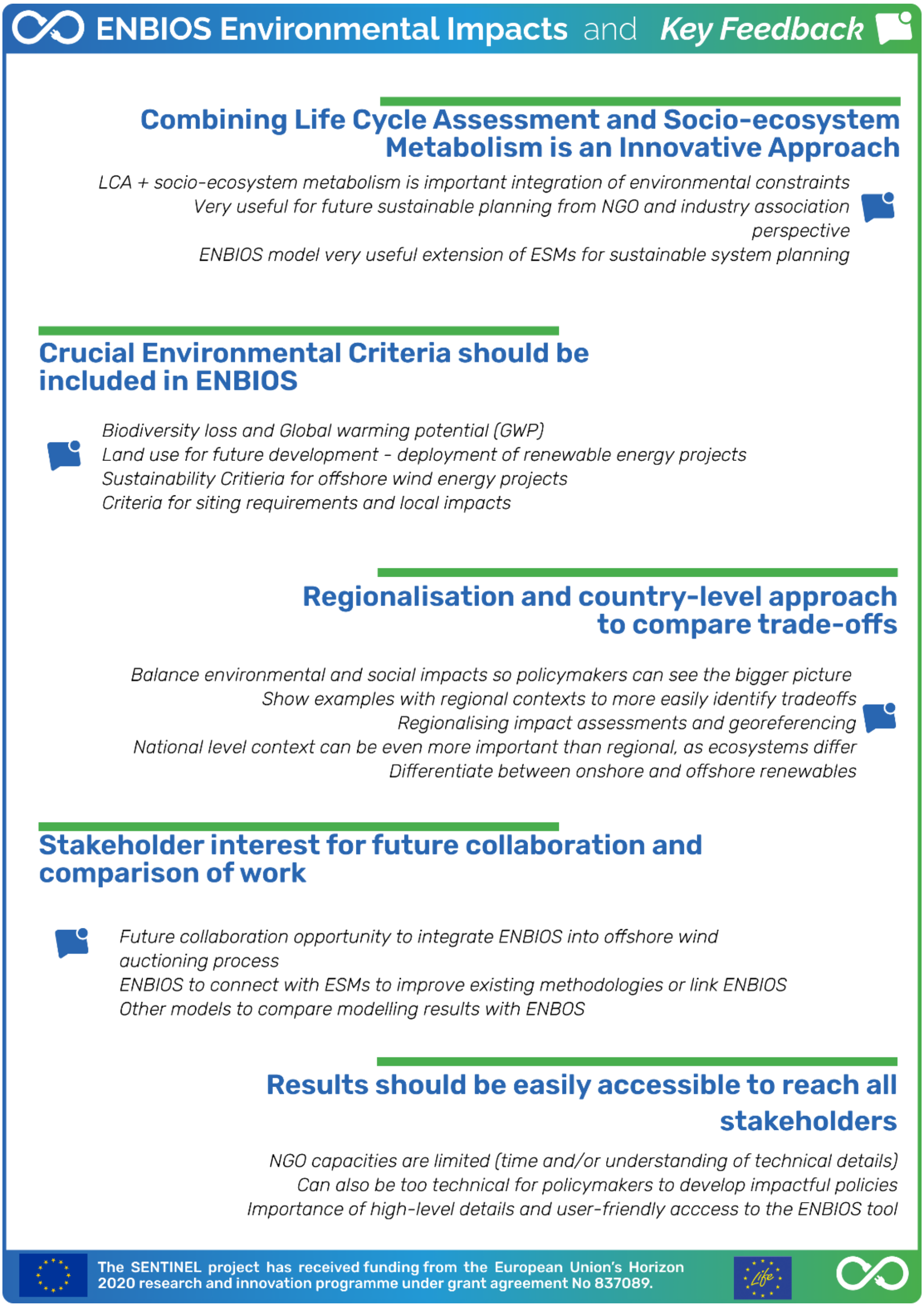


**Figure 13.** Key feedback from stakeholders during the online deep-dive session #2: "Environmental Impacts of Energy Technologies: Introducing the ENBIOS Model".

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### 3.2.3. Online deep-dive session #3: "Pathways to Decarbonising the EU Building Sector"

Modellers working with the building sector energy system models HEB and DREEM introduced the modelling results and received feedback about their general relevance and possible technical gaps or improvements. The two building sector models that were presented in this deep dive have a complementary approach, highlighting the importance of both holistic, performance-based building, and more modular, individual component-based modelling approaches. For this deep dive, diverse stakeholders with expertise in the building sector, including researchers, modellers, and non-technical representatives from industry and NGOs/civil society were invited.

#### *3.2.3.1. HEB application to the Continental case study*

Modellers presented the results answering the RQ: "Is a European net-zero building sector a dream or a reality?" This question expanded the use of the HEB, a performance-based model that considers buildings as complete systems, rather than sums of components. This whole building approach recognises that state-of-the-art building energy performance, such as passive house and net-zero energy buildings, can be achieved through a broad variety of designs and component combinations.

HEB was applied to the EU-27 and the UK, and it was parameterised as shown in **Figure 14**. Additional parameters included EU climate zones, and building classifications into residential or tertiary (commercial, public, and non-residential), including subcategories describing building types, such as office, retail, single-family, and multifamily. The final parameter describes the building's vintage, which considers the typical energy consumption, based on the age and quality of the building. Any buildings built during the period 2022-2060 are considered new buildings and standard buildings are any buildings built before 2022 that have not been retrofitted. The classification also considers buildings retrofitted between 2022-2060, while both new and retrofitted buildings during this period can be considered "advanced" if they use state-of-the-art building technologies.

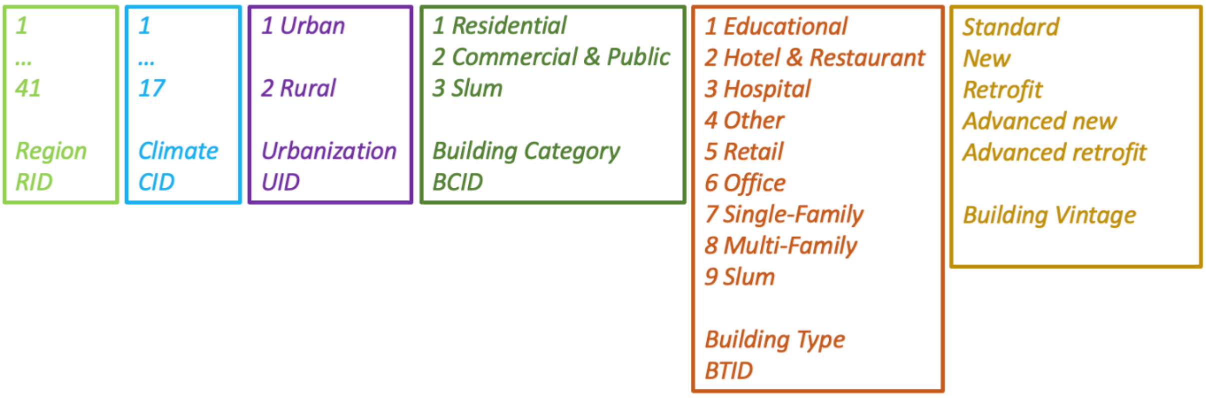


**Figure 14.** Building classification in the HEB model.

With this detailed classification, the HEB modelling team developed four scenarios to see which levels of specific policy measures (i.e., renovation rate targets) would be needed to achieve a net-zero European building sector. The four scenarios used, i.e., "Deep Efficiency", "Towards Net Zero", "Moderate Efficiency", and "Frozen", were not used to predict the future, but to give "*what if*" insights into the consequences of the selected policy measures.

Results produced by the HEB model showed that for annual total space heating, cooling, and hot water, total final energy use can be substantially reduced under both the "Deep Efficiency" and the "Towards

Net Zero" scenarios. Therefore, measures such as high renovation rates (over 3%), with the addition of state-of-the-art buildings, could reduce the energy demand in the residential sector by 98% by 2060.

An overview of the application of the HEB model to the Continental case study in terms of parameters, scenarios, and results is presented in **Figure 15**.

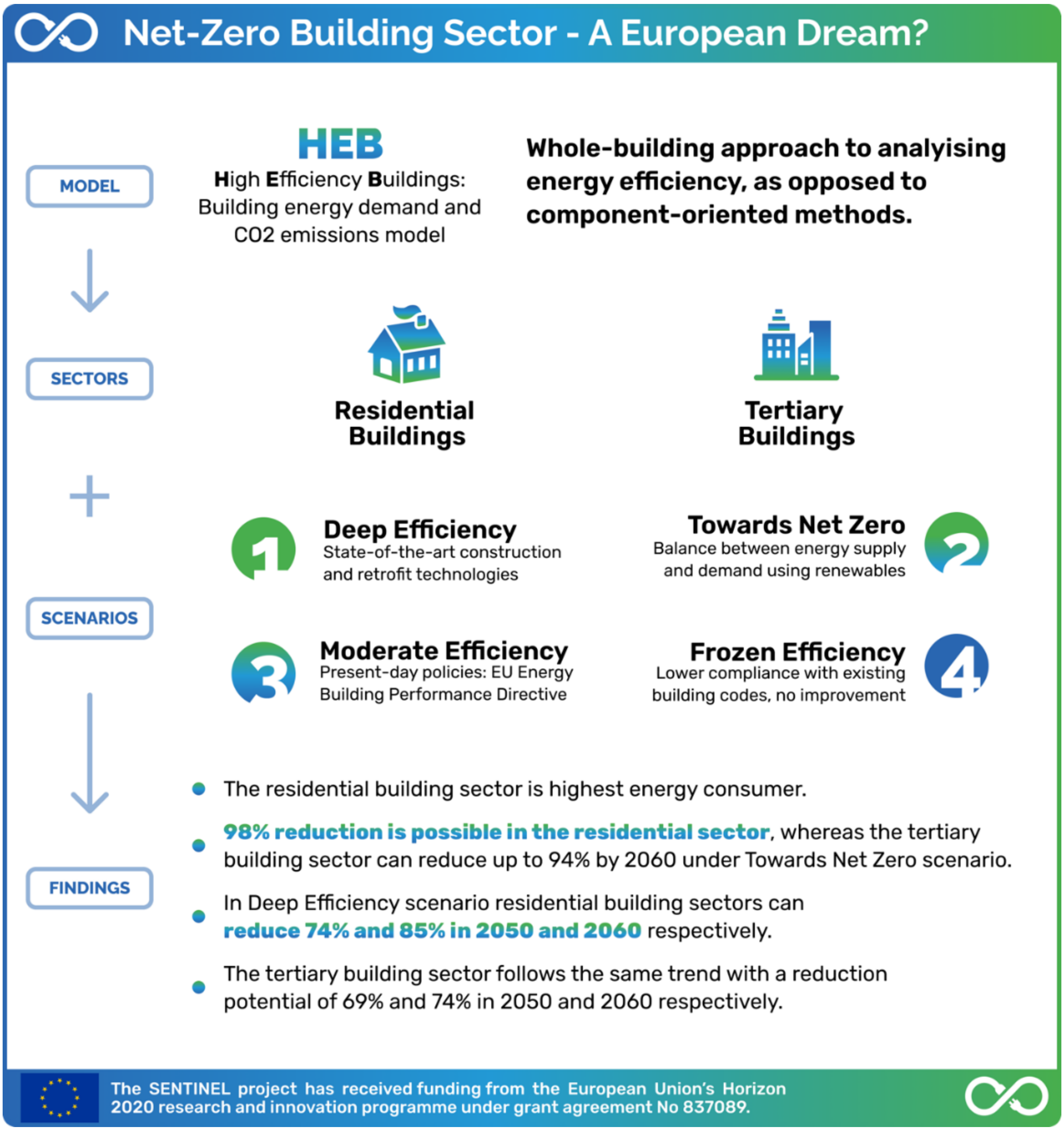


**Figure 15.** Application of the HEB model to the Continental case study: Parameters, scenarios, and results.

### *3.2.3.2. DREEM application to the Continental case study*

Modellers presented the DREEM model, an energy demand simulation model, that investigated the EU residential building stock from a country-specific and more modular way. The modular components and country-level context of the DREEM model offer a wide range of applications on Europe's energy

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transition towards 2050. DREEM was used to estimate the energy-saving potential and assess the cost effectiveness of nine different energy efficiency measures (EEMs) for eight different EU member states. **Figure 16** visualises the eight EU countries that were modelled with the DREEM model in the context of the Continental case study.


**Figure 16.** Mapping of the EU member states in which the DREEM model was used to evaluate the energy-saving potential and assess the cost effectiveness of different EEMs.

In this particular application, the DREEM model was used for two building categories based on construction period, visualised as an example for the case of Greece in **Table 10**. Category 1 refers to buildings built before 1981, as there was not thermal insulation requirements until 1981, and Category 2 refers to buildings built during the period 1981-2006. The objective of this categorisation was to see how different construction periods, and hence building characteristics, affect the energy-saving potential and cost-effectiveness of different EEMs, also considering the different geographical contexts around Europe.

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**Table 10.** Greek reference buildings in the city of Athens (Climate Zone B, Category 1 & Category 2).

| Parameter | Specifications | |
|---|---|---|
| **Year of construction** | **<1981 (Category 1)**  | **1981-2000 (Category 2)**  |
| **Type of building** | Residential (Detached) | Residential (Detached) |
| **Nº floors** | 1 | 1 |
| **Total floor area** | 102 $m^2$ | 88 $m^2$ |
| **Height** | 2.50 m | 2.50 m |
| **Total roof area** | 110 $m^2$ | 150 $m^2$ |
| **Total wall area** | 182 $m^2$ | 350 $m^2$ |
| **Total window area** | 46 $m^2$ | 42 $m^2$ |

DREEM was parameterised to consider the main building specifications in the residential sector in each one of the countries under study. Calculating the baseline energy demand scenario for each reference building, DREEM ran nine energy efficiency scenarios, exploring the impacts of EEMs on reducing building demand. The nine EEMs include traditional building performance improvements such as exterior and wall insulation, and double-glazed windows; heating system replacements such as condensing boilers and heat pumps; smart thermostats and light bulb replacement to LEDs.

