SENTINEL

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Matching user-needs for energy demand modelling to achieve European energy transition

February 2021

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Executive summary:

Energy demand globally has been increasing over the last few decades and, in order to achieve climate neutrality in the EU by 2050, the demand for energy needs to be reduced without affecting the comfort of the citizens. Therefore, the role of energy efficiency measures and renewable energy use has become pivotal in energy science. However, designing policies related to the promotion of energy efficiency or usage of renewable energy depends immensely on the evidence/predictions for a set of scenarios up to a certain timeline that can be provided by the energy demand models. In other words, the findings of energy models can help in identifying the focus area of the policies. Thus, different sector-specific energy demand models can showcase the impact of different policy measures on final energy demand.

Since the policy-design in a way depends on the findings of energy demand models, we need to understand whether the demand models can incorporate all of the key parameters and needs of model users (such as policymakers, academicians, NGOs, etc.) into consideration while calculating final energy demand. Thus, to understand the different user needs, this study has used a three-tier methodological approach consisting of a focused literature review (conducted under SENTINEL Deliverables D3.1 and D1.2), an online survey and online interviews with different user groups, and lastly, stakeholder workshops. This three-tier methodological approach unfolds mainly two categories of user-needs: generic/transversal user-needs, and sector-specific user-needs. With the help of four different demand models used in SENTINEL, most of the user-needs are taken into account and this report discusses in detail how individual user-needs are getting addressed through demand models. Some of the user-needs (for example 'energy demand transition between 2030-2050' and 'role of renewable electricity to meet demand') can be addressed with the SENTINEL demand models without requiring any upgrades of the models. However, for some of the needs (such as 'onsite energy production (prosumer profile)' for the building sector, or 'fleet distribution' in the mobility sector) the respective demand models for each sector need some upgrades to address the needs. The objective of this report is to discuss each of the user-needs identified through our three-tier methodology and, further, to document how these needs can be incorporated when calculating final energy demand until 2050.

Lastly, this report discusses the next steps after incorporating the energy-needs and also defines a conceptual framework on how different demand models can come together to calculate the sector specific total energy demand which can be then used by the SENTINEL system design and supply modelling module in WP4.

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1. Introduction

Energy demand globally has increased rapidly over the last decade which resulted in almost double the consumption of the average consumption growth rate since 2010 (IEA 2019). The increase in demand for energy does not only include conventional energy sources, such as natural gas and oil, but also the demand for renewable sources, which is mostly about solar and wind with double-digit growth (IEA 2019). Although the demand for renewable energy sources has increased, renewable sources were not able to substitute the non-renewable energy sources. Consequently, energy-related CO_2 emissions have increased by 1.7% (IEA 2018). A similar trend can be observed for the EU Member States where the share of renewable energy sources has been increasing over the years and the share of renewable energy was almost 19% in 2019 (Eurostat 2020). Both the final and primary energy consumption has decreased in EU-27 over the last few years. For instance, the primary energy consumption has decreased by 1.3% in 2019 compared to 2018, and the final energy consumption has decreased by 0.5%[1] led by a 17% drop in consumption of solid fossil fuels (EEA 2020). This fossil fuel consumption is mostly substituted by renewable energy generation. This continuous decrease in energy consumption and increase in renewable energy share has reflected in GHG emission- more precisely, total EU GHG emissions have fallen by 17% since 2005[2]. However, as per the IPCC (2018) 1.5-degree special report, global emission needs to be reduced by 25-30 Gt CO_2e/year by 2030 in order to limit the temperature rise to within 1.5 degrees. Furthermore, in order to achieve climate neutrality in the EU by 2050, it is necessary to reduce energy demand along with increasing the usage of renewable energy generation with immediate effects. Therefore, the importance of policies on both energy efficiency and renewable energy use are required around the world and certainly in the EU to curb energy related GHG emissions. These policy designs depend on evidence/predictions that can be provided by energy demand models. The results of energy models can help in identifying the focus area of the policies. More precisely, energy demand modelling plays a crucial role in understanding the different pathways to manage demand and reduce GHG emissions.

