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: 36 months**

Deliverable reference number and title:

D3.3: Integration of demand model results into system planning models

Version: 1

Due date of deliverable: 12.2021 **Actual submission date: 09.2021**

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)	

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

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Please cite as:

Chatterjee, S., Stavrakas, V., Oreggioni, G., Pickering ,B., Thellufsen, J., Staffell, I., Flamos, A., & Ürge-Vorsatz, D. (2021). *Integration of demand model results into system planning models. Deliverable 3.3. Sustainable Energy Transitions Laboratory (SENTINEL) project*. European Commission. Central European University (CEU), Budapest, Hungary.

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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*.

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 case study interview meetings, focus groups and thematic workshops. The content of this report is the sole responsibility of its authors and does not necessary reflect the views of the EC.

SENTINEL

SUSTAINABLE ENERGY TRANSITIONS

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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*.

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Executive summary

The demand side plays a pivotal role in order to understand the expanse of the whole energy system, especially when one considers the European Union's (EU) commitment to climate neutrality by 2050, in the context of which, energy demand needs to be reduced substantially. Therefore, the role of policies that support energy efficiency measures and demand-side management practices will be critical; however, the impacts of such policies can only be explored ex-ante using energy demand models. In this context, the energy demand models (EDMs) used in the Sustainable Energy Transitions Laboratory (SENTINEL) project provide yearly and hourly future demand profiles for each of the EU Member States. However, EDMs, including the ones used in SENTINEL, namely: BEVPO, DESSTINEE, DREEM, and HEB, are often criticized for not incorporating dynamic GDP, or socio-political dimensions. Having that in mind, the SENTINEL EDMs will be soft-linked with the QTDIAN toolbox from WP2 to incorporate storylines of different socio-political developments, while calculating the future energy demand. Furthermore, the SENTINEL EDMs use a linear economic (mainly GDP) projection as input data to calculate future energy demand profiles. However, the linear projection of economic input usually excludes market uncertainties, and hence, makes model outputs less realistic. To overcome this limitation in SENTINEL, EDMs will be also soft-linked with the macroeconomic model WEGDYN from WP5. This soft-linking will make the output of the SENTINEL EDMs much more realistic, and, hence, it is expected to increase their useability in decision-making. Thus, the demand profiles, more precisely the hourly and yearly demand profiles for the building, transport and industry sectors, will be used in WP4 as an input to calculate the energy balance in the context of the transition to climate neutrality in the EU. Finally, to make these exercises more policy relevant, all the aforementioned soft-linkages will take place for three case studies of different heterogeneous geographical scales and policy characteristics, namely: **a.** Greece (National level), **b.** Nordic countries (Regional level), and **c.** EU, Switzerland, and United Kingdom (Continental level). These case studies will serve as the testing ground to demonstrate the applicability of the SENTINEL EDMs, test their usefulness for potential end-users, and provide policy-relevant answers to different research questions, as identified in WP7. Overall, this report documents the technical details of the WP3–related soft-linking activities in SENTINEL and further discusses the expected impact of their application to the three case studies.

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1. Introduction

1.1. Background

Climate change mitigation targets, including achieving the climate neutrality goal in the European Union (EU) by 2050, tend to be more focused on supply-side technology solutions (Creutzig et al. 2018). However, direct emissions from final energy uses– including stationary sources (such as buildings and industries) and transport– account for 52% of the greenhouse gas emissions in the EU27 and the UK (Oreggioni et al., 2021). Furthermore, the end-use demand in these sectors determines the size and feasibility of the energy system in addition to associated investments (Grubler et al. 2018; Creutzig et al. 2021). Thus, reducing final energy demand is crucial to achieve the climate neutrality goal. There are several ways to accomplish this objective, involving different types of energy efficiency measures and demand-side practices to decrease final energy consumption and greenhouse gas (GHG) emissions with dissimilar impacts on the full energy system though. In this context, the role of policies that will support the right measures and practices will be critical; however, the impacts of such policies can only be explored ex-ante using energy demand models (EDMs). Therefore, the role of EDMs is vital when evaluating different decarbonisation pathways toward climate neutrality.

In the previous SENTINEL WP3 deliverable (D3.2) we discussed ***how*** climate neutral policies rely on the findings of EDMs and ***why*** modelling teams need to take the diverse needs of model users (e.g., policymakers, scientists and researchers from academia, NGOs, representatives from the energy industry, etc.) into consideration in order to increase the accuracy and useability of their models. We identified two categories of user needs relevant to energy demand modelling for the transition to climate neutrality in the EU by 2050, namely, generic, and sectoral user needs. Also, we discussed how the four EDMs used in SENTINEL will be upgraded to address these various needs of the model users. Each SENTINEL WP has identified such user needs relevant to their models and in order to develop a coherent and useable SENTINEL modelling framework, different models from all the modelling WPs should interact with each other to reflect on the reality of the energy systems' transition. In addition, as also discussed in the SENTINEL D3.1 and D3.2, one usual criticism in EDMs is that they do not incorporate socio-economic factors that influence both the demand and the supply sides of the energy system, and hence, findings from these models are often far from being realistic (Chatterjee and Ürge-Vorsatz 2020; Chatterjee et al. 2021). In this context, in SENTINEL, we have identified the key gaps and user needs related to energy demand modelling and we have updated each one of the SENTINEL EDMs accordingly.

In this context, the objective of the SENTINEL demand module (WP3) is to calculate the total annual final energy consumption and corresponding GHG emissions, for each sector and type of end-use, in addition to producing hourly power demand profiles. Outputs of the demand module will be used by the other SENTINEL modelling teams to define installed capacity and hourly load for electricity generation, crosschecking that the proposed solutions meet economic and environmental constraints, whilst securing supply in the context of highly intermittent renewable-based power generation matrices. To test the applicability of the SENTINEL EDMs and validate the usefulness of these soft-linkages for different end-users, modelling exercises will take place for three case studies of different heterogeneous geographical scales and policy characteristics, namely: **a.** Greece (National level), **b.** Nordic countries (Regional level), and **c.** EU, Switzerland, and United Kingdom (Continental level). This will also allow us to provide policy-relevant answers to different research questions, as identified in WP7 (Stavrakas et al. 2021).

Overall, and considering all the above, the SENTINEL EDMs will be soft-linked with a toolbox for the development of socio-political storylines from WP2 and (macro)economic models from WP5, to include the socio-political and economic reality behind demand-side policies. Furthermore, the output of the EDMs will be used by the system models of WP4 to explore the feasibility of the EU climate neutrality target by 2050 for the different scenarios developed under WP7 and WP8.

1.2. Objective and scope of this deliverable

The objective of this report is to document the technical details of the interlinkages between four EDMs (WP3) and one toolbox for the development of socio-political storylines (WP2), one (macro)economic model (WP5), and two system design models (WP4). By soft-linking these different types of models, the SENTINEL demand module incorporates both societal as well as economic aspects of the energy system and provides much more realistic representations of decarbonisation pathways for the transition to climate neutrality in the EU by 2050.

This report is organised into five sections. **Section 1** introduces the concept and need for upgrading the SENTINEL EDMs based on the user needs identified, while in **Section 2**, the demand models used in SENTINEL are being introduced. **Sections 3** and **4** discuss how the different demand models can be soft-linked, and also how the SENTINEL demand module (WP3) is soft-linked with the other SENTINEL WPs, either by giving them inputs or by feeding on their outputs. Furthermore, these two sections also provide an overview of the methodological framework to show how these different interlinkage methodologies are developed and used in the context of the three SENTINEL case studies. Finally, **section 5** concludes the key messages of the report.

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2. The SENTINEL energy demand models

The energy demand modelling module of the SENTINEL project has four different sector-specific models that are going to be used to explore different decarbonisation scenarios for the transition to climate neutrality in the building, the transport, and the industry sectors. A short presentation of the models and their key features and capabilities are presented below.

2.1. The Battery Electric Vehicle Policy (BEVPO) model

The BEVPO model creates car traffic and parking density maps given the time that vehicles need to travel between different city zones throughout an entire day (Aryandoust et al. 2019). Hereby the accuracy of the model in time is dependent on the granularity of travel time measurements given to the model by so-called Origin-Destination (OD) matrices. Its accuracy in space is dependent on the arbitrary granularity with which the modeler divides a city into different zones; this choice is made dependent on the scale on which the modeler wants to create her car parking density maps. At the core of the BEVPO model stands a hidden Markov model that translates travel time measurements into trip activities and destination choices based on the OD travel time matrices on the scale of entire cities.

2.2. The Demand for Energy Services, Supply and Transmission in EuropE (DESSTINEE) model

DESSTINEE is an open-source model developed at Imperial College London (ICL). It investigates the effects of demographic, economic, and technological changes on future final energy demand and power supply, both at yearly and hourly dimension. It has a country level geographical resolution, which can easily be expanded to cover sub-regions within a country. DESSTINEE has been used for simulating load curves under different decarbonisation scenarios, for example "two degree (2^o) target scenarios" in the United Kingdom and Germany (Boßmann & Staffell, 2015).