After calculating the energy demand, the cost-effectiveness of the different EEMs was found via a technoeconomic analysis using the Levelized Cost of Saved Energy (LCSE) indicator. Athens was presented as an indicative example of model results in a specific country context for both Category 1 and Category 2 buildings (**Figure 17** and **Figure 18**). For Athens, regardless of the housing age category, heat pumps outperformed any EEMs in terms of annual energy savings, while also having a relatively low LCSE. For housing older than 1981, the EEM of installing attic insulation provided high annual energy savings similar to the heat pump, but it was not a considerably important EEM for newer houses. LED light bulbs and smart thermostats were the most cost-effective for both building age categories, but the annual energy savings potential was rather low comparable to the other EEMs. Finally, the least cost-effective and low energy-saving EEM was installing double-glazed windows.

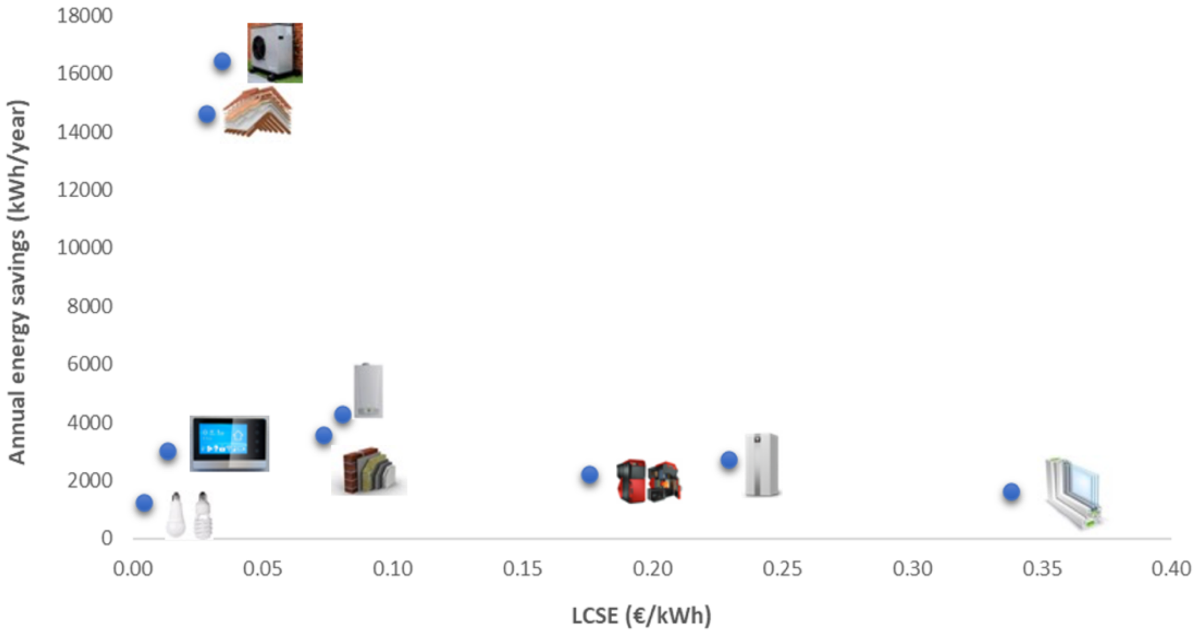


**Figure 17.** Annual energy savings and LCSE of a typical residential building constructed before 1981 in Climate Zone B (Athens).

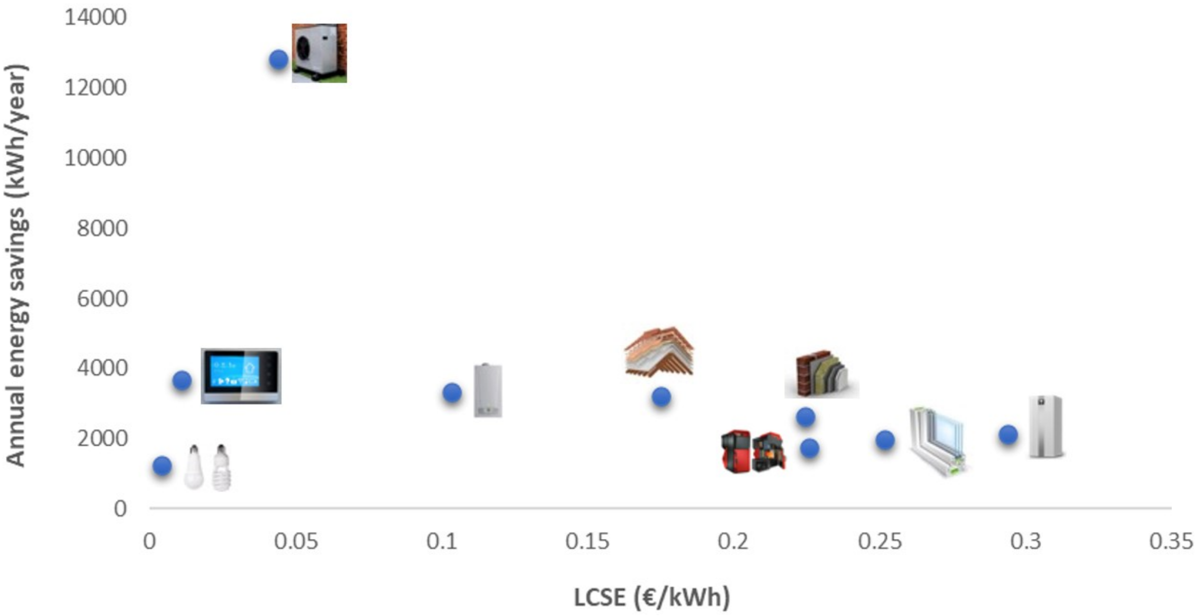


**Figure 18.** Annual energy savings and LCSE of a typical residential building constructed during 1981-2000 in Climate Zone B (Athens).

Key findings about EEMs that spanned throughout the countries modelled were presented. First, heat pumps are typically among the most cost-effective measures that have high energy-saving potential. While several other heating replacement systems were also modelled, none of these options performed well in comparison. "Low-hanging fruit" options, such as LED light bulbs and smart thermostats, were also consistently cost-effective options. Finally, windows were consistently the least cost-effective, while also not performing well in terms of energy-saving potential.

The extent of the energy-saving potential and cost-effectiveness varied throughout the countries modelled and the building age categories. This demonstrates the importance of a modular, component-based model, such as DREEM. Understanding that the most optimal EEMs in one country with a certain building stock are context-dependent can provide a complimentary and helpful tool for national renovation strategies, even informing the development of financial incentives for energy-saving actions.

An overview of the application of the HEB model to the Continental case study in terms of parameters, scenarios, and results is presented in **Figure 19**.

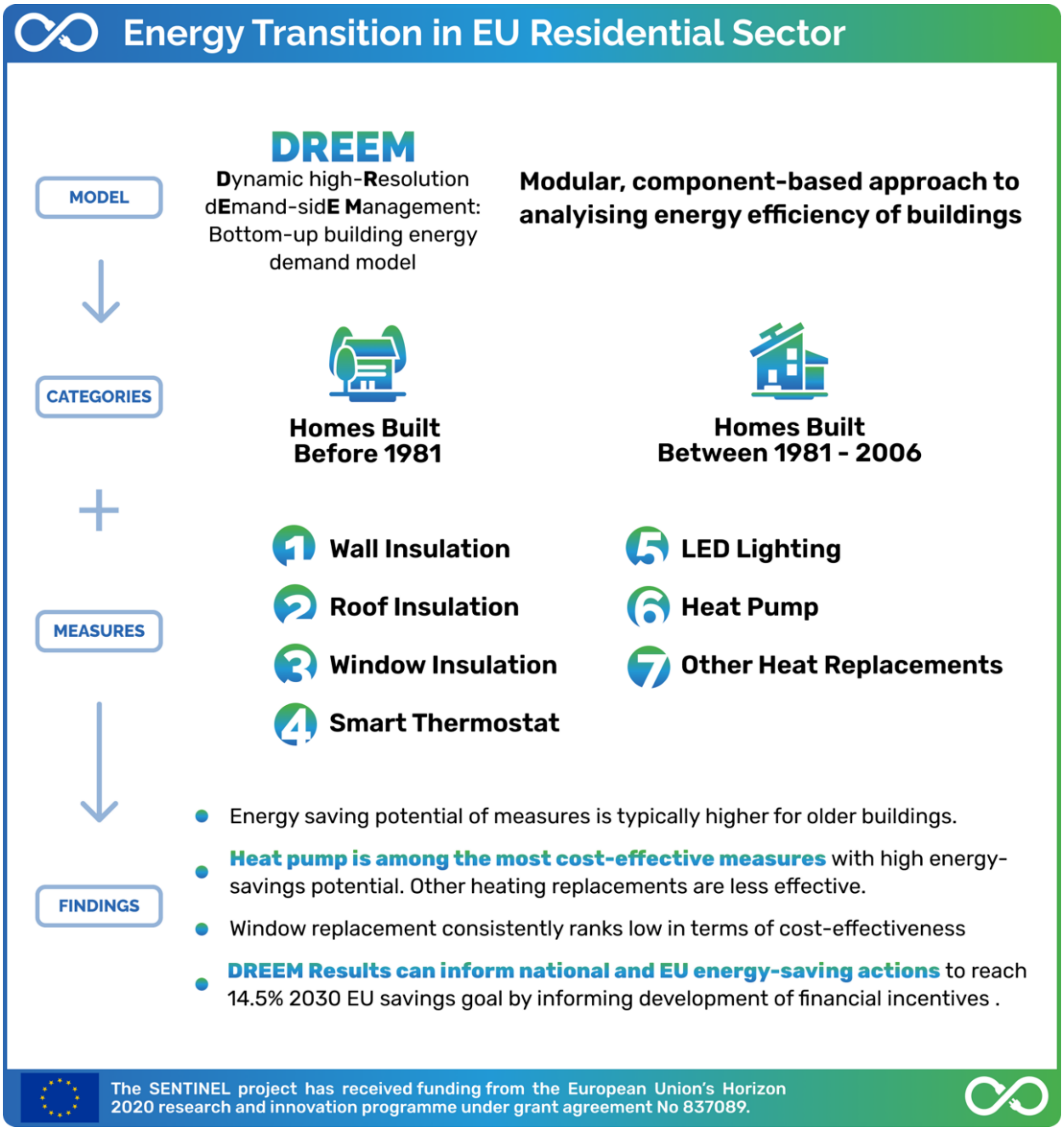


**Figure 19.** DREEM parameters, energy efficiency measures, and results.

#### *3.2.3.3. Round 1: Relevance and practicality of results*

*Looking at the state-of-the-art value chain is a nice complement to the modular component-based model*

Generally, stakeholders found the holistic, building-as-a-system and modular, component-based approaches of the SENTINEL building sector models very complimentary. Stakeholders who work closely with policymakers considered this combined approach more effective than the typical case-by-case discussion happening during the Energy Performance of Buildings Directive (EPBD) revision. As the state-of-the-art approach of HEB would allow policymakers to look at the holistic value chain of the building sector's decarbonisation, the modular approach of DREEM could help policymakers to understand which measures are most impactful in different EU member states and corresponding climate zones and building typologies. For example, this holistic look to generally understand the decarbonisation pathways generated by HEB with a granular national-level implementation could be a game-changer for the revision process of the EPBD.

*Behavioural change will be the most important indicator for building decarbonisation*

Stakeholders from research and NGO backgrounds emphasised the importance of future model developments to prioritise behavioural change in the building sector. While it has been difficult to model the behaviour of a building's inhabitants, due to uncertainty surrounding user behaviour in buildings, it would be extremely beneficial if models could improve their understanding of how user behaviours might change in the future. For example, while models can input the setpoint temperatures used for heating and cooling in buildings, it would be even more pertinent to indicate if/how the impressions of perceived temperature needs and heating demand in energy-efficient buildings change, and if these changes will be positive or negative, in the case of potential rebound effects.

Modellers agreed that the inclusion of behavioural change into their models will be challenging, but also an incredibly important indicator for decarbonisation in the EU building sector. Specifically, HEB only considers the building's technical potential and does not factor in user behaviour. If HEB took user behaviour into account, the resulting energy demand would be much higher. As the present energy crisis shows, behavioural change is necessary and must be incentivised via policy measures and included in the models. For example, HEB used to assume that the renovation rate would increase in 2027, giving the market ample time to prepare, but it is now only feasible to assume immediate impact. Therefore, HEB analyses uncertainty to see how scaling up renovation rates affects the demand scale. In contrast, DREEM approaches behavioural aspects in terms of what is needed and aligns it to the model. DREEM can create occupancy profiles and define setpoints based on typologies related to the users' thermal comfort, while it also able to take technology-related rebound effects into account via parameterisation. Modellers admitted that they are motivated to further develop their models to account for behavioural change.

*Non-technical barriers play a significant role in policy regulation*

Stakeholders further elaborated that there is a myriad of real-world barriers that exist when modelling the building sector. One expert with an academic background mentioned that while the modelling results presented by HEB and DREEM are great for mapping the technical potential of where we could get with energy efficiency improvement measures, real-world barriers are not always technical. For example, a known gap is the principal-agent problem, where the landlord-tenant dilemma hinders sustainable building renovation (Ástmarsson et al., 2013). While, in general, energy system models have shown improvement in taking these barriers into account recently, it would also be important to

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know the effect of different policy regulations on non-technical barriers. On the other hand, stakeholders understood the inability of the models capturing non-technical barriers, as they are difficult to quantify, and respective data is difficult to find. As this issue is representative of a larger phenomenon within technical energy models, SENTINEL emphasises the importance of soft linkages between technical and behavioural models, which can quantify the behaviour to project results more realistically.

*Modelling results are needed to inject more ambition into the policy framework*

Stakeholders from industry associations and NGO backgrounds found the modelling results from HEB and DREEM especially useful for informing more ambitious decarbonisation policies in the building sector. Modelling results and data are important puzzle pieces for the work of policy-oriented industry associations and NGOs. While stakeholders were disappointed with the current state of EPBD revisions, they were optimistic that modelling results could be one of the main means used to inject more ambition into the regulatory framework. As the discussions for EU policy frameworks and directives are typically discussed on a case-by-case basis, it is especially useful for the models to analyse holistic and country-specific decarbonisation pathways.

Industry association stakeholders were particularly interested in understanding more about which EEMs (as outlined in the DREEM model presentation) should be prioritised to improve energy efficiency policy discussions. For example, one expert representing industry asked explicitly if improvements to the building envelope, such as attic and wall insulation, or window replacements, were more efficient than installing heat pumps. Following up, stakeholders queried whether the Building Renovation Passport would be a useful tool in pursuit of cost efficiency of EEMs. Finally, stakeholders emphasised the importance of the DREEM model to find the preferred EEM portfolios compared to individual use, and observed that older buildings may need to prioritise which EEMs are invested in.