As it is discussed in the SENTINEL D3.1 report, most of the energy models are often criticised based on the fact that they do not incorporate various social and economic factors that influence both the demand and supply sides of the energy system, and are not able to project energy demand and supply beyond a narrow planning period. Furthermore, most of the existing energy models are considered as 'black boxes' because assumptions and calculations of these models are unclear. Since the designing energy and climate policies in a way depend on the findings of energy demand models, we need to understand whether the demand models can incorporate all the key parameters and

[1] Final energy consumption by product database-Eurostat. Accessed on 1st February 2021.

[2] https://www.iea.org/reports/european-union-2020

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needs of model users (such as policymakers, academicians, or NGOs, etc.) into consideration while calculating the final energy demand and demand-related emissions. Some of these needs – such as modelling of lock-in effects, integration of renewable and energy-efficient measures, modelling of the human factor, and data scarcity – have been identified during D3.1. More such needs are identified in D1.1 and also through different stakeholders' workshops under WP7.

Therefore, the objective of this report is to document the user-needs relevant for energy demand modelling and also to discuss the process through which the demand models are going to address different user-needs. This report is organised into five sections. The first section introduces the concept and need of energy demand with the help of some key data trends and energy demand modelling. Section two discusses the different demand models used in SENTINEL WP3 to project future energy demand and demand-related emissions. In section three user needs are discussed in the context of energy demand modelling. Lastly, section four and five provide an overview of the methodological framework to address the existing gaps and user needs related to energy demand modelling, as identified from prior SENTINEL work .

2. Introduction to the SENTINEL energy demand modelling suite

As it can be seen from the demand trend data discussed in section 1, energy demand is going through radical changes. These changes are not only observable at the overall demand scale, but sector-specific demand is also changing. Both the building and transport sector have visible transformations in their demand patterns, which will further affect the shape of electricity dispatch patterns. Therefore, the demand work package of the SENTINEL project has four different sector specific models to capture this changing demand pattern in both the building and transport sector. Each of the four models is discussed in the sections below:

2.1 DESSTINEE

DESSTINEE (Demand for Energy Services, Supply and Transmission in EuropE) is a model of the European energy system in 2050. It is designed to test assumptions about the technical requirements for energy generation and transport, particularly for electricity, and the scale of the economic challenge to develop the necessary infrastructure. Forty countries are considered in Europe and North Africa and ten forms of primary and secondary energy.

DESSTINEE consists of three modules: a scenario generator, a demand profile builder, and an electricity market simulator. The scenario generator (Module 1) calculates annual energy demand

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by vector and sector at national level. It takes inputs for macro-economic variables (such as population and economic growth) and the sectorial technology penetration (such as improvements in building envelope, shares of heat pumps and electrification of the transport fleet) to estimate the 2050 annual demand for each energy carrier (coal, oil, natural gas, biofuels, electricity, etc.). Inputs for several predefined scenarios from literature (e.g. the IEA Energy Technology Perspectives, Global Energy Assessment, European Commission scenarios for the Paris Agreement and 1.5 degree) have been incorporated in the model.

The second module focuses on electricity. It produces future hourly power demand profiles – based on the annual electricity consumption – estimated by Module 1. Module 3 builds on the outputs of Module 2 by simulating the least-cost generation and transmission of electricity around the continent, grouping the European countries into ten nodes.

2.1.1. Yearly energy demand for final uses

DESSTINEE models energy demand, fuel consumption and associated fossil CO_2 emissions for several sectors and final uses, including:

1. Space heating, water heating and cooking, cooling and appliances for buildings,
2. Industry,
3. Agriculture,
4. Road transport,
5. Rail, navigation and aviation.

Future energy demand is quantified by considering the figures for each final use in the reference year and incremental coefficients accounting for key variables associated with each of these uses. Different data sources and assumptions are employed for the estimations, as described as follows.

2.1.1.Buildings

In DESSTINEE, the building sector comprises households and commercial/service facilities for which calculations are independently undertaken. For the reference year, modelers need to provide information for the fuel consumption (in residential and tertiary activities) and allocation coefficients for different final uses. Default values in DESSTINEE correspond to the fuel usage reported by IEA's national energy balances (IEA, 2017) for 2015 while disaggregation for each final use is conducted using the data reported by the ODYSSEE-MURE database (Enerdata, 2020).

On the basis of the user supplied or default data, DESSTINEE estimates the energy demand for each final use considering the fuel consumption and the efficiency of the technologies being operated by each fuel type. The user can provide these efficiencies as input or opt for the default values, which are based on literature review and survey with vendors. In the case of electricity for space heating and cooling purposes, the modeler should also supply data for the penetration and coefficient of performance for heat pumps or consider using the parameters already in Module 1.