DESSTINEE is programmed in VBA with a user-friendly interface in Excel. It is constituted by 3 modules. Module 1 forecasts annual final energy consumption, accounting for 11 energy carriers, using sectorial partial decomposition for service demand. The latter is projected based on user defined population and GDP growth rates, efficiency improvements, and fuel switching towards electric heat and transport. In the context of the SENTINEL project, this module has been employed with the purpose of defining technology incorporation and fuel baskets for final energy uses, compatible with climate neutrality by 2050 and newly announced decarbonisation targets by 2030 (Oreggioni G D, in preparation). For key final energy uses, annual figures for power usage are hourly distributed (Module 2), having the resulting power demand profiles been validated for all countries in Europe by crosschecking against official data for hourly system load.

Hourly power demand profiles can be used as input for the DESSTINEE's Supply Module (Module 3)- allowing the simulation of the hourly operation of the power systems- by accounting for: user-provided generation potential for intermittent renewable sources; assumptions for transboundary transmission capacity; and efficiency and installed capacity figures for thermal generation plants. The model establishes a power matrix aimed at minimising running cost. Both for demand and supply, DESSTINEE reports fuel usage and fossil CO_2 emissions, and we are currently extending the model to also quantify other greenhouse gas emissions.

Forecasting service demand and final energy consumption relies on inputs and assumptions regarding behavioural changes, particularly, in terms of building occupancy, evolution for building surface area, thermal comfort patterns, and modal shifts for transport. Having access to detailed, and systemically obtained information in this domain will improve the accuracy and especially the policy relevance of the results as they will be closer connected to actual developments and pending political decisions. Linking DESSTINEE's inputs with the QTDIAN toolbox outputs (i.e., socio-political storylines) could significantly contribute to this (Süsser et al. 2020).

2.3. The Dynamic high-Resolution dEmand-sidE Management (DREEM) model

DREEM is a hybrid bottom-up model that combines key features of both statistical and engineering models. The model serves as an entry point in Demand-Side Management (DSM) modelling in the building sector, by expanding the computational capabilities of existing Building Energy System (BES) models, by not only calculating energy demand, but also assessing the benefits and limitations of demand-flexibility, primarily for consumers as well as for other power actors involved (Stavrakas & Flamos, 2020). The novelty of the DREEM model lies mainly in its modularity, as its structure is decomposed into individual modules characterised by the main principles of component-/ modular-based systems modelling approach, namely "the interdependence of decisions within modules; the independence of decisions between modules; and the hierarchical dependence of modules on components embodying standards and design rules" (Pereverza, Pasichnyi, & Kordas, 2019) (Figure 1). This modular approach allows for more flexibility in terms of possible system configurations and computational efficiency towards a wide range of scenarios, studying different aspects of end-use.

The modular structure of the DREEM model (Figure 1) allows for a wide range of functionalities regarding different decarbonisation scenarios of the European building stock. Next to calculating energy demand, such scenarios could also enable the evaluation of the performance and replicability potential of conventional and innovative energy efficiency measures, in terms of their long-term energy savings, sustainability, risk, and return of investment. Such an evaluation would focus on assessing the potential benefits of each measure at a disaggregated (i.e., households-neighbourhood) level, and then allowing for upscaling at a national level.

However, considering the role that the human factor is expected to play in these scenarios, it is important that socio-political aspects are incorporated into the model, to better ground model assumptions and to constrain otherwise free variables to reasonable ranges. In this regard, a synergy with the QTDIAN toolbox allows for more accurate parameterisation of the model than otherwise. This could also ensure that the model and its results represent energy transition pathways that are aligned with broader socio-political storylines.

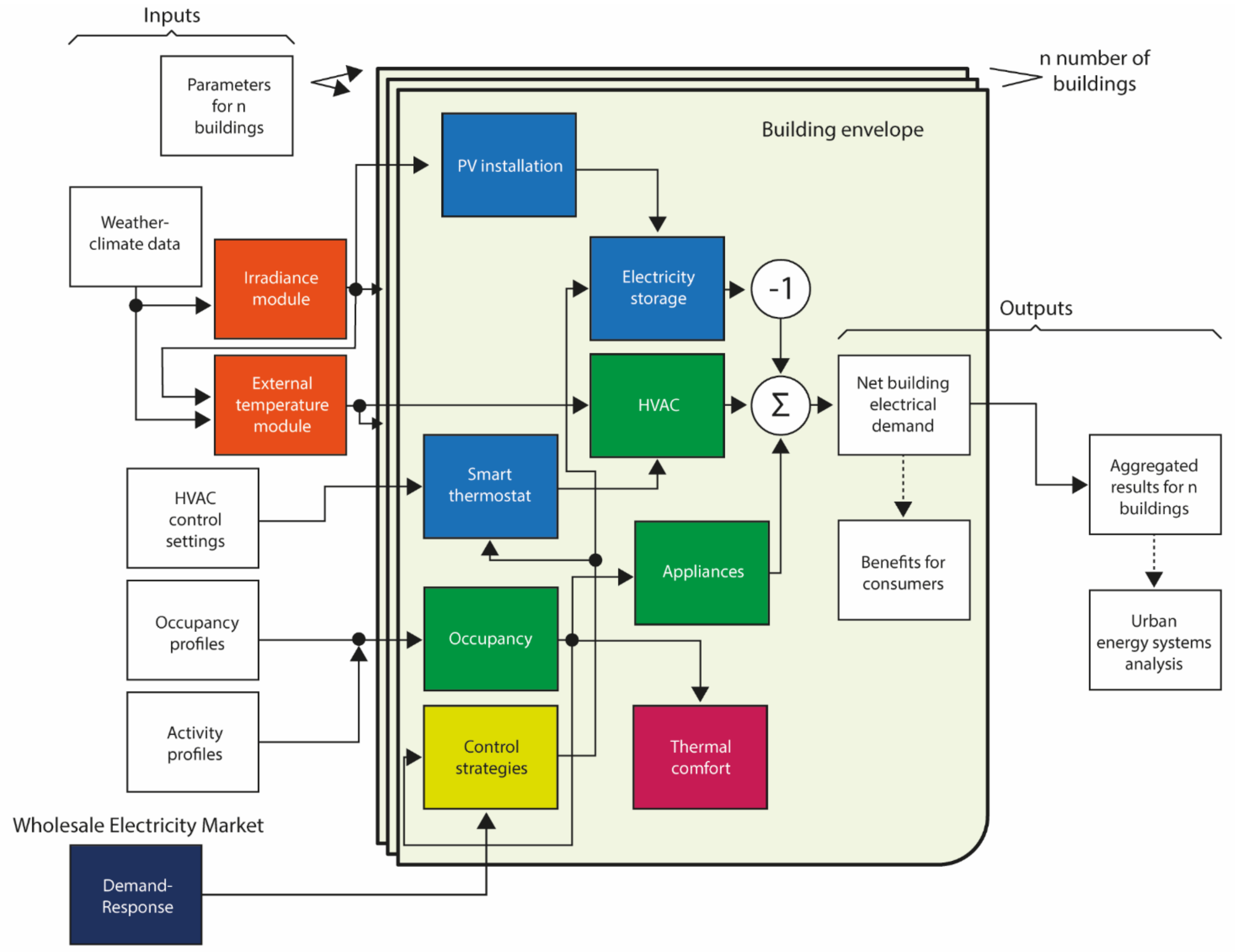

Figure 1: The DREEM model's architecture as it currently stands. Source: Stavrakas and Flamos, 2020.

2.4. The High-Efficiency Building (HEB) model

HEB model was originally developed in 2012 to calculate the yearly energy demand and CO_2 emissions of the residential and tertiary building sector until 2050 under three different scenarios (Urge-Vorsatz, 2012). However, in the SENTINEL context, HEB models has upgraded to incorporate the user needs and make the results more realistic. The upgraded version of the HEB model calculates both the yearly and hourly service energy demand profile for residential and tertiary building sector for four scenarios until 2060 based on the most recent data for macroeconomic indicators and technological development. This model is novel in its methodology as compared to earlier global energy analyses and reflects an emerging new paradigm: the performance-oriented approach to buildings energy analysis. The model takes a bottom-up approach, as it includes rather detailed technological information for the building sector, however, it also benefits from certain macroeconomic and sociodemographic data which include population, urbanisation rate, and floor area per capita. The four scenarios of HEB model are discussed below.

- **Deep Efficiency Scenario:** This scenario demonstrates the state-of-the-art of construction and retrofit technologies that can substantially reduce the energy consumption of the building sector and hence, CO_2 emissions, while also providing full thermal comfort in buildings. This scenario includes exemplary building practices that have been implemented in the EU for both new and renovated buildings.
- **Moderate Efficiency Scenario:** This scenario incorporates present policy initiatives as the implementation of the Energy Building Performance Directive (EPBD) in the EU and building codes for new buildings in other regions.
- **Frozen Efficiency Scenario:** This scenario assumes that the energy performance of new and retrofit buildings do not improve as compared to the baseline and retrofit buildings consume around 10% less than standard existing buildings for space heating and cooling. Furthermore. most new buildings have a lower level of energy performance than in moderate scenario due to lower compliance with building codes.
- **Towards Net-Zero Scenario:** This last scenario models the potential of deploying "Net Zero Energy Buildings" − buildings that can produce as much energy locally through the utilisation of renewables as they consume on an annual balance. It differs from the other three scenarios to the extent that it not only calculates the energy consumption but already incorporates the local energy supply to arrive at the final energy demand. In other aspects, it uses the same parameters as the Deep Efficiency Scenario.