#### *3.2.3.4. Round 2: Technical aspects and the modelling process*

*Consider sensitivity analysis*

Stakeholders with modelling expertise found the results of the models to be consistent with their expectations, but since there has been so much variation related to costs stemming from the energy crisis, they recommended performing a sensitivity analysis. Given the dynamic environment of the political landscape, modellers agreed that it would be important to conduct sensitivity analysis.

*Consider climate adaptation trends*

Stakeholders with research background asked whether HEB or DREEM considered climate adaptation trends and factored in what will happen in the future, considering increased temperatures and increased cooling demand. As policymakers are finding this more and more important, it is imperative to consider climate adaptation aspects in the building sector modelling in the future. Modellers agreed that it is important to account for these trends into demand-side modelling. Both models apply different climate zone classifications and characteristics, while DREEM also uses weather and satellite data to calibrate the upcoming years. However, historical data is limiting, as it does not accurately capture climate extreme conditions. In addition, DREEM is also able to quantify the energy-saving potential and cost effectiveness of different adaptive materials. For HEB, limited resources precluded many additional parameters beyond climate zone classifications, but they should be explored in future work. A potential future development for HEB would be to cooperate with existing climate models to better capture cooling demand, especially during the summer period.

*Consider incorporating circularity principles, especially during the construction phase*

When considering further interlinkages, stakeholders with modelling expertise shared their experience linking building, transport, and material industry models. Linking the building and the construction material sector opens an important link to circular economy, imported energy, and emissions. A key aspect to achieving net-zero energy demand it is to understand the supply chain. Looking forward, it is important to look at a broader set of measures, starting from demand reduction, increased dematerialisation, and extending the useful life of materials. In addition to soft-linkages with material industry models, considering the scale of buildings is also important. While buildings are local and embedded in specific contexts, building materials are traded at the global level and macro regions.

An overview of the feedback that the modellers received is depicted in **Figure 20**.

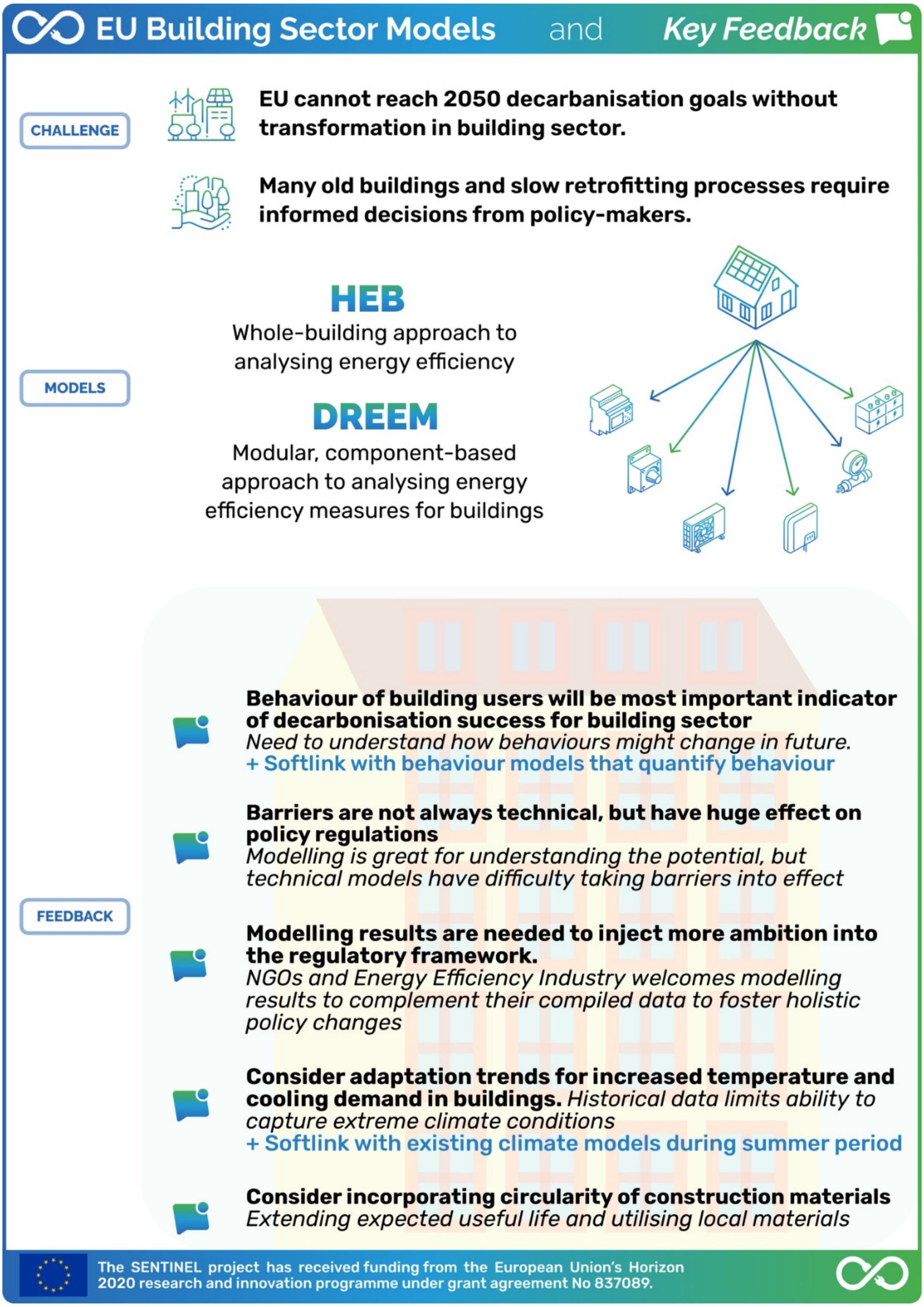


**Figure 20.** Key stakeholder feedback during the online deep-dive session #3: "Pathways to Decarbonising the EU Building Sector".

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## 3.3. Further model-specific bilateral interactions with stakeholders

In this sections, key insights on the model application to the SENTINEL case studies from further bilateral interactions that different modelling teams had with stakeholders are presented.

### 3.3.1. Application of the QTDIAN – Euro-Calliope – WEGDYN linkage to the Continental case study

The background of this model application is presented in **Section 3.2.1**. The objectives of the further bilateral interactions with key stakeholders related to this model application were presenting and discussing economic impacts of feasible net-zero development in Europe driven by socio-political storylines and highlighting interdependencies and interactions of the energy system transformation with the broader socio-economic system including indirect effects (e.g., employment, emission allowance market, etc.). Focus of the interactions was on relevancy and practicality of results, technical aspects with respect to modelling, and policy implications.

Stakeholders perceived the combination and soft-linkage of the three models innovative and useful for them, particularly the inclusion of underlying social preferences and political barriers/enablers for the system design questions and providing on top of bottom-up techno-economic assessment of climate-neutral energy system also top-down economy-wide effects. The various strengths of individual and on top combination of models has been made visible. Furthermore, focusing on various storylines that all are climate-neutral but are structurally different and hence connected to different socio-techno-economic impacts was highlighted by stakeholders as useful ("modelling to generate alternatives" instead of comparing against an arbitrary "business-as-usual"). A key challenge was that explaining and discussing the overall quantitative soft-linkage of the models would have required longer dedicated sessions for stakeholders to fully understand and discuss the work/data flow and potential issues. Modellers invited stakeholders to have a look at documentations, reports and deliverables as well as forthcoming papers and to reach out if further clarifications are needed. Overall, researchers and modellers found the social storyline approach interesting, as there is an increasing interest in the modelling community how to better capture social and political aspects.

### 3.3.2. Application of EnergyPLAN to the Continental case study

For the development of the different EnergyPLAN models for the case studies, modellers engaged with key Danish stakeholders representing the green think tank CONCITO[28], the transmission system operator Energinet[29], and the Danish Energy Agency[30] during the 8th International Conference on Smart Energy Systems (SESAAU2022) in Aalborg, Denmark. The overall objective was to listen to key inputs and interesting RQs regarding the application of the EnergyPLAN model to the Regional and Continental case studies. As a result of these interactions, modellers received updates on certain choices in the Nordic and European scenarios. This included how balancing should be prioritised, and to what extent e-methane could play a role in the Nordic and European energy systems.

[28] https://concito.dk/en

[29] https://energinet.dk/

[30] https://ens.dk/en

### 3.3.3. Application of DREEM to the National case study

TEESlab UPRC presented DREEM and its application to the National case study to experts representing the Greek MEE. The objective of the meeting was to discuss the experts' observations regarding modelling results with the aim of further enhancing the quality of the model application, while exploring the usefulness of the model for the work of the ministry.

Stakeholders wondered what added value DREEM brings compared to other commercial software. Modellers responded that the technical aspects of the model make the big difference. Specifically, DREEM is built with the Modelica language, which supports connection of components governed by mathematical equations. In this regard, it offers to the user enhanced functionalities for model applications. Modellers indicated that carefully designing a building in a 3D software is very time consuming and may even take months, while with DREEM this can be done in a couple of hours.

Stakeholders asked whether the demolition and construction of buildings has been considered in the model application. Modellers mentioned that even though the building demolition and construction rates can be captured by the model, it was challenging to have access to relevant data. Experts suggested that the Hellenic Statistical Authority gathers data regarding building construction and demolition permits.

Stakeholders were a little bit hesitant to reflect on long-term modelling results due to the uncertainty in the costs of oil, gas, and electricity as well as the EU Emissions Trading System (ETS) carbon prices. Modellers highlighted that the trendlines used for these prices are derived from the Long-term Strategy for 2050 policy document (Hellenic Ministry of Environment and Energy, 2019) and the prices used come from the Hellenic Association for Energy Economics latest report (Hellenic Association for Energy Economics, 2022). With regards to the assumptions used for these indicators, experts proposed considering average prices and not the current prices, since current prices are exacerbated because of the energy crisis. They also indicated that the electricity price is expected to further increase until 2030, having a decreasing trend afterwards. With regards to natural gas, stakeholders projected an increasing trend until 2026 which may be maintained by 2030. Concerning the EU ETS carbon price evolution, the stakeholders informed modellers that the specific amount of emission allowances that will be provided to households has not yet been decided. Stakeholders suggested to perform sensitivity analysis to account for the price uncertainty. The DREEM modelling team agreed and informed the ministry representatives that they already work on that part and will include their analysis in near future scientific publications.

Stakeholders were also interested to learn more about the assumptions behind the costs of energy saving measures. Specifically, they referred to whether the dimensioning of heat pumps considers central unit installations since they considered the heat pump cost used in the simulations somewhat high. Modellers replied that the cost used considers market prices for central unit installations and the thermal needs of the simulated buildings according to the EPBD. Experts mentioned that the ministry has conducted a gradation for heat pumps in the context of REPowerEU for the dimensioning of heat pumps based on the floor area of the building. They also commented that the envelope and windows renovation costs are expected to decrease towards 2030.

### 3.3.4. Application of the EMMA - BSAM linkage to the National case study

The initial interaction with stakeholders took place during the physical workshop "*Pathways to climate neutrality in Europe with a spotlight on Greece: Challenges, uncertainties, solutions*" in Athens. During the plenary's Q&A session, the consequences of Russia's invasion of Ukraine, and the need for Europe and Greece to reduce the dependency on gas imports from Russia were a major point of discussion. The energy crisis resulting from this conflict has affected commodity availability and led to skyrocketing natural gas prices, which in turn impacted the wholesale electricity prices. According to the stakeholders, natural gas cannot be considered as an intermediate solution for the energy transition under these geopolitical circumstances, thus it was suggested to shift the research focus towards solutions to replace natural gas.

Based on the received stakeholder feedback, modellers implemented refinements which also consider wider discussions about decoupling electricity generation from imported natural gas. Firstly, modellers considered current energy crisis implications in the form of natural gas and EU ETS carbon price uncertainty. Secondly, they incorporated in the scenario framework the uncertainty related to the availability of natural gas. Thirdly, following the recent policy considerations to prolong lignite use for power generation as a mitigation measure for the Greek power sector, the assessment of scenarios with extended exploitation of available domestic resources has been included in the modelling work.

## 3.4. SENTINEL final event

SENTINEL modellers presented their modelling results with regards to the Continental case study. Specifically:

- Euro-Calliope modellers showed that a European energy supply without any fuel electricity imports can be realised, and many options are technically possible, but preferences restrict the manoeuvring space.
- WEGDYN modellers presented the interlinkage framework (QTDIAN – Euro-Calliope – WEGDYN) for modelling the socio-economic impacts of the transition to climate neutrality.
- ENBIOS modellers showed that raw material supply risk increases significantly towards climate neutrality. This risk is predominantly linked to wind turbines (WT) and solar photovoltaic (PV) cells, both of which require large per-unit amounts of a variety of materials with relatively precarious supply chains. They also showed that the energy scenarios are labour demanding. In all cases, the observed rises are strongly linked to electricity generation from solar technologies, which tend to have significantly higher requirements in this regard.
- HEB modellers presented key messages about expected floor area growth by 2050. They indicated that total floor area will increase by 16% until 2050, while the increases in the residential and tertiary floor area will be 7% and 53%, respectively.
- DREEM modellers highlighted that the replacement of an old heating system with a heat pump is among the most cost-effective measures for all countries, while also illustrates high energy-saving potential. They also pointed out that investing in more energy efficient diesel boilers is shown to be the least cost-effective measure in most cases.

After the presentations, SENTINEL modellers collected questions from participants with regards to their work and discussed them during the panel debate.

### 3.4.1. Insights from the panel debate

The key discussion topics for the panel debate regarded **(i). the usefulness of modelling results**, **(ii). model integration and design**, **(iii). the value of energy system modelling and complementarity with other approaches**, and **(iv) further research areas**.

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#### *3.4.1.1. Usefulness of modelling results*

A key output from this debate is that modellers need to find ways for reducing model complexity in terms of lowering possible energy system configurations resulting from model application. For example, more than 400 technically feasible energy system configurations can be created via the developed interactive interface based on Euro-Calliope results [31].

Furthermore, participants posed specific questions with regards to the SENTINEL modelling results. They were interested to learn how welfare was measured in the economic impacts deriving from WEGDYN. Modellers emphasised that welfare effects only reflect the economic dimension of the energy system, and specifically the consumption capacity based on available income. Modellers argued that this definition can be considered narrow when addressing the energy transition holistically since other welfare benefits from other dimensions (e.g., environmental) can be neglected. In this regard, modellers highlighted that further efforts should be put into integrating other models, such as ENBIOS, in the QTDIAN – Euro-Calliope – WEGDYN interlinkage framework.

#### *3.4.1.2. Model integration and design*

Participants were also interested to learn how QTDIAN was developed and how it was used to develop boundary conditions for energy system modelling. Modellers explained how the storylines were developed and the integration with Euro-Calliope, highlighting that the scope of QTDIAN is not to perform model simulations but instead to serve as a data provider to other modelling tools. According to modellers, a key challenge for model integration is that models use different semantics of technologies, e.g., the definitions of technologies specified in energy system models differ to those of environmental impact models. In this regard, modellers still elaborate on the integration of Euro-Calliope and ENBIOS to better understand and solve the issue of technological change. As an example, modellers highlighted the uncertainty regarding the environmental impact of perovskite (a material specifically used for constructing solar panels) penetration to the energy system.

Participants with expertise in energy system modelling were interested in coupling the SENTINEL modelling suite with their own models, asking what the best approach for this linking would be. Modellers emphasised that hard-linking models is very challenging, as it requires a lot of adjustments in the model software and documentation and thus proposed model soft-linking as a better solution. They noted that to achieve model integration, appropriate interfaces between models should be developed. Modellers suggested using the Python programming language for easier collaboration with other models and the IAMC format for standardising energy system model outputs. This strategy has been useful for ENBIOS in soft-linking exercises with other energy system models, such as TIMES and EnergyPLAN. Modellers added that the models will be openly available in the SENTINEL website[32] after the end of the project, and that the model interfaces will also be available for those in request of the technical specifications regarding the input/output format of the data.

[31] https://explore.callio.pe/?spore-id::data=None&slider-storage=%5b0.0027201042426852,%201%5d&slider-curtailment=%5b0.0185844496790347,%201%5d&slider-biofuel=%5b0,%201%5d&slider-import=%5b0.0542322709410837,%201%5d&slider-elec-gini=%5b0.7257623221316274,%201%5d&slider-fuel-gini=%5b0.6522944837756298,%201%5d&slider-ev=%5b0.5626366117766397,%201%5d&slider-heat=%5b0.0398350997108831,%201%5d&slider-transport=%5b0.5264832433794119,%201%5d

[32] https://sentinel.energy/model-catalog/

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#### *3.4.1.3. Value of energy system modelling and complementarity with other approaches*

Moreover, participants mentioned that experience in working with community groups has given prominence to what is missing from models. Participants also asked whether the stakeholder engagement process followed in SENTINEL has changed the perspectives of modellers with regards to the importance of modelling tools, noting that models carry a lot of weight in policy discussions but provide very simplified pictures of specific energy system configurations. Modellers answered that experimenting with different tools enabled better reflecting on their weaknesses and strengths, and that they gained a lot of value from interacting with other modelling teams. Modellers also replied that stakeholders have some critical questions that do not concern modelling but social science, and thus require field research.

However, they added that SENTINEL modelling results can bring important added value to European policy because most implications come from integrated assessment models (IAMs) and even these models have certain limitations. Of course, modelling tools only show what is possible, consequently, policy discussions for taking concrete actions should be implemented afterwards. Furthermore, participants wondered what non-modelling approaches are needed or would be complementary to handle aspects that cannot be neatly captured by the models. Modellers highlighted that further qualitative insights are definitely required to complement the modelling insights from the SENTINEL models.

#### *3.4.1.4. Areas for further research*

The final discussion topic regarded areas that should be further researched to improve modelling insights. Participants wondered whether consensus exists as to how the consequences of electrification of building heat demand are best met, considering the demand seasonality and the mismatch with the availability of RES, like solar, in the northern hemisphere. Modellers argued that they are in fact conducting a follow-up study on comparing the daily and monthly profiles of renewable heat supply with heat demand to identify mismatches between supply and demand. They intend to find out whether thermal energy storage can help eliminate such mismatches and whether district heating systems can be a viable alternative, where waste heat is available, given that this alternative is less cost-effective due to its high infrastructure cost.

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# 4. Further modelling refinements

In this section we present already implemented or planned modelling work for the different SENTINEL models based on the stakeholder feedback on modelling activities reported in **Section 3** is presented below.

## 4.1. Application of the QTDIAN – Euro-Calliope – WEGDYN linkage to the Continental case study

Given the stakeholder interest in the mixed storyline approach, modellers will further work in the context of the QTDIAN-Calliope-linking on analysing what will happen if specific countries follow a different storyline. Considering that similar storyline approaches have already been developed, better emphasis should be put to differentiating this approach to others. A further issue was raised by stakeholders that energy system transformation may come with extensively increased material and critical resource demands. As such, the modellers aim to expand the **QTDIAN – Euro-Calliope – WEGDYN** linkage by linking outputs to the ENBIOS model, which would indicate relevancy and implications of such kind of questions.

Moreover, taking into account that stakeholders were interested in country-, and/or sector-specific results, modellers will consider those in the ongoing analysis. One issue mentioned by stakeholders was how to counteract reinforcing inequalities across EU member states. Alternative ways of distributing the public budget were of specific interest to stakeholders and thus different ways of how carbon pricing revenues can be distributed among the society will be explored. Modellers will also consider the challenges of how to communicate modelling results when presenting them in the future, specifically to non-technical audience (e.g., via storytelling, etc.).

## 4.2. Application of HEB to the Continental case study

Although most of the user needs relevant to the building sector that have been identified during the 1st round of the SENTINEL stakeholder activities have already been incorporated into the HEB, there are some needs including 'sector coupling', and 'digitalisation of buildings', that were perceived quite important for both the modellers and the model users. Precisely because electricity is expected to become the most used energy carrier in the road transport and the residential sector, and due to the increasing use of Electric Vehicles (EVs), the residential electricity is expected to grow in the future as EVs are charged mostly in the buildings.

Thus, when it come to the future development of the HEB model, it will be interesting to explore whether EEMs in buildings could outweigh the extra electricity consumed by EVs, and how the demand dynamics in the building sector will change by 2050. Also, user needs such as 'behavioural changes' or 'co-benefits of demand measures' seem to be a critical aspect of the energy transition, which further needs to be evaluated in the next version of HEB. By doing that, HEB will not only consider the potentiality of the consumer but also the prosumer who will play a pivotal role in achieving climate neutrality target by 2050. Finally, another aspect that the stakeholders often talked about was building lifecycle and embodied emission. Going forward, HEB needs to incorporate the lifecycle emissions of a building as well considering the potential energy footprint from material use.

During model application in SENTINEL, modellers figured that user needs related to 'behavioural changes' or 'sector coupling and digitalisation' are challenging as these needs are quite broad and when it comes to quantification, they need to be narrowed down. More precisely, HEB model requires specific input data to model any parameter, and 'lifestyle change' or 'sector-coupling' need to be defined more

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strictly in terms of a particular change in lifestyle or interlinkages to a particular sector through a particular activity. Once the definition is narrowed down, then modellers will face the issue of obtaining input particular at a national level for that specific activity. Thus, for the future upgrade of HEB, first, modellers aim to define the lifecycle and sector-coupling activities specifically related to the building sector, and then extrapolate the existing small-scale data at the national level to model energy demand at a national scale.

## 4.3. Application of EnergyPLAN to the Continental case study

The main outcomes of the stakeholder interactions have been the updated scenarios of the EnergyPLAN European model. In the initial runs, modellers used offshore wind energy as a proxy to illustrate build-out in the renewable energy capacity. This confused certain stakeholders, and thus in the updated runs, modellers have specified onshore wind potentials and build-outs, offshore wind, and PV technologies have a more diverse supply, and the amount of offshore wind is not overestimated (**Figure 21**).

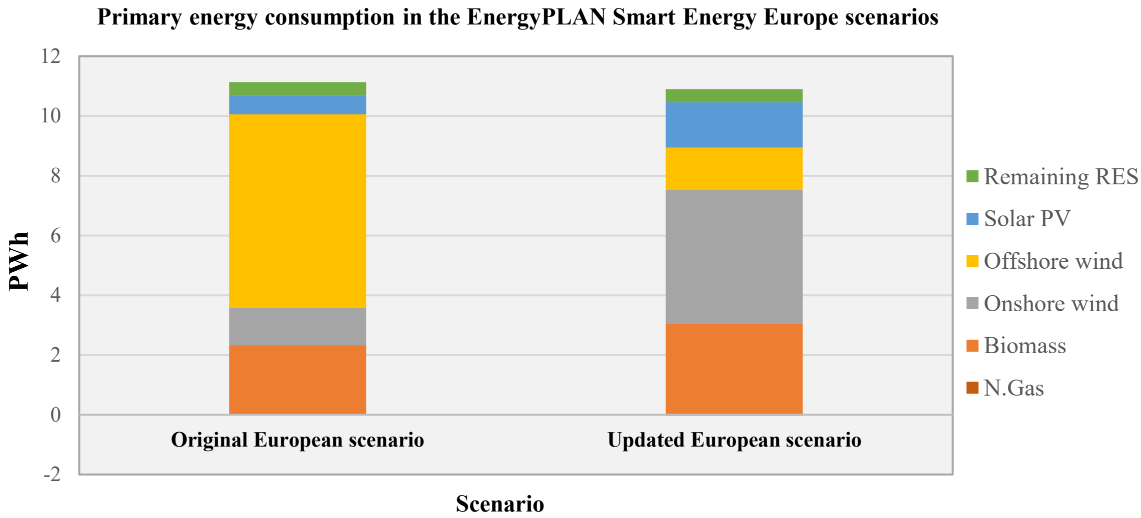


**Figure 21.** Primary energy consumption in the EnergyPLAN "Smart Energy Europe" scenarios.

Another change made was regarding the discussion of how much curtailment could be expected from renewable energy. In the first set of scenarios, modellers developed a system with very little curtailment, utilising the excess electricity in combination with electrolysers and CCS to create e-methane to be used in industry and power stations. Instead, in the updated version much higher curtailment rates were allowed, hydrogen production was downsized, e-methane was eliminated, and thus a more cost-efficient solution was identified (**Figure 22**). In this update, the use of solid biomass in power stations was also lowered and instead only relied on green gas. This modelling refinement was made possible with an updated algorithm for operating electrolysers more flexibly.

Both scenarios have been run in the latest EnergyPLAN version[33]. The key lesson from this process is that an active user environment and discussions about the use of the model allow for better modelling results and essential model updates.

[33] https://www.energyplan.eu/download/

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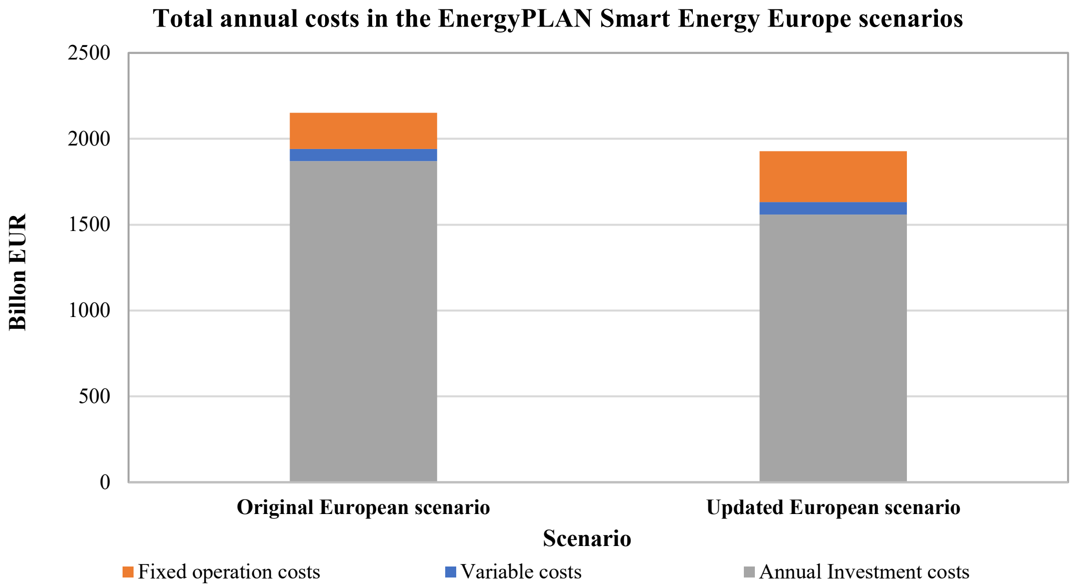


**Figure 22.** Total annual costs in the EnergyPLAN "Smart Energy Europe" scenarios.

## 4.4. Application of DREEM to the National and Continental case studies

While lifestyle changes was one of the key aspects that stakeholders considered that demand-side models should integrate, modelling experience during the SENTINEL project showed that it is difficult to address lifestyle changes as a whole since they can describe a quite broad spectrum of activities when it comes to modelling. DREEM requires specific input data to model any parameter, and lifestyle changes need to be defined more narrowly in terms of a "particular change in lifestyle," which mostly can be related to specific citizen activities and behaviours. For example, adjusting the thermostat to a lower setting can achieve considerable energy savings to those achieved through renovation measures. But, also, it is important that occupants do not sacrifice their thermal comfort and energy needs.

DREEM tackles the issue of thermal comfort by including a modelling component dedicated to finding optimal interior thermal conditions and temperature ranges that result in the occupants' thermal satisfaction based on the "DIN EN ISO 7730", "ASHRAE 55", and "EN 15251" international standards. In this context, the DREEM model will be utilised to predict the potential for energy savings through the setback analysis of thermostat setpoints in this setting, as well as behavioural factors of people. This study proposes that energy savings may be realised if consumers are prepared to lower their thermostat setpoints without sacrificing thermal comfort. This activity will also allow behavioural elements of heating and cooling to be explored.

In this context, one basic indicator that is used for the identification of energy poor households in Greece is the energy poverty ratio, based on which, "*a household is considered energy poor if it is required to spend over 10% of its income on all domestic energy use…*" Furthermore, there are clear indications that a significant amount of energy consumed in residential buildings is used for thermal comfort. In this context, the DREEM model will be used to explore the correlation between thermal comfort, income, and energy poverty in Greece. The novelty of this application will mainly lie in using statistical data, the energy poverty ratio, and DREEM outputs, to identify energy-poor households in the Greek residential sector, in accordance with their thermal comfort and income. DREEM will be used for the calculation of the energy consumption of the Greek residential sector for marginal cases of thermal comfort that are accepted for a very limited part of the day, according to different global standards, and an annual income threshold for each scenario will be calculated and compared against the expected annual income of each household.