The aim of the scenario analysis is to capture the importance of different policy acts on building energy efficiency measures and show how much the final energy consumption of the building sector can be reduced across the EU. Each of these scenarios has certain parameters (these parameters determine the future energy demand) and assumptions, based on which each of the scenarios varies from each other. **Table 1** summarises the actual parameters of the four scenarios.

Table 1. Key parameters of the four scenarios that are handled by the HEB model.

Parameter	Deep Efficiency Scenario	Moderate Efficiency Scenario	Frozen Efficiency Scenario	Towards Net Zero Scenario
Initial renovation rate	Country-specific data from the from IPSOS-Navigant report.	Country-specific data from IPSOS-Navigant report.	Country-specific data from the IPSOS-Navigant report.	Country-specific data from the IPSOS-Navigant report.
Accelerated renovation rate	Market-driven storyline renovation from QTDIAN after 2027.	Government-directed storyline renovation data from QTDIAN after 2027.	Country-specific data from the People-powered storylines from QTDIAN.	Market-driven storyline from QTDIAN after 2027.
Energy Efficiency measures of new buildings	New buildings are built to regional standards.	New buildings are built to regional standards.	New buildings do not improve as compared to the existing stock.	New buildings are built to regional standards.

Energy efficiency measures of renovated buildings	Renovations reduce the energy demand approximately by 30%.	Renovations reduce the energy demand approximately by 30%.	Renovations reduce the energy demand approximately by 10%.	Renovations reduce the energy demand approximately by 30%.
Share of advanced buildings within new and retrofitted stock	All new and retrofitted buildings have very low energy demand (advanced buildings) after 2027 in the EU.	70% of the new and retrofitted buildings have very low energy demand (advanced buildings) after 2027.	Advanced buildings are only introduced by the same share as present share of advance buildings.	All new and retrofitted buildings have net zero energy demand after 2027 in the EU.

Source: Source: Süsser et al. 2021

Based on these four scenarios, the key outputs of the HEB model are floor area projection for different types of the residential and tertiary buildings in different regions and EU Member States, the total energy consumption of residential and tertiary buildings, energy consumption for space heating and cooling, energy consumption for hot water energy, total CO_2 emissions, CO_2 emissions for heating and cooling, and CO_2 emissions for hot water energy.

3. Intra-WP linkages: Soft-linking the SENTINEL energy demand models (WP3)

The SENTINEL energy demand module seeks to provide answers to two key overarching research questions, namely:

I. *How will energy demand profiles in the building, transport. and industry sectors look like in 2030 and 2050 if no further actions/ policies are taken compared to considering the recently announced EU decarbonisation targets*?

II. *What is the potential of the EU Member States to reduce final energy consumption and energy-related GHG emissions by 2030 and 2050 following best-practice policies dictated by the recent policy developments*?

In this context, in the previous WP3 deliverable (D3.2) we discussed ***how*** climate neutral policies rely on the findings of EDMs and ***why*** modelling teams need to take the diverse needs of model users (e.g., policymakers, scientists and researchers from academia, NGOs, representatives from the energy industry, etc.) into consideration in order to increase the accuracy and useability of their models. We identified two main categories of user needs relevant to energy demand modelling for the transition to climate neutrality in the EU by 2050, namely, **generic**, and **sector-specific** user needs. Also, we discussed how the four SENTINEL EDMs are constantly being upgraded in the duration of the project to address these various needs of the model users to produce more realistic modelling representations of the demand side (Chatterjee et al. 2021). **Figure 2** below summarises both the generic and sector-specific user needs as identified in D3.2 and indicates how the SENTINEL EDMs will address these user needs, along with the models' key outputs.

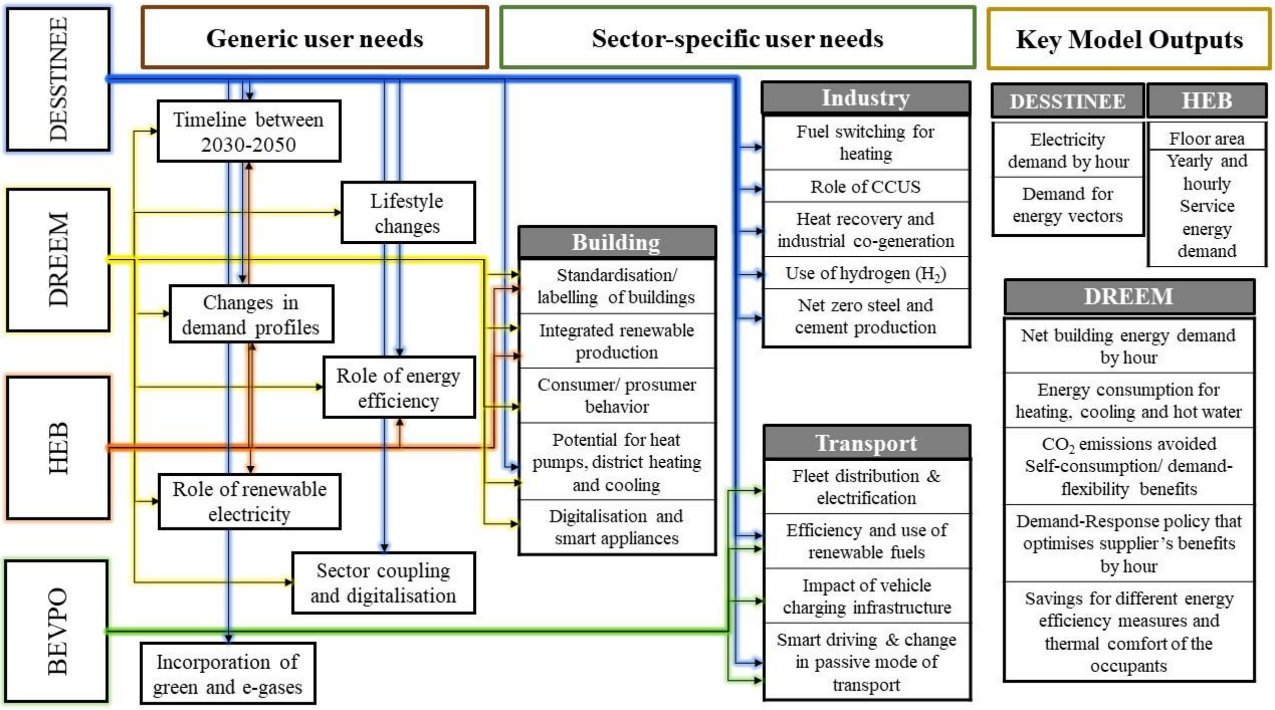

Figure 2. SENTINEL energy demand models addressing the user needs identified under D3.2 and key model outputs.

In many cases, there are overlaps in terms of models producing the same or similar output. Thus, it is important to understand how these overlaps in modelling output can be addressed while addressing different research questions in three different case studies. Furthermore, each of the EDMs has certain limitations in terms of technological or geographical coverages. Therefore, we evaluate each of the models' strengths and weaknesses, to derive the best possible linkages among the EDMs to strengthen the overall demand module of SENTINEL. The overarching conceptual framework of the linkages between the SENTINEL EDMs is presented in **Figure 3**.