Furthermore, by bringing together all of the fundamental features of end-use with a demand-response modelling framework that relies on the notion of time-based demand-response techniques, the DREEM model will be utilised to investigate further applications related to behavioural components. Time-based demand-response methods are the most successful demand-side management solutions because their intrinsic features are better suited to real-world uncertain and variable energy consumptions. This exercise will explore the decision-making framework and solve the dynamic pricing problem in a hierarchical electricity market that takes into account service providers' profits, but more significantly, customers' costs/benefits, capturing the energy citizen's perspective. Different probabilistic approaches will be used to simulate citizens' decision-making behaviour in order to investigate different degrees of benefits based on consumers' likelihood to comply with these demand-response signals (i.e., their intention to shift loads to the next hours without compromising thermal comfort and energy needs).

In addition, the DREEM model will be employed to tackle various aspects of prosumerism in the residential sector, assessing in parallel potential costs and benefits, and explore business models that could incentivise citizens to invest in technological infrastructure towards energy sufficiency, such as small-scale PV and battery storage systems. These are prime examples of prosumerism and can be expanded from the individual level of energy citizenship to the collective level by simulating a collection of households investing and participating in such activities.

Using representative data from the literature, the DREEM model will also address selected rebound effects due to behavioural consumption trends/patterns, such as the quantification of direct rebound effects associated with the shift from incandescent or halogen bulbs to more energy efficient compact fluorescent lamps or light emitting diodes. These shifts in types of lighting technologies are the external result of internal behavioural aspects that characterise energy citizens.

Finally, regarding the application of DREEM in the context of the SENTINEL National and Continental case studies, modelling results as presented in (Michas et al., 2022), will be further refined to consider proper adjustments on prices and other variables/parameters, based on the recent geopolitical developments around Europe and the energy crisis.

Modelling developments regarding DREEM are already/will be further supported in the context of the EC-funded H2020 ENCLUDE[34] and Horizon Europe IAM COMPACT[35] projects.

### 4.5. Application of ATOM to the National and Continental case studies

Including socio-economic and behavioural aspects into energy system models was at the heart of the feedback that stakeholders shared with modelling teams throughout the duration of all the SENTINEL engagement activities. Many technological advancements and government programmes fail because they do not take into account what is important to the public, i.e., the motivating factors that shape their adoption preferences. Stakeholders stated that people and their social connections have a significant impact on the diffusion of technological/social innovations, as well as the general dynamics of

[34] https://encludeproject.eu/

[35] Website under development

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technological/social transformation. They also highlighted that transitions are difficult to scientifically comprehend due to the effect of a wide variety of contextual factors on policy processes, society, and agency, and that taking into account the variety of interests, motives, and other elements that influence people's decisions can assist lessen the ambiguity that can lead to policy failure.

Further developing and upgrading ATOM and adapting it to knowledge gaps/user needs/research priorities/social trends/patterns remains critical in this regard, as modelling agents' decisions and interactions represents a more "real-world" process that addresses the limitations and constraints of centralised, optimization models, by introducing a layer of control and decision-making, thereby allowing greater understanding of macrophenomena (Süsser, et al., 2022). ATOM at its current form, i.e., as was used during the SENTINEL project, is able to simulate the adoption of small-scale PV systems and to explore the various behavioural aspects and internal thought processes and preferences of citizens.

In this context, ATOM's initial modelling framework (Stavrakas et al., 2019) has been enhanced to investigate the impact of more agent-related characteristics on the further diffusion of small-scale PV systems in the National case study through its linkage with the QTDIAN tool and its use in the context of three different socio-political storylines, i.e., qualitative and quantitative descriptions of social and political drivers and constrains of the energy transition. This allowed a better representation of social and political aspects of PV adoption in Greece. In this context, ATOM will be further linked to the QTDIAN tool to explore scenarios of PV adoption in different geographical and socioeconomic contexts around the EU. Different ideal/typical and distinct storylines that are based on transition theory and empirical observations of actual social/political drivers and barriers in the EU's energy transition will be explored, and quantitative, empirical data for a range of key social/political parameters will be collected. Particular focus will be given to the selection of member states of different climatic regions, e.g., northern Europe, central Europe, southern Europe, etc., to reflect on how weather and climatic conditions specifically affect PV adoption.

In addition, although the current version of ATOM was used to simulate adoption scenarios of small-scale PV systems, given the availability of historical data/observations, the model will be expanded so that it simulates adoption scenarios for other technologies that increase demand flexibility, such as, for example, electricity storage, smart-grid devices, electric vehicles, etc. In this context, the current set of the agent-related parameters used by the model is technology specific, meaning that it has been selected, based on the most updated insights of the scientific literature, so that it matches adoption trends of small-scale PV systems. However, this module of ATOM will be expanded so that it brings together all relevant adoption parameters for a different set of technological options of interest, also considering the role of context. For example, representatives from the Greek MEE highlighted that the attitude of Greek consumers toward installing small-scale PV systems also differs according to their income and education levels and appears to be connected with their consumption patterns and demographic factors. To perform socially well-informed modelling activities, an extensive database will be developed so that the model is able to simulate technology adoption, taking into account the specifications of the technology and the context under study

Furthermore, in accordance with the United Nations' goal to ensure that "no one is left behind" involving "hard to reach" citizens and understanding how their objectives and views might be translated into the needs, or opportunities, of a low-carbon transition, is essential. As a result, ATOM will be further enhanced to reflect on the decision-making process of distinct consumer/citizen profiles in order to effectively develop and conduct socio-technically informed modelling exercises. User profiles that go beyond capturing the mainstream dominant groups, focusing on communities and groups that face social/economic alienation, including women and other genders, and/or demographics that are typically excluded due to racialisation, face other forms of discrimination, or face challenges, such as forced migration as a result of conflicts, will receive special attention, also considering recent geopolitical developments around Europe and the energy crisis.

The factors/parameters that are anticipated to control human behavior will be utilised as inputs into the model to investigate the effects of human-centred interventions in various geographic and socioeconomic contexts and levels. This exercise will show how the model can evolve from a technology adoption stand-alone model to a model that simulates the diffusion of social innovations, scaling them up from individuals to large social structures like energy communities, ecovillages, etc. In this approach, the ATOM modeling framework might be used to investigate how envisioned social improvements and technical infrastructure are embraced by, and distributed throughout, households/communities with various socioeconomic, behavioural, and lifestyle profiles.

Finally, events of the past three years have proven that policy measures must adapt to uncertain and continuously changing conditions. This was also at the heart of the stakeholder feedback received during this last round of engagement activities. Thus, a policy design process that utilises an agent-based modelling tool like ATOM should be structured around the concept of adaptability. This means that, as new data on the actual decisions of the relevant actors is accumulated, the initial policy design should adapt in the same way as it adapts to changes in its environment. As a result, ATOM will be further soft-linked with the **A**daptive pol**I**cymaking **M**odelling (AIM) toolbox (Michas, et al., 2020), which focuses on the development of dynamic adaptive policy pathways; thus, support policy measures for further PV adoption towards the achievement of national targets in the EU can adapt to uncertainties-generated by their assumptions and their environment- that may hinder their performance. This exercise will also build on the strengths of a new round of stakeholder engagement activities, which will provide a more comprehensive and detailed assessment of policy interventions, towards a more participatory policymaking approach that collaboratively explores policy needs and underlying model capability requirements, to improve policy decision usability.

Modelling developments regarding ATOM are already/will be further supported in the context of the EC-funded H2020 ENCLUDE and Horizon Europe IAM COMPACT projects.

### 4.6. Application of the EMMA – BSAM linkage to the National case study

Based on stakeholder feedback, modellers simulated additional scenarios considering the uncertainty related to natural gas and EU ETS carbon price, as well as natural gas availability. Therefore, the capacity expansion simulation that was performed with EMMA incorporated **(i).** a variation with higher natural gas and EU ETS carbon price where investments in other thermal dispatchable generation sources besides gas-fired plants are allowed (*Energy crisis with CCS*), and **(ii).** a variation where the only thermal dispatchable generation sources are gas-fired plants (*Energy crisis without CCS*). All respective cases of EMMA simulations achieve the 2030 power sector emission target set by the National Energy and Climate Plan (NECP), equal to 7 $MtCO_2$, cover the same annual electricity demand (**Table 11**), and are listed below:

- *EMMA (No energy crisis)*: The energy system evolves given the conditions before the energy crisis and the current governmental coal phase-out plan. Projections for the natural gas and EU

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ETS carbon prices were made using a trendline fitted to the price developments observed by the end of 2021 and the projections mentioned in the National Resource Adequacy Assessment (NRAA) published by the Greek Independent Power Transmission Operator (IPTO) in summer 2021 (Greek IPTO, 2021) (**Table 12**).

- *EMMA (Energy crisis with CCS)*: Natural gas and EU ETS carbon price projections were made similarly as above, using the price developments observed by June 2022 (**Table 12**) as an initial estimation. Investments in coal-fired plants are allowed if they are equipped with CCS to meet emission targets.
- *EMMA (Energy crisis without CCS)*: Natural gas and EU ETS carbon price projections remain similar to the *EMMA (Energy crisis with CCS)* case. No CCS is allowed, rendering gas-fired plants the only modelled thermal generation technology.

**Table 11.** Evolution of the annual electricity demand in Greece.

| Year | Case | Annual electricity demand (TWh) |
|---|---|---|
| 2030 | **"IPTO-Baseline"**[36] | 57.3 |

**Table 12.** Natural gas and emission allowance price projections in 2030.

| Case | "No energy crisis" | "Energy crisis" |
|---|---|---|
| Natural gas price projection (€/MWh) | 22.43 | 102.71 |
| EU ETS Cost Projection (€/tonne) | 64.67 | 145.20 |

The capacity stack resulting from the EMMA calculations for the aforementioned cases were used by BSAM to perform unit commitment and economic dispatch simulations. **Figure 23** depicts the refined scenario framework for the application of BSAM to the Greek power sector that incorporates the simulation results of EMMA. It is worth noting that the BSAM energy crisis scenarios build on the EMMA cases with and without CCS, however they have been amended to account for the lignite extension scenario discussed in the Greek policy agenda. This follows the notion for a potential prolongation of available domestic resource use beyond 2028, which was the original lignite phase-out horizon, to secure electricity supply. As such, lignite-fired plants were considered in BSAM simulations instead of coal-fired CCS plants, as derived by EMMA, given that lignite is the only coal source available in Greece, and that CCS deployment is not planned for lignite power plants.

[36] The "IPTO-Baseline" and "IPTO-Green Deal" cases follow until 2035 the capacity specifications of the NRAA report published by the Greek IPTO, which sets more ambitious requirements than the variable renewable energy source targets mentioned in the NECP.

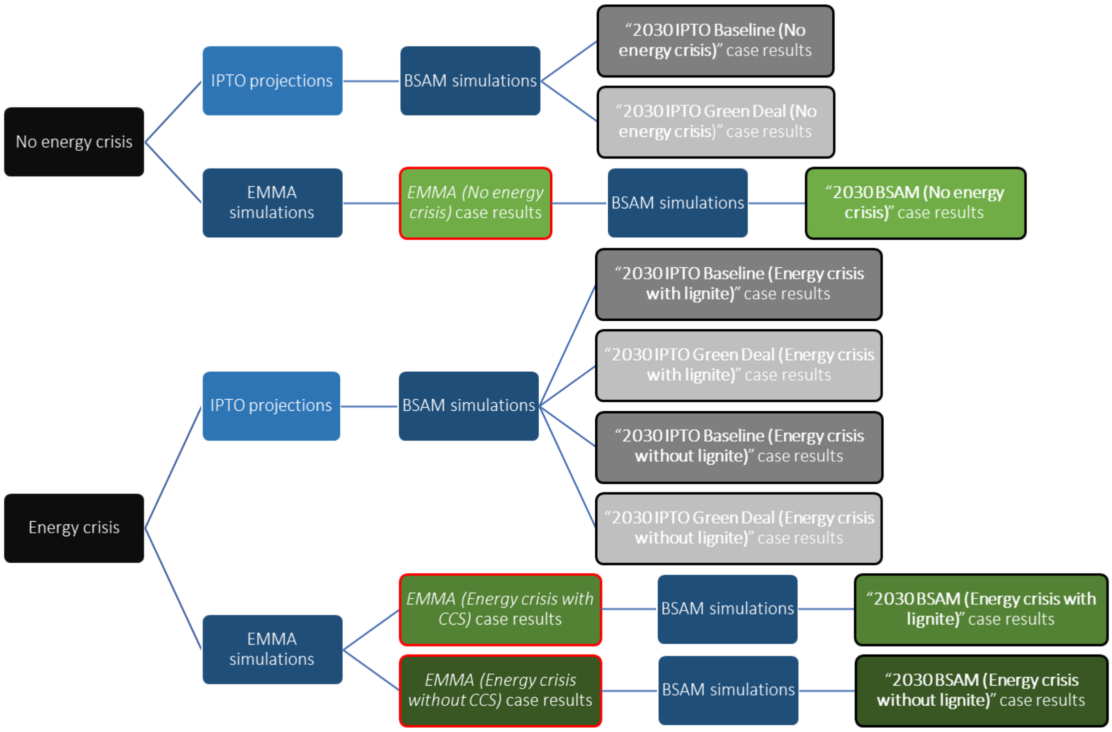


**Figure 23.** Updated scenario framework for the EMMA-BSAM model application to the Greek case study. Cases simulated by EMMA are the cells with red outline. Cases simulated by BSAM are the cells with black outline.

### 4.6.1. Modelling results

After specifying the scenario framework for the model application, the modellers utilised the integrated framework consisting of EMMA and BSAM, and outputs from Euro-Calliope (Bachner, et al., 2021; Thellufsen, et al., 2021), to explore the refined technology deployment scenarios, and answer the following RQs identified in Deliverable 7.1 (Stavrakas, et al., 2021):

- **RQ5**: How much Variable RES (VRES), i.e., WT and PV, and storage capacity is needed in 2030 to meet demand requirements?
- **RQ3** & **RQ10**: What would be the expected contribution of fossil-fuel and RES GUs in the electricity mix in 2030? What level of power independency could be achieved?
- **RQ61**: How are the total $CO_2$ emissions of the electricity system expected to evolve?
- **RQ8**: How would the System Marginal Price (SMP) be affected?