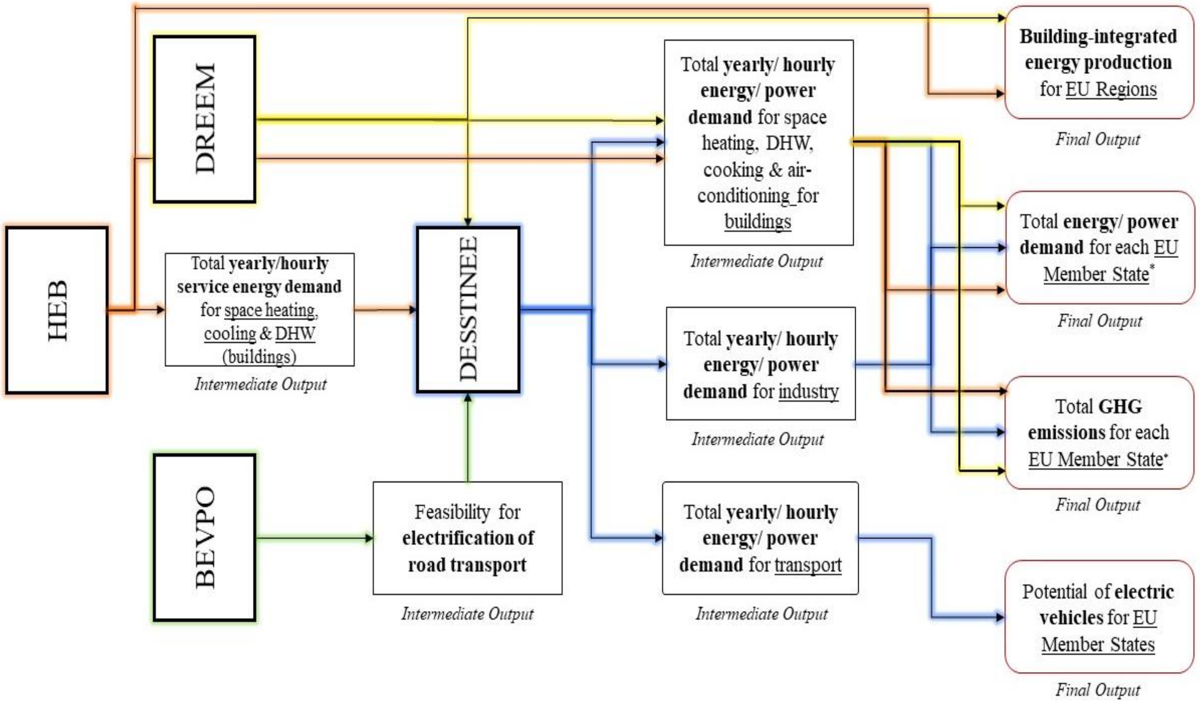

Figure 3. Methodological flowchart of all the possible interlinkages between the SENTINEL energy demand models (WP3) to produce certain outputs that address the user needs identified in a more efficient and realistic way.

To link different EDMS, output of one model is used as an input in another model. For instance, to calculate the final energy demand of the building sector, the HEB model provides both yearly and hourly service energy demand data for each one of the EU Member States and the UK in 2030 and 2050. Based on the data provided by HEB, DESSTINEE will provide the yearly and hourly power/ electricity demand for the building sector. Since the HEB model has a detailed classification of both residential and tertiary buildings, the output of the HEB model- consisting of the service demand for space heating, water heating, and cooling- will be used as an input to the DESSTINEE model for calculating the yearly final power energy demand, GHG emissions and hourly electricity usage.

On the other hand, the DREEM model can also provide both yearly and hourly service energy demand data, but considering its bottom-up structure, at this stage, can also do so for the residential sector in Greece. However, its bottom-up structure allows to consider the different aspects of end-use in the residential sector in more details, also incorporating behavioural aspects of end-use, to increase resolution and improve the accuracy of modelling outcomes. Finally, for the industry and transport sectors, those outcomes will be mostly produced using the DESSTINEE model, which will be fed by BEPVO, as both DREEM and HEB are BES models.-In this way, the WP3 models are complementing each other to estimate both hourly/ annual energy demand and demand-related emissions according to the case study at hand. Considering the latter, **Figure 4** presents the final linkages of the SENTINEL EDMs in the context of the project case studies.

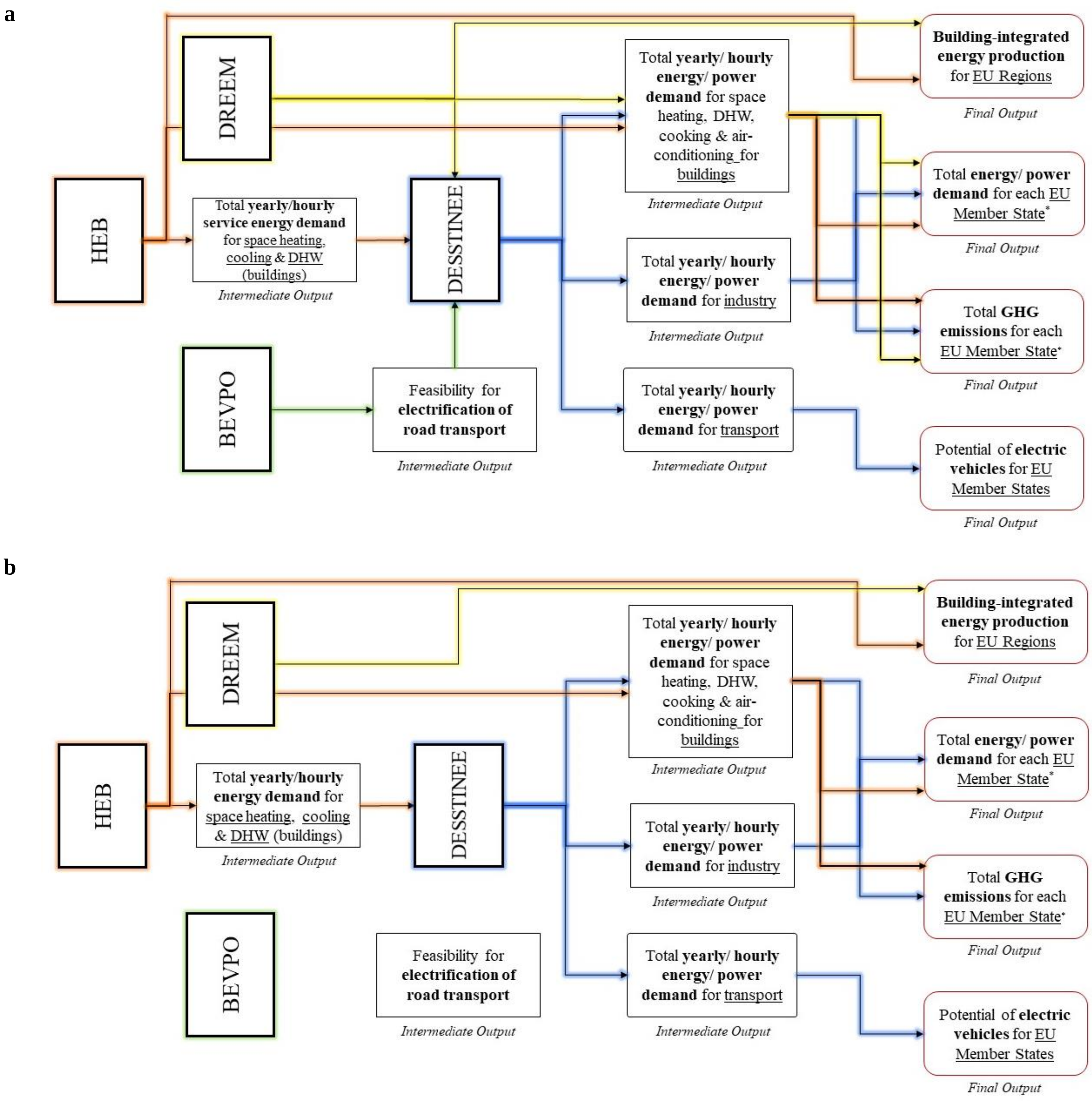

Figure 4. Implementation of the methodological flowchart presented in **Figure 3** in the context of the SENTINEL case studies: **a.** National case study (Greece), and **b.** Regional and Continental case studies (Nordic countries, EU Member States, United Kingdom, and Switzerland).

In particular, we see that for the case of Greece, the theoretical flowchart of all the potential interlinkages between the SENTINEL EDMs can be applied, as limitations concerning the calibration and parameterisation of the models along with issues of data availability (BEPVO) can be more easily handled at the national scale. In the case of DREEM, its bottom-up structure doesn't allow for simulating energy demand for the Regional and Continental cases[1]. However, considering the capabilities of the model, in the context of these two case studies the model could be used to give answers to very sector-specific research questions (as these have been identified under D7.1), to which neither DESSTINEE nor HEB could contribute. For a more detailed description of the different usages of DREEM we refer the reader to D3.2.

The latter speaks of the efficiency based on which the WP3 modelling team planned the different interlinkages between the SENTINEL EDMs, as, for each one of the project case studies, we made sure to interlink the models in such a way that we make use of each model's strengths, avoiding modelling constraints and limitations of data availability.

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[1] Note that the unit of analysis of the model is the household level, simulating energy demand for all the different types of dwelling typologies, e.g., different years of construction, different climate zones, different occupancy profiles, etc., at the level under study. In the context of SENTINEL, the model has been already calibrated and parameterised for the case of Greece; however, it would take significant amount of time to be properly calibrated and parameterised for each EU Member State.

4. Inter-WP linkages: Soft-linking the energy demand models with the rest of the SENTINEL models

Moving forward, WP3 will produce energy demand results for each one of the SENTINEL case studies following the flowcharts presented in the previous section. Considering the modelling framework and structure of the SENTINEL project (**Figure 5**), WP3 builds on inputs from WP2 and WP5, while its final outcome is eventually fed into the system module (WP4). In the next sub-sections, we describe all the different linkages of the energy demand module (WP3) with the rest SENTINEL modules, namely: **(i).** the Socio-environmental transition constraints module (WP2) and **(ii).** the "Economic impacts" module (WP5), both inputs to WP3, and **(iii).** the "System design" module (WP4), which feeds on outputs of WP3.

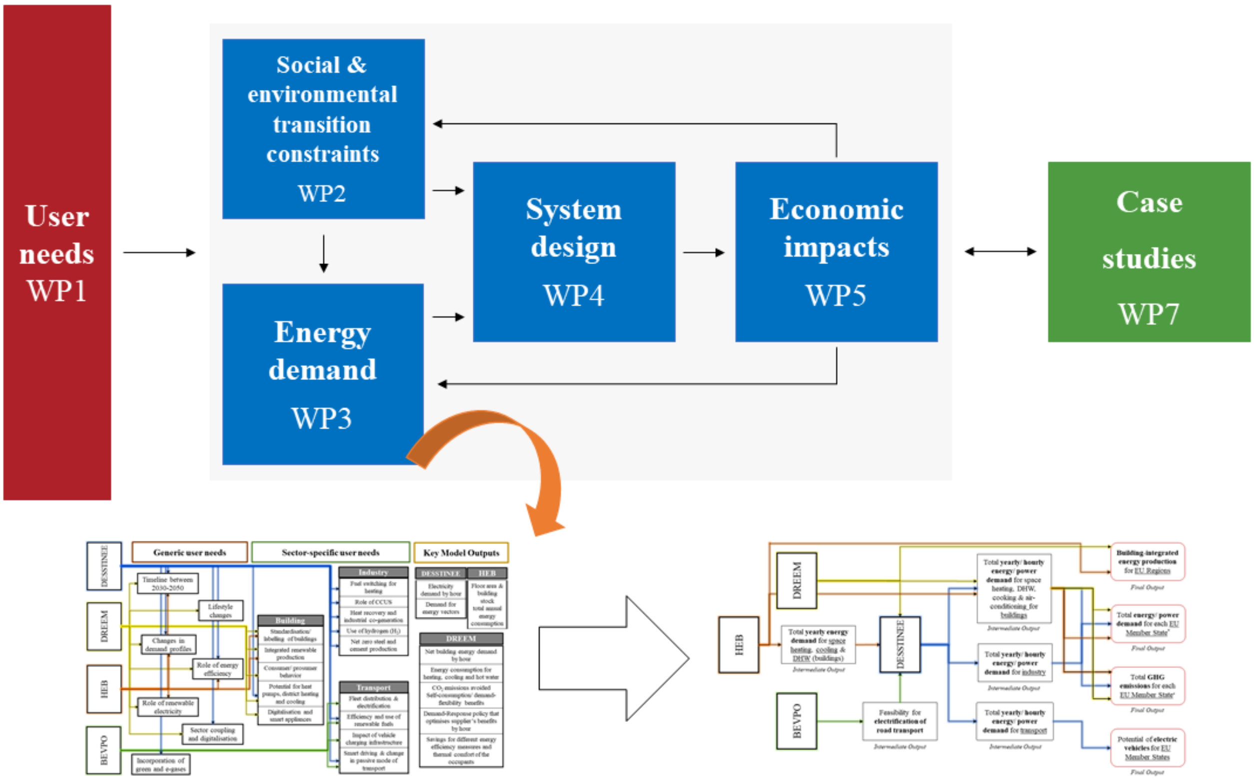


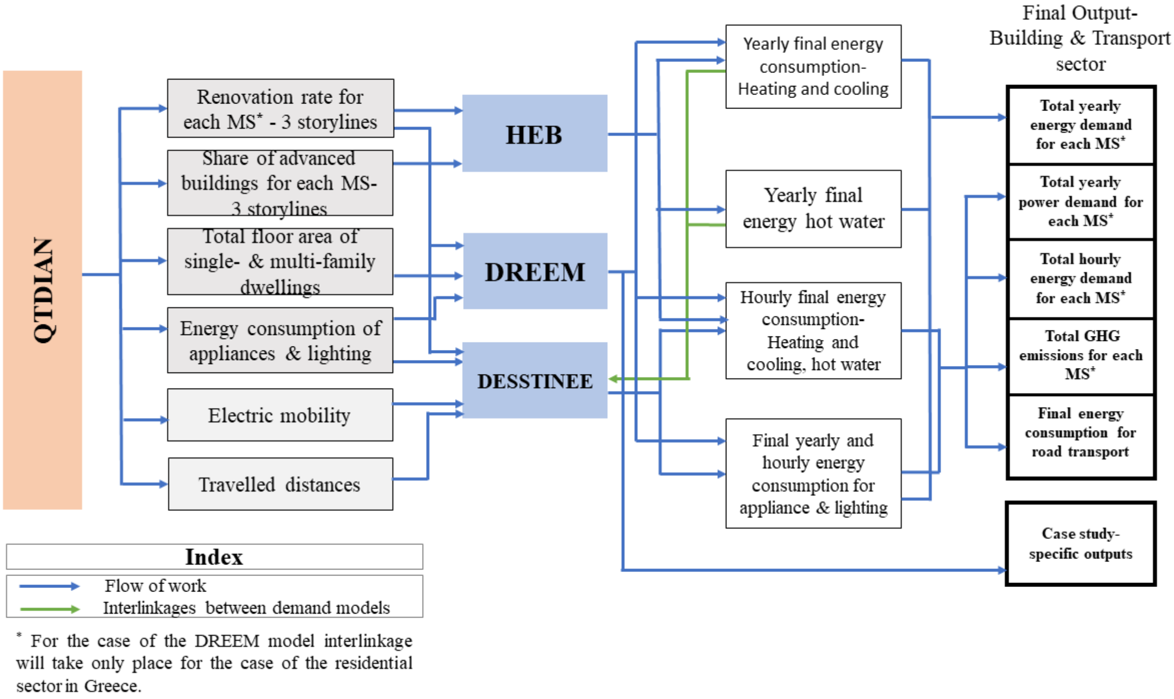
Figure 5. The role of energy demand module (WP3) in the overall modelling framework of the SENTINEL project.

4.1. Linking energy demand to the "Socio-environmental transition constraints" module (WP2)

The existing energy system models, including EDMs, are often criticised for not incorporating socio-political factors, as this makes the models far from being realistic (Trutnevyte et al., 2019; Turnheim et al., 2015). This is because long-term changes in the energy system are largely shaped by several socio-political choices, such as lifestyles and policies for energy-related appliances (Cherp, Vinichenko, Jewell, Brutschin, & Sovacool, 2018). Therefore, including socio-political factors into the SENTINEL EDMs is essential for providing more realistic representations of the future demand profiles in the context of the transition to climate neutrality in the EU by 2050.

In this context, the SENTINEL EDMs will build on inputs of the "Quantification of Technological DIffusion and sociAl constraiNts (QTDIAN)" toolbox in order to include useful socio-political aspects of the energy transition that are usually neglected by modellers. QTDIAN is a toolbox of qualitative and quantitative descriptions of socio-technical and political aspects of the energy transition that influence the overall potential, the rate of energy-related technology and service diffusion and the design of the future energy system. For more information on the toolbox please see Süsser et al., (2020).

Soft-linking of the SENTINEL EDMs to the QTDIAN toolbox is a complex task as it requires the identification and quantification of different socio-political storylines that can be directly used as input by the demand models. Thus, after examining each of the demand model's input and output data requirements along with their assumptions, we have identified five key parameters of the QTDIAN toolbox that can be used by the demand models. The magnitude of the five parameters, namely: **1.** renovation rate, **2.** share of advanced buildings within new and renovated buildings, **3.** energy consumption for appliances, **4.** electric vehicles, and **5.** travelled distances, vary across three different storylines of QTDIAN in order to reflect different socio-political scenarios. Therefore, by using these parameters as input in the demand models, the demand models are able to produce more realistic representations. **Figure 6** summarises the soft-linking approach between WP3 and WP2.



* For the case of the DREEM model interlinkage will take only place for the case of the residential sector in Greece.

Figure 6. Linking the QTDIAN toolbox (WP2) as input to the SENTINEL energy demand models (WP3).

Source: Süsser et al. 2021

4.1.1. Linking the QTDIAN toolbox to the DESSTINEE model

QTDIAN outputs have been considered in the simulation of scenarios compatible with climate neutrality by 2050. Especially, in the case of modelling service demand for heating and appliances within buildings and distance travelled and fleet penetration within road transport

Trends and projections for building renovation, for each QTDIAN storyline, will be used for estimating the improvement rates in building envelope efficiency. This value in DESSTINEE is currently nationally updated – accounting for building age profiles- and data from EU wide scenarios (European Commission, 2018, 2020). Input from QTDIAN will be used for defining a future age profile for buildings, which will be supplemented with assumptions on building energy performance and country-level statistics for building stocks.

Household area is another key driver for demand, both for heating and cooling. The future evolution for country-level household surface is currently forecasted, in DESSTINEE, as function of trends for national GDP per capita. Inputs from QTDIAN will allow to consider different continentally wide evolution, based on the different storylines, whilst the mathematical relationships will be used for disaggregating total continental household area by countries.