### 4.6.2. EMMA simulation results

**Table 13** presents the results of the EMMA cases for the evolution of VRES and storage capacity until 2030 along with the projections of the IPTO. The *EMMA (No energy crisis)* case enables newbuild capacity of natural gas, VRES and storage. The *EMMA (Energy crisis with CCS)* case allows investment in fossil fuels with CCS, VRES and storage. The *EMMA (Energy crisis without CCS)* case does not allow for investments in CCS thus rendering an exceptionally high need for VRES and storage capacity. The full capacity stack as calculated by EMMA for the three 2030 cases is summarised in **Figure 24**.

**Table 13.** Different cases for the evolution of VRES generating capacity.

| Year | Case | PV (MW) | WT (MW) | Storage capacity (MW) |
|---|---|---|---|---|
| 2021 | - | 3,055 | 3,755 | - |

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| | | | | |
|---|---|---|---|---|
| 2030 | IPTO-Baseline | 7,342 | 6,619 | 1,050 |
| | IPTO-Green Deal | 9,763 | 7,149 | 1,050 |
| | EMMA (No energy crisis) | 6,842 | 13,836 | 1,880 |
| | EMMA (Energy crisis with CCS) | 8,951 | 13,297 | 3,380 |
| | EMMA (Energy crisis without CCS) | 20,627 | 17,850 | 8,717 |

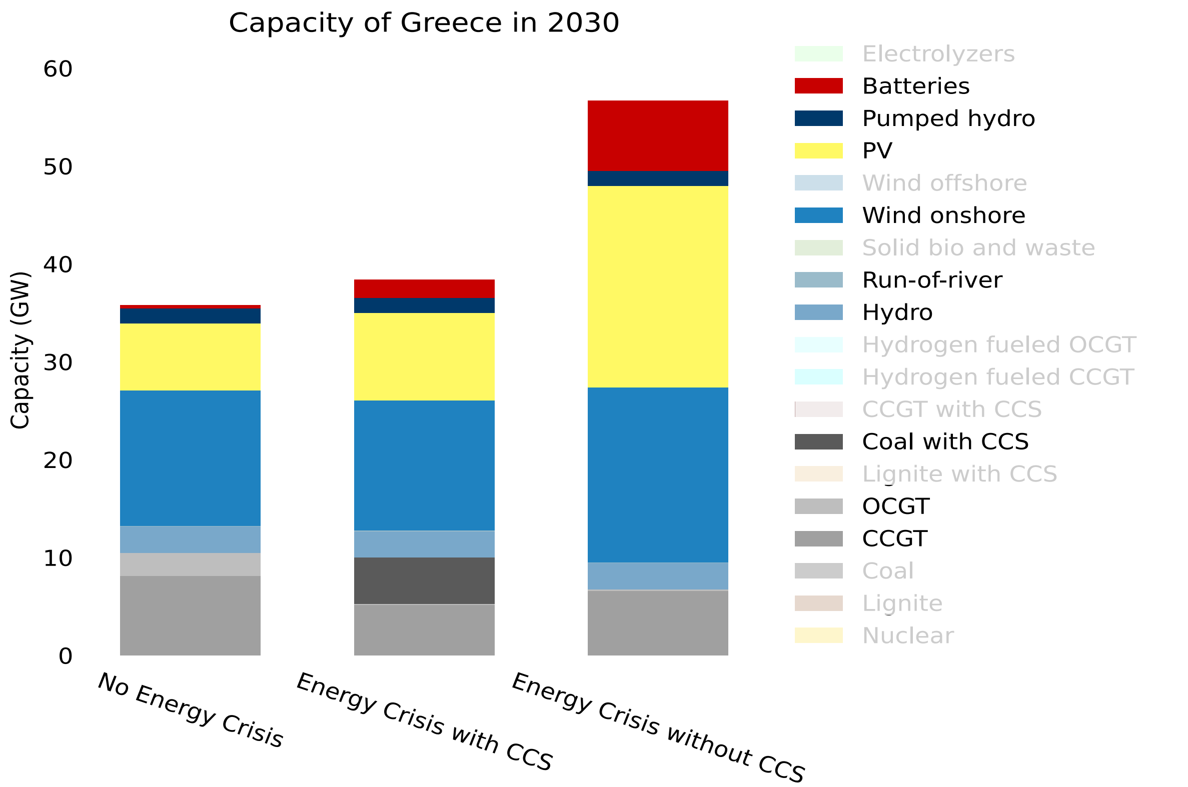


**Figure 24.** Capacity stack calculated by the capacity expansion model EMMA. Greyed out technologies do not exist in the capacity stack.

### 4.6.3. BSAM simulation results

**Table 14** shows how the different cases presented above were combined in BSAM simulations.

**Table 14.** BSAM simulation cases.

| Year | BSAM Simulation Case | Gas and Carbon Price Case | Demand Case | VRES Case | Storage Case |
|---|---|---|---|---|---|
| 2030 | "2030 IPTO-Baseline (No energy crisis)" | "No energy crisis" | "IPTO-Baseline" | "IPTO-Baseline" | "IPTO-Baseline" |
| | "2030 IPTO-Green Deal (No energy crisis)" | "No energy crisis" | "IPTO-Baseline" | "IPTO-Green Deal" | "IPTO-Baseline" |
| | "2030 BSAM (No energy crisis)" | "No energy crisis" | "IPTO-Baseline" | EMMA (No energy crisis) | EMMA (No energy crisis) |
| | "2030 IPTO-Baseline (Energy crisis with lignite)" | "Energy crisis" | "IPTO-Baseline" | "IPTO-Baseline" | "IPTO-Baseline" |
| | "2030 IPTO-Green Deal (Energy crisis with lignite)" | "Energy crisis" | "IPTO-Baseline" | "IPTO-Green Deal" | "IPTO-Baseline" |
| | "2030 BSAM (Energy crisis with lignite)" | "Energy crisis" | "IPTO-Baseline" | EMMA (Energy crisis with CCS) | EMMA (Energy crisis with CCS) |
| | "2030 IPTO-Baseline (Energy crisis without lignite)" | "Energy crisis" | "IPTO-Baseline" | "IPTO-Baseline" | "IPTO-Baseline" |

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| | | | | |
|---|---|---|---|---|
| "2030 IPTO-Green Deal (Energy crisis without lignite)" | "Energy crisis" | "IPTO-Baseline" | "IPTO-Green Deal" | "IPTO-Baseline" |
| "2030 BSAM (Energy crisis without lignite)" | "Energy crisis" | "IPTO-Baseline" | EMMA (Energy crisis without CCS) | EMMA (Energy crisis without CCS) |

In the Energy crisis without lignite scenario, higher commodity prices lead to a reduction in the use of natural gas. Yet, this reduction does not allow for an adequate decoupling of power generation from imported gas in the IPTO cases, due to the lack of alternative generation technologies after the lignite phase-out. Such a decoupling could only be accomplished with the further integration of RES. This is exacerbated in the "**2030 BSAM (Energy crisis without lignite)**" case where VRES dominate the electricity mix, as shown in **Figure 25**, limiting the contribution of natural gas-generated electricity. Nevertheless, such a case would require expanding the existing VRES capacity by approximately 5.5 times until 2030.

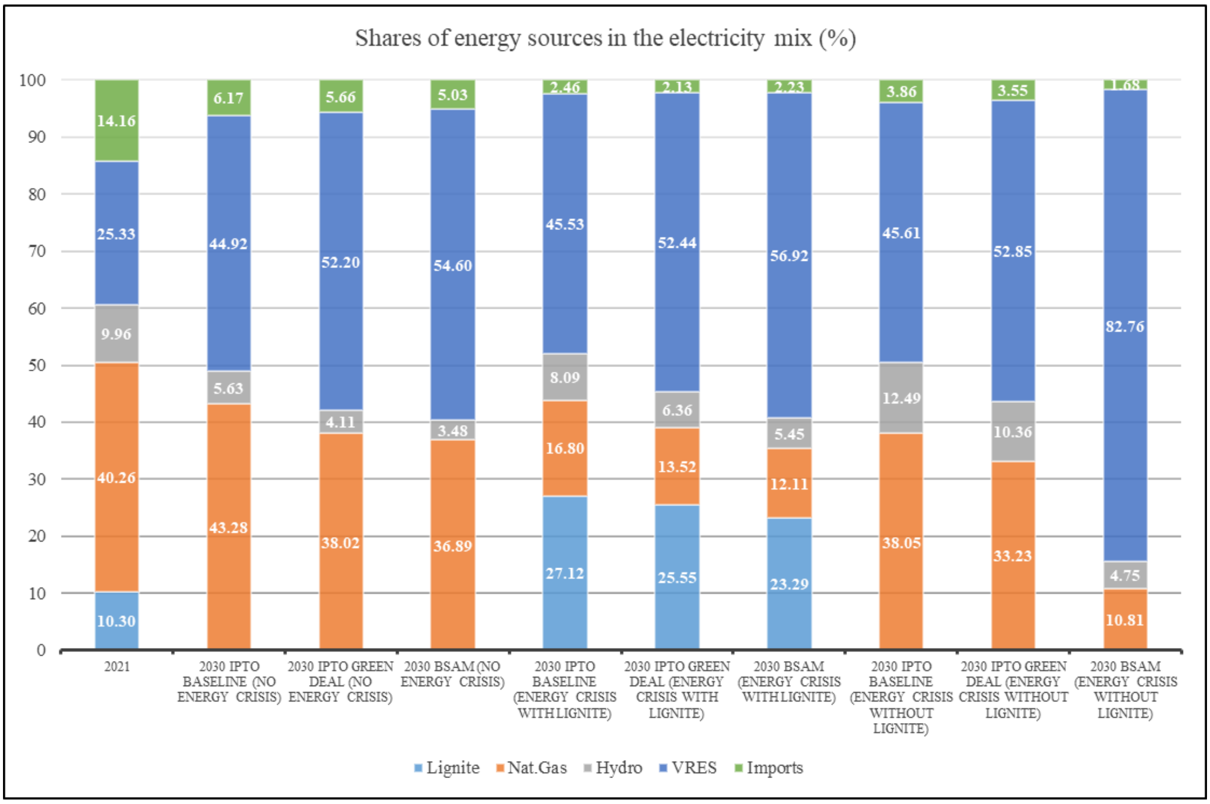


**Figure 25.** Electricity mix shares (%) of 2021 and BSAM simulations for 2030.

On the other hand, in the Energy crisis with lignite scenario, the electricity mix changes drastically and the dependence of Greece to imported gas is significantly reduced. Specifically, lignite-fired electricity displaces almost two thirds of the natural gas-fired electricity across all examined cases. The displacement is owing to the assumption for a persisting increase in natural gas prices, which makes electricity generation from natural gas less economically viable. Yet, as shown in **Figure 26**, such a strategy to decouple electricity generation from natural gas would result in a major setback with respect to carbon emissions, which could even exceed the 2019 levels, when the lignite phase-out decision was taken. This highlights once more the significance of accelerated RES deployment in order to limit both the short-term use of lignite, as well as the long-term use of natural gas for electricity generation. This is showcased both in the No energy crisis and Energy crisis without lignite scenarios, where significant

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$CO_2$ emissions reductions by 2030 are simulated with increasing RES capacity. Specifically, the dark grey cases in **Figure 26** are the most polluting due to less RES deployed, while the green cases result in less $CO_2$ emissions due to wider deployment of RES capacity. It should also be noted that the energy crisis is not the mere responsible for underachievement of carbon reduction targets by 2030 in Greece. Further deployment of RES would also be required even without the effects of an energy crisis, as shown in the respective scenarios of **Figure 26**.

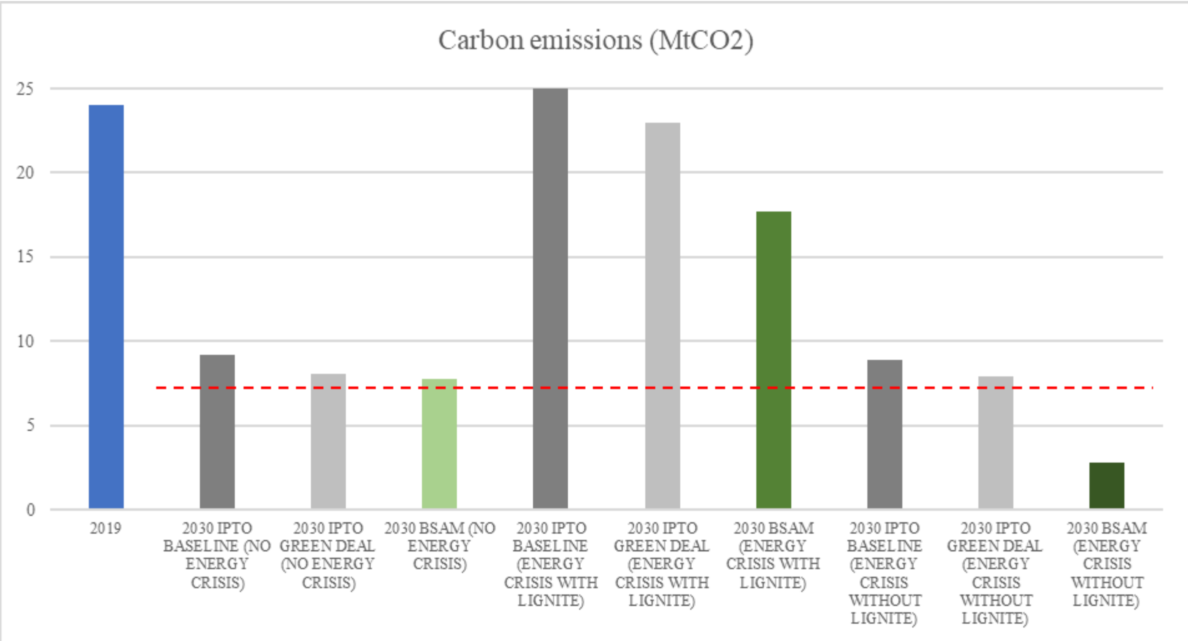


**Figure 26.** Total carbon emissions ($MtCO_2$) of 2019 and BSAM simulations for 2030. The red dashed line indicates the 2030 power sector emission target (7 $MtCO_2$).