DESSTINEE uses an appliance index to compute for the increase of power consumption within residential buildings. This index includes the effects associated with the number of appliances per building and the possible efficiency increases. This coefficient is, in DESSTINEE, currently based on projections for power usage by appliances from EU wide scenarios (European Commission, 2018, 2020) and country-level functions that correlate power consumption with GDP per capita. The figures provided by QTDIAN, will be considered for modelling EU wide level final figures for power consumption by appliances which will be nationally allocated by employing the afore mentioned mathematical correlations.

National increases for travelled distance by passenger cars, in DESSTINEE, are based on the forecasts presented in the 2016's EU Reference Scenario (European Commission, 2016; Loulou & Labriet, 2008). These inputs will be replaced using the EU wide growth rate, informed by QTDIAN, whilst the data from the afore mentioned scenario will be considered for allocating the total service demand among countries.

Future national fuel shares, within the passenger car fleet, are modelled in DESSTINEE based on: forecasts in continentally wide scenarios, econometric relationships for country-level electric car ownership; and present distribution of biofueled units among Member States. Inputs from QTDIAN will partially replace the assumptions for electrification and fossil fuel shares at European level whilst the national allocation methodology currently used in DESSTINEE will be kept.

The integration between QTDIAN and DESSTINEE at continental level is quite straightforward. The main challenges are related to the downscaling of the EU defined targets into country-level circumstances. This could lead to estimates which are representative for the whole EU27+UK bloc but that could be more uncertain at national level, both because country-l data is not always present and hence unknown, and because single policy decisions may have large effect on the national level, making the future more uncertain the deeper we zoom in.

There are benefits of such an interlinkage, especially for the service demand quantification in heating in buildings and transport. In DESSTINEE, several aspects of service demand quantification account for the future evolution of income indicators. Updating such projections with figures that also consider possible behavioural changes is of great value– given that some of these variables have a key societal component in terms of population and family dynamics, consumer preferences, and patterns for building refurbishing and mobility.

4.1.2. Linking the QTDIAN toolbox to the HEB model

The QTDIAN storylines and the outcome of the storylines are used as an input data to the HEB model to incorporate the socio-political aspect in each of the HEB scenarios. This incorporation of socio-political aspect into scenarios make the HEB scenarios much more realistic. From QTDIAN, two key inputs are used in HEB: 1) building renovation rates, and 2) share of advanced buildings for each of the EU MS. More precisely, the sum of medium and deep renovation rates from the "IPSOS-Navigant" report (refer to Ipsos-NAVIGATE 2019) are used as total renovation rate for each of the EU MS till 2027. After 2027, the renovation data varies as per HEB scenarios and QTDIAN storylines. For instance, the data for people-powered storyline is used as frozen efficiency renovation data in the HEB model after 2027, and government-directed and market-driven storylines data are used in the Moderate and Deep Efficiency Scenarios of the HEB model respectively after 2027. Similarly, the share of advanced buildings data is used from QTDIAN for different HEB scenarios. More detailed discussion is documented in D2.5 (refer to Süsser et al. 2021).

Developing the linking process is not easy, especially when two very different models are considered. However, with some assumptions (for example, in HEB we assume there is no difference between primary and final building end-use energy, and thus, theoretical debates souring these two terms are avoided) and detailed understanding of the models constructs, we manage to feed QTDIAN data as an input to HEB model. These assumptions and hard work of soft-linking is justified as the soft-linking exercise in SENTINEL is outweighed the disadvantages with benefits. The most significant advantage of soft-linking QTDIAN to HEB is that HEB now has more representative and realistic scenarios. As a result, HEB's demand data is considerably more precise and closer to reality, and it can help with better informed decision-making.

4.1.3. Linking the QTDIAN toolbox to the DREEM model

Figure 6 shows how linking the QTDIAN toolbox to the DREEM model could improve our understanding of energy transition pathways if we incorporate qualitative and quantitative storylines into demand-side management modelling. In particular, quantitative data for the three social storylines of QTDIAN will be used as inputs to parameterise the DREEM model, which will be then used to simulate different pathways of the energy transition to 2050 in the residential sector in Greece. Simulations will take place for the different values of the storyline variables presented in Error! Not a valid bookmark self-reference. and will test a different mix of energy efficiency measures (in terms of deep renovation) and technologies for heating and cooling (i.e., natural gas boilers, heat pumps, air-conditioning units), based on the specifications of the national scenarios developed under WP7 (Stavrakas et al., 2021). Indicative final results will include final energy consumption per type of fuel, total energy savings due to renovation, total fuel savings due to renovation, tonnes of CO_2 avoided, economic benefits for households, implications for households from the extension of the emission trading scheme (ETS) to the residential sector for different feasible values of the carbon price, etc. For more information on the linkage between the QTDIAN toolbox and DREEM we refer to Süsser et al., (2021).

Table 2. Storyline variables and quantifications for linking the QTDIAN toolbox to the DREEM model for the case of the residential sector in Greece. Source: Süsser et al., (2021).

Storyline variables & values	People-powered	Government-directed	Market-driven
Building renovation (residential, floor space)	Deep renovation rate of 0.2% annually; medium renovation of 1.1%	Deep renovation rate of 2.1% annually, 0.9% medium renovation	Deep renovate rate of 3% annually
Total floor area of single- & multi-family dwellings	Single: 160792.9 mm^2 (2016) Multi: 212390.53 mm^2 (2016)	Single: increase by 0.2% annually Multi: increase by 0.09% annually	Single: increase by 0.4% annually Multi: increase by 0.2% annually
Private electricity consumption of appliances and lighting	Linear decrease as of today	Exponential decrease to meet the 2030 target	Constant

Source: Süsser et al. 2021

4.2. Linking energy demand to the "Economic impacts" module (WP5)

Demand for energy services tends to be aligned with the evolution of socio-economic indicators. Countries, at a more advanced development stage, are characterised for larger energy usage consequence of higher access to energy consumption technologies – including larger properties and a greater demand for heating and cooling, more appliances in households, and a higher number of vehicles being more often used (Toktarova et al., 2019).

The transition to climate neutrality will involve radical changes in the socio-economic structure of the European continent, with new industries and service categories being developed and high-carbon intense sectors being restructured (EU, 2018). These transformations will influence macroeconomic variables, which in general are used by EDMs for the quantification of demand drivers or service demand. Research conducted under WP5 aims to evaluate the (macro-)economic impacts of the

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

energy transition in the three SENTINEL case studies. This modelling exercise will be able to predict how GDP growth will deviate from baseline projections.

It is worth mentioning that energy demand and supply in the SENTINEL project are being modelled using a bottom-up approach, profiting from different highly sectoral disaggregated modelling tools within the consortium. This is a significant difference with top-down models that can straightforwardly and directly incorporate, in a closed loop, the effects of decarbonisation in GDP projections and how altered GDP projections can influence projections on energy demand. These tools, nonetheless, do not offer the technology and temporal (hourly) resolution that the SENTINEL models can provide, and which is required for a complete analysis of the energy system's transition to climate neutrality.

Given that different models are being integrated in a linear way and the level of sectoral disaggregation in bottom-up demand and supply modelling tools, the best way to account for changes in GDP growth rates is that the initial inputs from WP5 will be based on the so called "free run experiments"- defined in WP8- or literature figures for the modelling of future energy systems. These predicted GDP growth rates will be inserted to the SENTINEL EDMs, the outputs of which will feed the system design module (WP4), while the results of the latter will refeed the economic models (WP5). **Figure 7** presents the flow of linkage between WP3 and WP5. As it can be seen, both HEB and DESSTINEE use GDP growth forecast data as an input to calculate the final service demand and power profiles. Thus, using a dynamic GDP forecast minimises the risk of excluding future market uncertainties and hence, soft-linking with "Economic impacts" module (WP5) greatly benefits the SENTINEL EDMs in producing realistic demand profiles that can be then used by the system models.

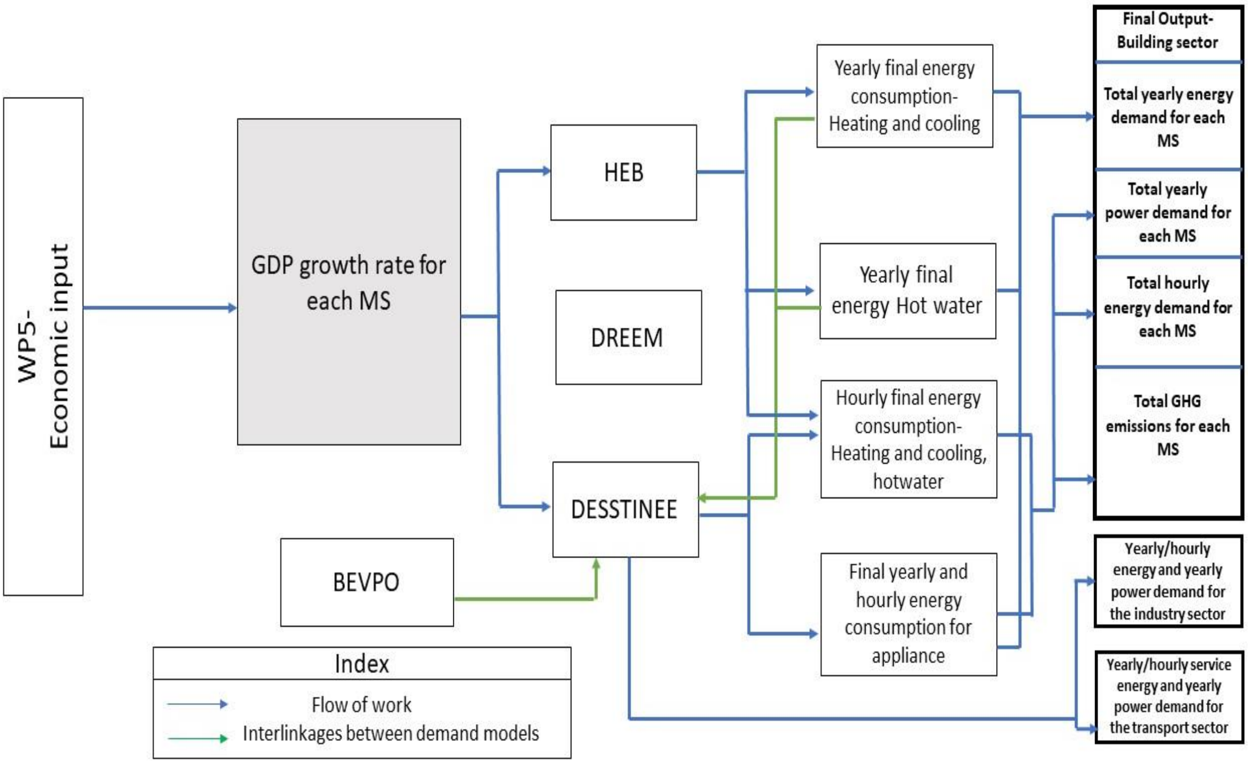


Figure 7. Linking the SENTINEL "Economic impacts" module (WP5) as input to the "Energy demand" module (WP3).

4.2.1. Linking the "Economic impacts" module (WP5) to the DESSTINEE model

Service demands for certain final energy uses are function of GDP trends; in DESSTINEE, in particular, those relate to the energy usage within buildings and the industrial sector. If DESSTINEE was to run in a "stand-alone" mode, without the inputs from HEB, trends in GDP per capita would influence the building occupancy rates in addition to the covered surface in households. Furthermore, consumption trends for appliances are nationally allocated on the basis of the evolution of country-level GDP evolution. In the case of industries, the evolution for the sectorial value added (or the share in total GDP) is correlated with the trends in the GDP per capita. Data supplied by the "Economic impacts" module (WP5) will be incorporated as main model inputs and DESSTINEE will automatically estimate the aforementioned demand drivers.

4.2.2. Linking the "Economic impacts" module (WP5) to the HEB model

Similar to the DESSTINEE, GDP in the HEB model is used as a key input to determine the growth of the non-residential floor area. More precisely, HEB has six different commercial and public building types, namely: educational, hotel & restaurant, hospital, other, retail, and office buildings. GDP forecasts are used as a proxy method to determine the total floor space area of commercial and public buildings. HEB model has geographical (according to weather conditions buildings could be located at urban or rural areas) and climate classifications (the climate classification is calculated based on heating degree days, cooling degree days, relative humidity, and hottest temperature of the month). The share of yearly GDP disaggregates according to these building locations and climate classifications to determine the urban and rural floor area of the commercial and public buildings.

4.2.3. Linking the "Economic impacts" module (WP5) to the DREEM model

In contrast to DESSTINEE and HEB, GDP is not an input in the DREEM model, since the model builds on existing census and survey data and established databases, e.g., the Tabula WebTool[2], etc., while specifications on the evolution of the building stock are taken each time based on official projections for the case under study. However, there is one linkage that could take place between DREEM and the "Economic impacts" module, and in particular between DREEM and the Business Strategy Assessment Model (BSAM), which is an agent-based model that simulates the operation of a central dispatch, wholesale electricity market (Kontochristopoulos et al. 2021).

In particular, BSAM simulates the day-ahead scheduling procedure of the wholesale electricity market considering technical constraints of generating units, market rules and agents' competition. Among the results of the simulations are the electricity mix, potential curtailment that occurs due to mismatch of generation and demand, and the resulting system marginal price, all in hourly resolution. Demand-side management capabilities, though, are not accounted for in BSAM. Thus, for the national SENTINEL case study (Greece), BSAM will be linked to DREEM to explore what is the potential of residential demand-response in reducing the curtailment resulting from high RES penetration in the Greek electricity system (**Figure 8**).

DREEM simulates demand-response mechanisms considering: **(i).** Hourly Electricity Prices and **(ii).** a central planner, who attempts to maximise flexibility value by issuing demand-response signals. The optimal demand-response signals dispatch (in terms of revenue maximisation) is learnt by the central planner via an optimisation approach based on Reinforcement Learning theory (Stavrakas & Flamos, 2020). The signals required by the central planner in order to "learn" the demand-response strategy include **(a).** the System Marginal Price (SMP), **(b).** the demand forecast for each household, and **(c).** the actual demand of each household.

BSAM outputs the SMP in an hourly resolution, without considering any demand-response signals. This is a situation with a typical demand forecast for each hour of the next day, a problem with which the system operator deals every day. With the SMP produced by BSAM as input, DREEM can simulate what could be the new demand timeseries, after demand-response signals have been sent to households. Then, a feedback loop is realised. The new demand timeseries can be fed anew to BSAM to simulate what could be the curtailment change that results from load-shifting.

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[2] https://webtool.building-typology.eu/#bm

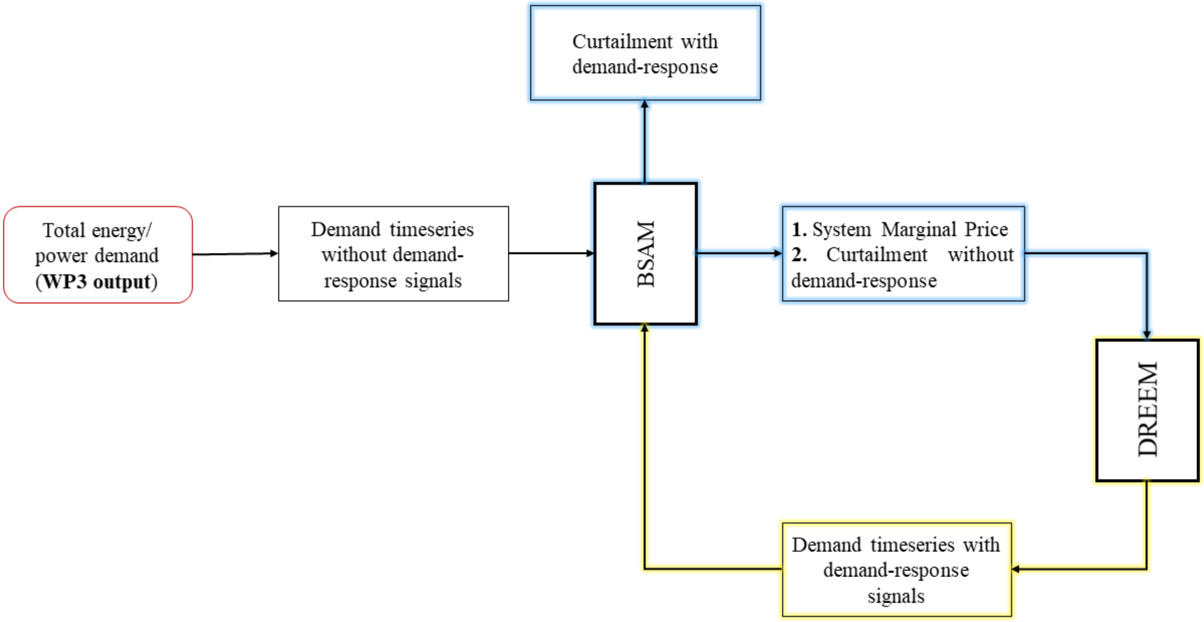

Figure 8. *Schematic description of the conceptual linkage of the BSAM model (WP5) to the DREEM model (WP3).*

4.3. Linking energy demand with the "System design" module (WP4)

Energy system models in SENTINEL will consider several types of inputs from the demand module (WP3). These tools will use both service demand and final energy consumption, at yearly and hourly resolutions, for the definition of the fuel basket for final energy uses and power supply, detailed as follows (**Figure 9**):

1. Yearly and hourly service demand for heating and cooling,
2. Yearly service demand for different categories of road transport vehicles,
3. Final energy consumption and fuel basket for aviation, navigation and rail,
4. Hourly power consumption for appliances.