Finally, in terms of power prices, the increase of VRES power generation also leads to lower SMP values, as indicated by the average SMP of "**2030 BSAM (No energy crisis)**", "**2030 BSAM (Energy crisis with lignite)**" and "**2030 BSAM (Energy crisis without lignite)**" cases (**Figure 27**). This is due to the displacement of dispatchable generation by priority-dispatched renewable electricity, which limits the residual demand and increases the competitiveness among dispatchable generators who must reduce their bids to remain cost competitive and enter the market. Nevertheless, even though increased VRES electricity generation reduces the SMP, its maximum reduction is relatively low, namely 23.6% between the "**2030 IPTO Baseline (Energy crisis without lignite)**" and "**2030 BSAM (Energy crisis without lignite)**" cases, in comparison to the increase caused by the soaring natural gas prices in the energy crisis scenarios. Furthermore, as implied by the energy crisis with lignite scenario, the continuation of lignite use for power generation is not expected to have a significant impact on the average SMP. Lignite-based power production is significantly affected by the rising EU ETS carbon prices; however, the main reason for the negligible difference in the SMP between the Energy crisis with lignite and Energy crisis without lignite scenarios is the use of natural gas. Under the 'Pay-as-Clear' market model currently in place, the SMP is set by the last clearing bid that satisfies residual demand, and thus natural gas-fired power generators will continue setting the prices. The above observations highlight that just sharply increasing VRES capacity is not enough to offset the significant increase in the electricity price (even when supported by cheaper, highly emitting technologies), unless

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the wholesale electricity price is decoupled from natural gas-generated electricity, and fossil-fuelled electricity in general.

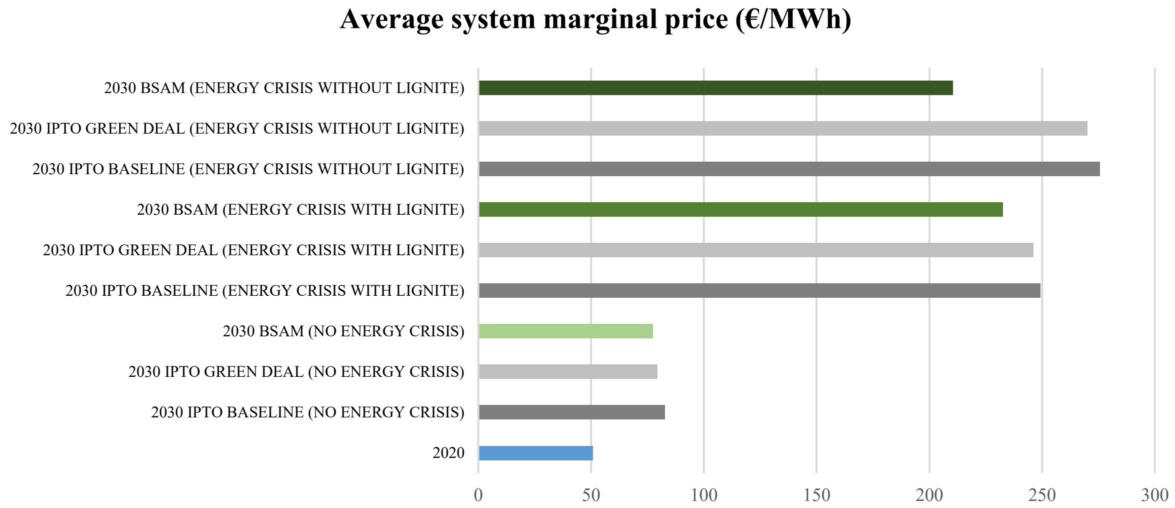


**Figure 27.** Average system marginal price (€/MWh) of 2020 and BSAM simulations for 2030.

### 4.6.4. Lessons learnt and key insights

Given the prevailing energy crisis situation and according to the REPowerEU plan ambitions, energy modellers specified and improved the scenario framework used to explore various technology pathways for the electricity system whilst considering the uncertainty faced by the energy system. The iterative process followed, refined the results generated by the integrated modelling framework and the related insights about the potential evolution of the Greek power sector until 2030.

Specifically, results showed that VRES and storage capacity expansions are a major instrument not only to meet emission targets but also to reduce Greece's dependence on natural gas and electricity imports from other countries. Considering the effects of the gas crisis and the slow VRES capacity growth, lignite could be considered as a last-resort dispatchable electricity generation source. However, extending the coal-phase out until 2030 to provide baseload generation cannot be reconciled with the $CO_2$ emission reduction efforts.

Moreover, the projected EU ETS carbon and natural gas prices are shown to translate in higher wholesale market prices, which can lead to potentially unbearable electricity prices for consumers. Higher VRES penetration does not only mitigate this increase via the merit-order effect, but also because (ceteris paribus) it increases the competition to supply the reduced residual demand. However, an ambitious VRES capacity expansion might not be sufficient to mitigate the electricity price increase. Other policies capable of mitigating the effects of short-term fossil fuel price shocks on the electricity market appear to be a sensible next step for further research.

# 5. Conclusions

As stakeholder involvement was at the heart of the SENTINEL project, it was crucial to develop a user-oriented evaluation of the SENTINEL modelling suite. To assess the strengths, weaknesses, and limitations of the SENTINEL modelling process and results, we employed diverse methods concerning specific aspects of modelling and applied different formats to collect stakeholder feedback. In this deliverable, we presented the outcomes of a four-tier participatory multi-method approach consisting of stakeholder consultation in 10 events (workshops, conferences, focus groups, bilateral meetings, etc.). During these events, we had the opportunity to discuss 12 model applications to the case studies (9 for the Continental and 3 for the National case study) to receive robust feedback on the feasibility and legitimacy of the SENTINEL modelling results as well as to collect valuable insights and recommendations on ways to further improve our modelling work.

The flexibility to organise generalised workshops and events, such as the physical workshop in Athens and the SENTINEL final event, combined with the thematic online deep-dives sessions and the further model-specific bilateral interactions with stakeholders, ensured that we could reach our objectives. A multitude of stakeholders representing different institutions participated in the events. In this process, we also engaged with stakeholders participating in synergy projects of SENTINEL that have developed modelling platforms and state of-the-art modelling suites for covering the multiple dimensions of a clean energy transition (i.e., PARIS REINFORCE and openENTRANCE). Discussions with synergy project partners enabled the SENTINEL modelling teams to collect useful feedback and good practices with regards to the further refinement of the SENTINEL modelling suite and the development of the SENTINEL modelling platform.

Overall, stakeholders found the SENTINEL model integration and application to the case studies an innovative approach and were interested in the presented modelling insights, as they revealed useful information for their work. The physical workshop in Athens allowed the SENTINEL researchers to present the key results of the SENTINEL modelling work for the Continental and the National case studies and provided the opportunity to receive feedback on the modelling approaches and results as well as the SENTINEL modelling platform. During the workshop, we found out that stakeholders paid particular attention to how different models were coupled together and how modelling results compare to those of other models when similar scenario specifications and assumptions are used. Moreover, they were keen on learning more about what modellers considered as the most significant challenges that they faced during the model application.

Stakeholders were also able to examine multifaceted European- and Greek-specific challenges and issues of the transition to climate neutrality, for which energy system models can provide important insights. A key outcome deriving from the consultation is that stakeholders are particularly interested in further research and modelling studies that could shed light to the strategic EU decisions regarding the faster reduction of the dependence on fossil fuels, and especially Russian oil and gas. With regards to the use of energy system models to support policymaking in Greece, stakeholders highlighted that more light should be shed on the costs of the net-zero transition, policy implementation realities, and citizen-led energy transition pathways. The perspectives from this workshop allowed to gain vital stakeholder feedback to effectively communicate and disseminate modelling results and to further advance the SENTINEL modelling tools as well as to provide insights for developing a user-friendly online platform.

The iterative planning process of the thematic online deep-dive sessions, including the coordination and facilitation, were essential for cohesive interaction. By understanding what type of feedback energy modellers wanted to receive, we were able to identify stakeholders who could provide diverse feedback. While it was a challenging exercise to communicate highly technical modelling design, data, and results to non-technical audiences, it was important to bring different stakeholders into the energy modelling sphere by improving accessibility and user friendliness. With this challenge, the deep-dive session format allowed stakeholders to openly express their opinions and build a bridge between the realities of the modellers and the practitioners. In the course of the three thematic online deep-dive sessions, stakeholders provided useful insights regarding the feasibility, relevance, and usefulness of the SENTINEL modelling results.

During the "Socio-economic Impacts of a Just European Energy Transition" online deep-dive session, stakeholders discussed the complementarity of social storylines to energy scenarios and, given that the PPO storyline implies the highest long-term European-wide welfare, they highlighted the need for policy and civil society to leverage modelling results. They also concentrated on the technology cost assumptions considered in the model application. During the "Environmental Impacts of Energy Technologies: Introducing the ENBIOS Model" online deep-dive session, stakeholders talked about key environmental criteria that should be included in the ENBIOS tool, indicated the need for having a country-level approach to examine trade-offs with other energy system impacts, and showed interest for future collaboration and comparison of work. Finally, during the "Pathways to Decarbonising the EU Building Sector" online deep-dive session, stakeholders emphasised the importance of behavioural change for achieving decarbonisation, referred to non-technical barriers that cannot always be modelled but play a significant role in policy regulation, and placed stress upon the significance of modelling results for injecting more ambition into the policy framework. They also suggested conducting sensitivity analysis of key input assumptions to better capture the current price uncertainty and climate adaptation trends.

The bilateral meetings also provided useful feedback to modellers in terms of identifying further model refinements. A key challenge during this step was that that in some cases properly explaining the model workflow would have required longer and better designed dedicated sessions for stakeholders to fully comprehend it, which validates our decision to also include the thematic deep-dive sessions in our overall working approach. This challenge can be translated into a key lesson learnt for the modelling community, i.e., results must be comprehensible beyond an academic lens, so that stakeholders with no background in energy system modelling can provide feedback on the relevance of modelling and their needs.

Furthermore, during the SENTINEL final event, the panel debate provided insights for critical modelling topics, such as the need for reducing model complexity, the added value that energy system modelling has on policy design, and its complementarity with other approaches (e.g., IAMs, qualitative methods like multi-criteria analysis). To be noted that all implemented stakeholder engagement activities, enhanced knowledge and lessons learnt mutually for the stakeholders and the SENTINEL energy modellers. The energy modellers were able to prioritise future model improvements and components within the SENTINEL project and were empowered to further collaborate with other modellers and practitioners to contribute to a better understanding of the pathways and means to decarbonise the European Union.

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A key limitation of our work is that even though we were able to engage more than 90 stakeholders (21 during the physical workshop in Athens, 30 during the thematic online deep-dive sessions, and 43 during the SENTINEL final event), we were not able to involve all stakeholder groups equally. Specifically, representatives from the policymaking field were the hardest to reach, while stakeholders from academia and research could be reached with ease. This confirms previous SENTINEL findings that energy modelling traditionally has been a domain either of research institutes or big energy companies and utilities. Apparently, many of policymakers, industry experts, and representatives of the civil society still do not have sufficient capacities (at least in their own view) to get involved and committed to activities dedicated to energy system modelling.

In addition, throughout the SENTINEL project, we have faced significant and disruptive events that affected both our process-related developments as well as how our results realistically apply to a changing world. First, the COVID-19 pandemic affected the process of engaging our stakeholders in the early stages of the SENTINEL project by moving all engagement activities online. While we were able to incorporate COVID-19's implications into our research questions during the duration of the SENTINEL project, it did influence the research design and delays affected modelling capacities. The second disruptive event was Russia's invasion of Ukraine and the consequential European energy crisis. As the SENTINEL modelling teams had already completed their modelling runs answering the existing research questions, it was difficult to integrate the impacts and implications of this disruptive event into the modelling results. Again, this calls for further modelling studies regarding the faster reduction of reliance on fossil fuels, particularly imported oil and gas from Russia.

Modellers have already implemented or planned to implement further modelling refinements based on the received stakeholder feedback. In this report, we present some examples of implemented (i.e., EnergyPLAN application to the Continental case study and EMMA - BSAM application to the National case study) and planned modelling refinements (i.e., QTDIAN – Euro-Calliope – WEGDYN and HEB applications to the Continental case study as well as DREEM and ATOM applications to the National and Continental case studies). However, the modelling refinements will not be limited to those mentioned above. Almost all the SENTINEL modelling partners have participated in stakeholder interactions and received concrete feedback with regards to potential modelling improvements. These improvements will be clearly visible when they publish their work in scientific journals. In this regard, a virtual special issue[37] has already been launched in the "Energy" scientific journal (IF: 8.857) that aims at bringing together a collection of scientific articles that will present results from a suite of different energy system models, including SENTINEL models. To this end, we call for existing and future consortiums to use different modelling suites to respond to the critical issues and challenges towards climate neutrality to enable better-informed decision-making.