The output of the "Energy demand" module (WP3) is used directly by the "System design" module (WP4) to provide evidence on EU's climate neutral pathways. These outputs from the demand module are produced by two of the demand models HEB and DESSTINEE. For instance, HEB provides both yearly and hourly service demand for heating and cooling the residential and non-residential building sector. To provide the hourly service energy demand profiles, HEB develops a new module to calculate hourly service demand. In HEB, the hourly demand is calculated based on ambient temperature data that has been collected for each climate zone and MS. This results in a dataset containing temperature data for 8,760 hours of the year in 28 geographical areas in Europe (EU-27 plus UK). Using this dataset, heating and cooling degree-hours are calculated first, based on an arbitrary chosen setpoint temperature. The set temperature is usually lower than the required indoor temperature both in case of heating and cooling, because additional energy is captured in buildings due to solar radiation and other factors (like internal heat gain of occupants and/ or appliances). This additional energy covers a certain part of the heating energy demand, thus resulting in a lower threshold for heating energy demand. Also, this implies an extra load for cooling systems in summer as the required temperature is set to a lower level. Based on the schedule and temperature factors, the heating and cooling profile values are calculated.

Similar to the HEB model, in the context of the research activities conducted within the SENTINEL project, the DESSTINEE model was updated to produce outputs for road transport sector – accounting for country-level travelled distance for passenger cars, vans, heavy duty units, and buses as well as associated fuel consumption on the basis of different fuel basket for each category. Such routine combines the inputs from the EU Reference Scenario (EU, 2021), outputs from QTDIAN and nationally adjusted continental fleets - as furtherly explained in D3.2. and in our upcoming publication (Oreggioni et al., 2021). A similar approach is considered for passenger and freight sub modes for aviation, navigation and rail. For the latter, hourly power generation profiles are also being simulated and provided to "System design" module (WP 4). Part of the model upgrades included a further disaggregation of the hourly power demand, which nowadays present results for different final uses within buildings – including power usage for heating, cooling, and appliances. The latter will also be supplied to WP 4.

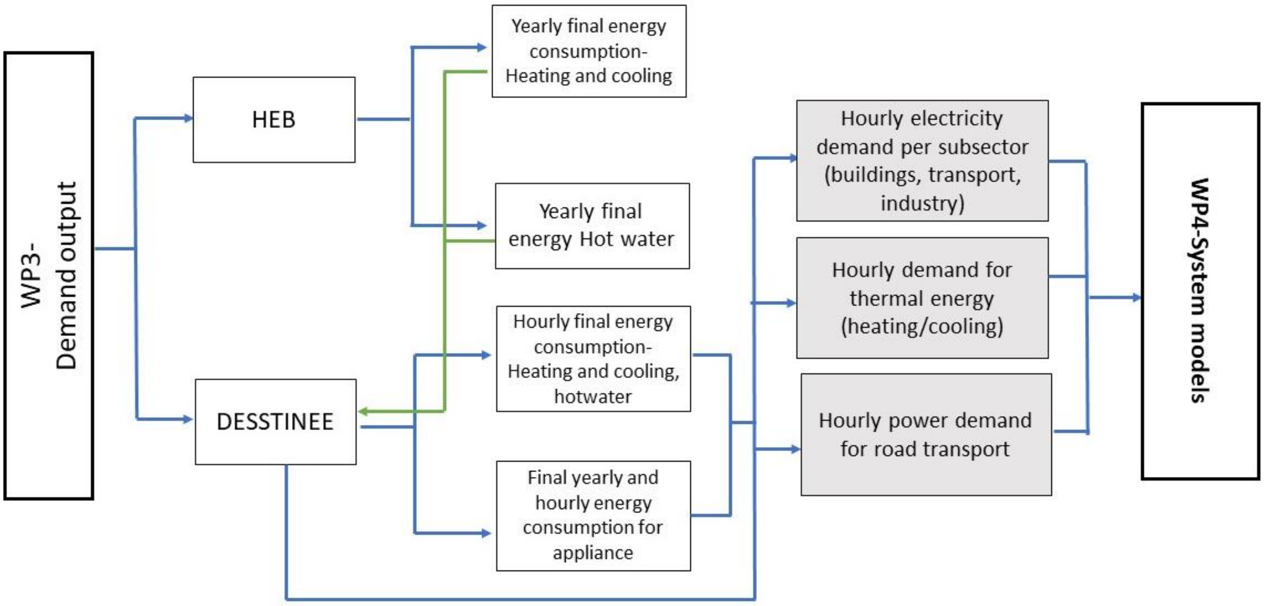

Figure 9. Conceptual framework of linking the outputs of the "Energy demand" module (WP3) to the "System design" module (WP4).

These four outputs from the demand models will be used to calculate the hourly energy balance under different scenarios, and as per the energy balance data, SENTINEL modelling exercises will be able to show the feasibility of climate neutrality target in the EU by 2050. Since demand profiles determine the size of the energy system, using demand profiles from the "Energy demand" module will enable exploring overall the sensitivity of the "System design" module's parameters. Furthermore, with the help of the demand profiles, the "System design" models can better perform a sensitivity analysis in terms of technology diffusion drivers. The system models precisely, EnergyPLAN, and Euro-Calliope models use the outputs from the demand models in the following ways.

4.3.1 Linking demand modules to EnergyPLAN

EnergyPLAN utilises annual demand in combination with hourly time series for the distribution of the demands. Thus, the linking from WP3 to EnergyPLAN will be the inclusion of aggregated heat demands provided as an output of HEB alongside, the hourly timeseries. The same will be done for the cooling demand and the associated time series for cooling. These will be used on the according geographical scale, depending on the case-study.

For electricity demand, the modelled annual demands will be used in EnergyPLAN alongside associated time series. EnergyPLAN allows for demands to be covered as residential and services, and industry demands. Furthermore, electricity demand can be included along side a time series data for this.

If potentially fuel demands in industries are included, EnergyPLAN can in the long run also accept annual industry demands.

In total, by applying the output demands and time series from WP3, EnergyPLAN can be used to design energy systems that can supply these demands. This includes complete decarbonised, sector coupled smart energy systems, with the utilisation of large amounts of renewable energy in combination with various energy storage solutions not limited to electricity storage, but also including thermal storage and fuel storages associated with district heating and power to x facilities.

4.3.2 Linking demand modules to Euro-Calliope

Hourly space heating, hot water and cooking demands are directly used in a nationally resolved Euro-Calliope to replace equivalent profiles that have been generated using the "When2Heat" simulation method (cite: 10.1038/s41597-019-0199-y & SENTINEL D4.2). The benefit of replacing these profiles is in their depiction of demands according to a change in the building stock by 2050. Indeed, the current method used in Euro-Calliope simulates today's demand only, so is scaled to existing demands for heat. For a 2030 or 2050 model year, it is instead necessary to depict expected changes in demand, both annually and sub-annually. In Euro-Calliope, these demands will be aggregated to space heat and hot water ("heat") and cooking heat energy carriers. For countries not included in the output of HEB, i.e., those in Europe, but neither an EU MS nor UK, , HEB-derived heat demands from neighbouring countries will be scaled according to the relative difference in today's heat demand between the country of interest and its neighbours. For instance, demand profiles for Norway will be the HEB-derived demand profiles for Sweden multiplied by the difference in annual heat demand between Norway and Sweden today.

Hourly appliance, cooling, and rail energy demand will be combined into a single end-use electricity demand profile for use in Euro-Calliope. In addition, electricity demand from industry will be scaled from those used in Euro-Calliope currently to an updated demand based on the projected change in productivity of industrial subsectors according to DESTINEE. Demand for road transport, in terms of distance travelled in a year by different vehicle types, and aviation and shipping, in terms of fuel demand, will be used to constrain annual demand in Euro-Calliope. Meeting energy demand on a sub-annual basis is a model output, based on the constraints currently applied in Euro-Calliope (see D4.2).

In total, outputs from the SENTINEL EDMs will provide a more representative depiction of energy demand across all sectors for 2030 and 2050. In turn, cost-optimal, decarbonised energy systems for Europe, derived from Euro-Calliope, will depict feasible systems for expected demand of the future, not just demand of today. Since energy demand today is conservative relative energy demand profiles projected for the future (we assume no end-use service demand reduction), we do not expect results from Euro-Calliope to differ qualitatively through implementing this change. Namely, the benefit of this exercise is to ensure comparability of Euro-Calliope results with those from the other models (i.e., EnergyPLAN, DESTINEE, and IMAGE) in the SENTINEL inter-comparison exercise under WP8.

5. Conclusions

The transition to net- zero emissions signal radical changes for the energy system, both in terms of the way that energy is both generated and consumed. Given the role of final energy uses, understanding the potential that different measures and technology incorporation may have on fuel consumption and associated GHG emissions is essential for efficiently supporting policymakers.

In this context, the SENTINEL "Energy demand" module (WP3) integrates four high-resolution sectoral models in addition to inputs from socioeconomic, political and behavioural analysis (WP2 and WP5) in view of increasing representativeness and detail for the quantification of final energy consumption. The soft-linking approaches between the different SENTINEL modules presented in this report provide a framework for understanding the full system impact of different measures and technology solutions. This unique framework enables to cover multidisciplinary aspects of the energy transition, which are of great relevance for model users and stakeholders. The presented linkages are currently being tested in the context of the three SENTINEL case studies (WP7) and are expected to provide valuable inputs for the design of comprehensive policies for decarbonising Europe.

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