[37] https://www.sciencedirect.com/journal/energy/about/call-for-papers

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

## Appendix

### Section A. Agenda of the workshop "Pathways to climate neutrality in Europe with a spotlight in Greece: Challenges, uncertainties, solutions

# WORKSHOP

# Pathways to climate neutrality in Europe with a spotlight in Greece: Challenges, uncertainties, solutions

**Thursday, 30th of June 2022**

| |
|---|
| **Venue:** "Oasis Hotel Apartments", 27 Poseidonos Avenue, Glyfada, 16675, Athens, Greece<br>Conference Room «Kefalonia Hall»<br>**Contact:** vasta@unipi.gr, anikas@epu.ntua.gr |

## Agenda

| | |
|---|---|
| **09.30-10.00** | **Registration & Welcome coffee** |
| **10.00-10.25** | **Opening: Putting projects into context** |
| 10.00-10.05 | Welcome<br>*Alexandros Flamos (University of Piraeus Research Centre)* |
| 10.05-10.15 | Introduction to the "SENTINEL" project<br>*Anthony Patt (ETH Zurich)* |
| 10.15-10.25 | Introduction to the "PARIS REINFORCE" project<br>*Haris Doukas (National Technical University of Athens)* |
| **10.25-12.00** | **Plenary Session I: Transition pathways to climate neutrality in Europe** |
| **Session chair:** *Alexandros Flamos*<br>**Presentations:** | |
| 10.25-10.35 | "How can the decarbonisation of final energy uses contribute to meeting the European Union's emission reduction targets?"<br>*Gabriel D. Oreggioni (Imperial College of London)* |
| 10.35-10.45 | "Towards a net-zero building sector: A European Dream?"<br>*Souran Chatterjee (Central European University)* |
| 10.45-10.55 | "Using a global integrated assessment model to assess the policy environment in the European Union"<br>*Mark Roelfsema (Utrecht University)* |
| 10.55-11.05 | "Modelling of a smart energy system in Europe"<br>*Jakob Zinck Thellufsen (Aalborg University)* |
| 11.05-11.15 | "Diversity of options to eliminate fossil fuels and reach carbon neutrality across the entire European energy system" |

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| | |
|---|---|
| | *Stefan Pfenninger (TU Delft)* |
| 11.15-12.00 | Q&A session<br>*Facilitation: Andrzej Ceglarz (Renewable Grid Initiative)* |
| **12.00-12.15** | **Coffee break** |
| **12.15-13.30** | **Plenary Session II: Decarbonisation pathways and the role of natural gas in Greece** |
| **Session chair(s):** *Haris Doukas*<br>**Presentations:** | |
| 12.15-12.25 | "Energy transition in the residential sector in Greece: Investing in natural gas or in electrification?"<br>*Vassilis Stavrakas (University of Piraeus Research Centre)* |
| 12.25-12.35 | "Greek NECP and Climate Law: are they ambitious enough? The role of natural gas en route to decarbonisation"<br>*Alexandros Nikas (National Technical University of Athens)* |
| 12.35-12.45 | "Identifying bottlenecks for the decarbonisation of the Greek power sector"<br>*Philine Warnke (Fraunhofer ISI)* |
| 12.45-13.30 | Q&A session & Interactive elaboration on the list of bottlenecks<br>*Facilitation: Philine Warnke* |
| **13.30-14.15** | **Group photo & Lunch break** |
| **14.15-15.45** | **Climate-neutral World Café sessions** |
| **Session facilitators:** *Alexandros Nikas, Andrzej Ceglarz, Diana Süsser (IASS Potsdam), Philine Warnke, Vassilis Stavrakas* | |
| 14.15-14.25 | Live polling on "Which are the most relevant bottlenecks?"<br>*Facilitation: Diana Süsser & Philine Warnke* |
| 14.25-14.30 | Explanation of proceedings & settling in tables |
| 14.30-15.45 | **Session 1: Bottleneck Specification** - "*What are the main aspects of the bottleneck and how is it hindering the transition?*"<br>**Session 2: Policy Mixes & Interventions** - "*What policies and other interventions could overcome the bottlenecks?*"<br>**Session 3: SENTINEL models to support policymaking** - "*What answers would you like to get from (energy) models?*"<br>**Session 4: SENTINEL modelling platform** - "*What kind of energy modelling platform would you like to use?*" |
| **15.45-16.00** | **Climate-neutral World Café gallery & Final round of reflections** |

**Institutions & stakeholders participating in the consultation process**

Ministry of Environment and Energy (MEE)
Public Power Corporation S.A. (PPC S.A.)
PPC Renewables S.A. (PPCR S.A.)
Public Gas Company S.A. (DEPA S.A.)
Hellenic Electricity Distribution Network Operator (HEDNO)
Independent Power Transmission Operator (IPTO)
Regulatory Authority for Energy (RAE)
Hellenic Gas Transmission System Operator S.A. (DESFA S.A.)
Hellenic Energy Exchange S.A. (HEnEx S.A.)
Technical Chamber of Greece (TEE - TCG)
Hellenic Association of Independent Power Producers (haipp)
Hellenic Petroleum Marketing Companies Association (SEEPE)
Hellenic Association of Renewable Energy Sources Power Producers (hellasres)
Hellenic Wind Energy Association (HWEA/ELEATEN)
Hellenic Association of Photovoltaic Companies (HELAPCO)
Hellenic Small Hydropower Association (HSHA)

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Centre for Renewable Energy Sources (CRES)
Institute of Zero Energy Buildings (INZEB)
National Technical University of Athens (NTUA)
Bruegel
Fraunhofer
Institute for European Energy and Climate Policy (IEECP)
Technical University of Mombasa (TUM)
Swiss Federal Institute of Technology in Zürich (ETHZ)
Utrecht University (UU)
Imperial College London
Delft University of Technology (TU Delft)
Aalborg University (AAU)
Hertie School of Governance (HSOG)
Central European University (CEU)
Universitat Autònoma de Barcelona (UAB)
Institute for Advanced Sustainability Studies (IASS)
Renewables Grid Initiative (RGI)
University of Piraeus (UNIPI)
Private sector companies
Independent Energy Consultants
Greenpeace
WWF Greece

# SENTINEL at a glance

SENTINEL
SUSTAINABLE ENERGY TRANSITIONS

**DURATION:** July 2019-November 2022
**FUNDING PROGRAMME:** EU Horizon 2020 Research and Innovation programme under grant agreement No. 837089
**WEBSITE:** https://sentinel.energy/
**CONTACT:** contact@sentinel.energy

The transition to a **low-carbon energy system**, as understood by the scientific and policy communities, will involve a major **redesign** of the energy system, primarily around renewable sources, in accordance with **2030** and **2050** targets that the European Commission has defined. The **SENTINEL** project is aligned with the Energy Union strategy and the EU's commitment under the **Paris Agreement**, which implies the necessity of **accelerating** the energy transition, ultimately leading to the **complete elimination** of energy sector greenhouse gas emissions. At the core of the funding call is the recognition that accelerating this transition requires us to develop a **new** set of energy **modelling tools**, able to represent and analyse the **drivers** and **barriers** to complete decarbonisation, including **decentralisation**, a **large-scale expansion** of fluctuating renewable power leading to a vastly increased need for **system-side flexibility**, **sector coupling** including the electrification of mobility and heating, and the impacts of different **market designs** on the behaviour of energy sector actors.

We are creating a new modelling framework, which we call the **Sustainable Energy Transitions Laboratory** (SENTINEL). The SENTINEL framework will be **modular** in structure incorporating many separate models which will look in detail at specific **technological**, **geographic**, and **societal** aspects of the transition to a low-carbon energy system. The models will be able to be **linked** together to answer a wide range of different questions. For a given **user** in a given **situation**, only a subset of the models are likely to be needed, and this will make it a manageable task to understand how those particular models operate. The **models** in the framework, together with the **data** on which they rely, will be **accessible** via an online platform. The platform will also make available the model **source code** and data, together with supporting **documentation** and **guidance**. This will achieve complete **transparency**, and also enable **other** models to be added to the SENTINEL framework and online platform over time. The project is now officially underway with partners working to pool their modelling expertise with the eventual aim of creating **Sentinel's online platform**.

Extensive **collaboration** with **stakeholders** will inform the development and refinement of the SENTINEL framework. First, we will learn from key stakeholders what **functionality** they

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need. Second, we will apply the framework to address a set of **case studies**, to address specific problems that policy- and decision-makers will face in the next three years. They will help us **evaluate** how well the framework meets their **needs**, in order to improve it further.

Finally, we will **disseminate** our results and **promote** the platform to the appropriate target **audiences**: **policy**-analysts; model **developers**; and **research** scientists. In addition, we will organise a set of **conferences**, in which we help to build a **community** of model users and developers to carry this work forward. Keep an eye on the website for further details: Your involvement and ideas are key in guiding the project objectives and we look forward to **working with you**!

*The SENTINEL project responds to the topic call "LC-SC3-CC-2-2018, Modelling in support to the transition to a Low-Carbon Energy System in Europe" of the European Union H2020 work program.*

## Meet the partners!

| No | Participant organisation name | Country |
|---|---|---|
| 1 (Coordinator) | Swiss Federal Institute of Technology ***(ETH Zurich)*** | CH |
| 2 | University of Aalborg ***(AAU)*** | DK |
| 3 | Central European University ***(CEU)*** | HU |
| 4 | Hertie School of Governance ***(HSOG)*** | DE |
| 5 | Imperial College of Science, Technology and Medicine ***(Imperial)*** | UK |
| 6 | University of Utrecht ***(UU)*** | NL |
| 7 | Public Power Corporation ***(PPC)*** | GR |
| 8 | Renewables Grid Initiative ***(RGI)*** | DE |
| 9 | Autonomous University of Barcelona ***(AUB)*** | ES |
| 10 | University of Graz ***(UniGraz)*** | AT |
| 11 | Technoeconomics of Energy Systems laboratory, University of Piraeus Research Centre ***(TEESlab- UPRC)*** | GR |
| 12 | Institute for Advanced Sustainability Studies ***(IASS)*** | DE |

# PARIS REINFORCE at a glance

**DURATION:** June 2019-November 2022
**FUNDING PROGRAMME:** EU Horizon 2020 Research and Innovation programme under grant agreement No. 820846
**WEBSITE:** https://paris-reinforce.eu/
**CONTACT:** contact@paris-reinforce.eu

Responding to climate change requires transdisciplinary processes to come into play in order to put together a jigsaw of initiatives that altogether constitute effective national, regional and global climate policies. These **policies must be science-based, technically feasible, financially viable, socially acceptable, and robust, as well as globally coordinated in a cooperative, Talanoa-spirit manner**. In this challenging domain, PARIS REINFORCE aims to revolutionise the scientific paradigm and underpin climate policymaking with authoritative scientific processes and tangible results, towards effectively supporting the design of climate policies.

In particular, the project has developed a novel assessment framework for effectively supporting the design of climate policies globally and in the EU as well as in all other major emitters and selected less developed countries, in respect to the objectives of the Paris Agreement. This builds on a **strong ensemble of complementary—in terms of geographic, sectoral, emission coverage, mathematical background and investigation focus—IAMs**, in order to support the effective implementation of NDCs, the preparation of future action pledges, the development of 2050 decarbonisation strategies, and the reinforcement of the 2023 Global Stocktake, in light of the need to increase decarbonisation ambition and to align these efforts with sustainable development goals.

Among its core objectives also lies enhancing the legitimacy of the scientific processes in support of climate policymaking, by introducing an **innovative stakeholder co-creation framework and improving the transparency of the respective models/tools**. Beyond effectively communicating outputs and fostering societal acceptance of climate policy, we actively involve policymakers and other stakeholders in all stages of the project. Their participation ranges from the formulation of policy questions and the definition of modelling assumptions in a demand-driven approach, to the design of the envisaged platform

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

and the mobilisation of tacit knowledge embedded in experts towards bridging knowledge gaps. In other words, the project creates a shared science-stakeholders ground to facilitate targeted, effective, and sustainable policy processes. This effort is also reflected in the **open-access and transparent data exchange platform, I²AM PARIS**, which features all modelling theories, descriptions, assumptions, input data, modelling results, visualisations, associated policy prescriptions, scientific papers associated with each exercise.

Finally, the project introduces innovative policy support frameworks to **improve the robustness of modelling outputs against different types of uncertainties**, inherent in both the climate change domain and integrated assessment processes. These revolve around a series of well-established, quantitative and qualitative methodologies, with which IAMs are further interlinked towards effectively tackling said weaknesses and leading to robust, sustainable, and effective policy strategies.

*The PARIS REINFORCE project responds to the topic call "LC-CLA-01-2018, Supporting the development of climate policies to deliver on the Paris Agreement, through Integrated Assessment Models (IAMs)" of the European Union H2020 work program.*

## Meet the partners!

| No | Participant organisation name | Country |
|---|---|---|
| 1 (Coordinator) | National Technical University of Athens ***(NTUA)*** | GR |
| 2 | Basque Centre for Climate Change ***(BC3)*** | ES |
| 3 | Bruegel ***(Bruegel)*** | BE |
| 4 | University of Cambridge ***(Cambridge)*** | UK |
| 5 | CICERO Centre for International Climate Research ***(CICERO)*** | NO |
| 6 | Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici ***(CMCC)*** | IT |
| 7 | E4SMA s.r.l. ***(E4SMA)*** | IT |
| 8 | Ecole Polytechnique Fédérale de Lausanne - LEURE ***(EPFL)*** | CH |
| 9 | Fraunhofer Institute for Systems and Innovation Research ***(Fraunhofer ISI)*** | DE |
| 10 | Imperial College London - Grantham Institute ***(Imperial)*** | UK |
| 11 | HOLISTIC P.C. ***(HOLISTIC)*** | GR |
| 12 | Institute for European Energy and Climate Policy ***(IEECP)*** | NL |
| 13 | Société Eeropéenne d'Economie ***(SEURECO)*** | FR |
| 14 | University of Brasilia - Centre for Sustainable Development ***(CDS)*** | BR |
| 15 | Energy Economics, Finance and Policy Research Centre, China University of Petroleum Beijing ***(CUP)*** | CN |
| 16 | Institute of Economic Forecasting, Russian Academy of Sciences ***(IEF-RAS)*** | RU |
| 17 | Institute for Global Environmental Strategies ***(IGES)*** | JP |
| 18 | The Energy Resources Institute ***(TERI)*** | IN |

SENTINEL

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## Section B. Agenda of the "Socio-economic Impacts of a Just European Energy Transition" deep-dive session

| Agenda<br>**"Socio-economic Impacts of a Just European Energy Transition" deep-dive session** | |
|---|---|
| **Aim:** Present and discuss the issues related to **distributional effects** of energy transition, providing you the **opportunity to share your perspectives and feedback on our interlinked modelling framework and our modelling results regarding socio-economic impacts.** | |
| 10.00-10.30 | **Welcome** to SENTINEL and Introduction to the energy system models |
| 10.30-11.00 | **Focus Group** – Relevance of Results |
| 11.00-11.05 | Technical break |
| 11.05-11.30 | **Focus Group** – Technical Aspects and the Modelling Process |

## Section C. Agenda of the "Environmental Impacts of Energy Technologies: Introducing the ENBIOS Model" deep-dive session

| Agenda<br>**"Environmental Impacts of Energy Technologies: Introducing the ENBIOS Model" deep-dive session** | |
|---|---|
| **Aim:** Introduce the **ENBIOS** architecture and present criteria for **environmental impacts**, giving you the opportunity to share **your perspectives** about the **relevance, understandability, and potential future needs.** | |
| 10.00-10.35 | **Welcome** to SENTINEL and Introduction to ENBIOS |
| 10.35-11.25 | **Two parallel Focus Groups** – Feedback to the ENBIOS model |
| 11.25-11.30 | **Closing** |

## Section D. Agenda of the "Pathways to Decarbonising the EU Building Sector" deep-dive session

| Agenda<br>**"Pathways to Decarbonising the EU Building Sector" deep-dive session** | |
|---|---|
| **Aim:** Introduce the results of the **HEB** and **DREEM** models, giving you the opportunity to share **your perspectives** about the **relevance, understandability, and potential future needs.** | |
| 10.00-10.30 | **Welcome** to SENTINEL and Introduction to the energy system models |
| 10.30-11.00 | **Focus Group** – Relevance of Results |
| 11.00-11.05 | Technical break |
| 11.05-11.30 | **Focus Group** – Technical Aspects and the Modelling Process |