2.1.1.1. Heating and cooling

The projection of energy demand for space and water heating and cooling is a function of: changes in building covered area, heating and cooling degree days, building envelope efficiency, and defined thermal comfort indices. Some of these indicators are automatically calculated by DESSTINEE on the basis of the values supplied for the reference year while others will be intrinsically function of the scenario being modelled.

The increase in the building covered area for the residential sector is consequence of the trends for the number of households and their surface. The number of households vary according to population increase and the number of people per household, which is a function of the GDP per capita alike the evolution of household surface. These mathematical relationships have been programmed in the DESSTINEE's VBA code, requiring user defined inputs such as: the population in the reference year and in the time horizon being simulated; the trends in GDP per capita; and the number of households in the reference year. Default values for these variables are based on the UN population statistics and projections (UN, 2019), the 2018 Ageing report (EU, 2018a) and the household area from ODYSSEE (Enerdata, 2020) for 2015. In the case of commercial buildings, the trends for covered area follow the changes for the value added for the tertiary sector. User defined inputs are the value added and the surface occupied by commercial buildings during the reference year. Default values for 2015 were calculated considering the share of GDP related to the value added of the service sector (WB, 2020 a) and the total GDP reported by the World Bank (WB, 2020b). Data from ODYSSEE was also used for the building area in 2015. DESSTINEE estimates the future value added for the service sector, using functions that correlate it with the GDP per capita, and assuming that each building produces a 67% larger income per surface unit (literature review, survey and direct communication with IEA).

The building envelope efficiency is another modeler defined parameter and it relates to the energy losses in the buildings. Users can opt for the default values, calibrated to fulfil the emission reduction targets for different decarbonisation scenarios, or for using their own assumptions. Future heating and cooling degree days are calculated employing the data for the reference year, default in DESSTINEE or uploaded by the modeler, and a linear variation over time.

Trends for the heating and cooling indices are based on the increase of GDP per capita and the evolution for heating and cooling degree days, following the functions presented by Isaac and Van

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Vuuren (Isaac and Van Vuuren, 2009). Future energy demand for water heating and cooking is forecasted on the basis of: the values for the reference year, the population increase, and the "hot water index". The latter is estimated in DESSTINEE using a linear relationship with the changes in the GDP per capita.

According to the scenario being modelled, users can define: the future fuel basket for heating, the efficiency for heat production associated with each fuel, and the penetration of heat pumps and their performance coefficients. Predefined values for these indicators from different decarbonisation scenarios are also available in DESSTINEE Module 1. These inputs allow the estimation of total and fuel disaggregated final energy consumption.

2.1.1.2. Appliances and lighting

DESSTINEE can also quantify future power demand for appliances and lighting on the basis of the reference year and an appliance index, which accounts for the increase in the number of devices and their associated efficiency. The appliance index is another user defined input, linked to household or service income and the improvement of device performances. Default values for this parameter, corresponding to different decarbonisation scenarios, are also available in DESSTINEE Module 1.

2.1.2. Industry and agriculture

DESSTINEE quantifies final energy demand in the secondary sector, distinguishing between "Light" and "Heavy" Industries. "Light Industries" mostly comprise the manufacture of: food and tobacco; paper and pulp; wood and wood products; textile and leather; and the construction sector related activities. The production of metals, chemicals and non-metallic goods (such as cement and lime) are grouped under the umbrella of "Heavy Industries". For the latter, a specially tailored routine has been developed taking account of the trends in demand – using data from the EU Reference 2016 (EU, 2016) – and nationally tailored efficiency and fuel basket trends, on the basis of EU wide different decarbonisation scenarios. Average default values and changes in the fuel matrix are also incorporated for light industries using the data in the afore mentioned sources. Default values for the reference year rely on the IEA national energy balances (IEA. 2017) and sectorial value added from the World Bank database for 2015 (WB, 2020a). Modelers can opt for employing the routine with its default values or else they could run DESSTINEE considering their own values for the reference year and projections for future demand and specific energy consumption.

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Energy usage for the agriculture sector is forecasted, in DESSTINEE, based on the evolution of the value added for the agriculture sector and assumptions regarding fuel matrices. As default, balances from IEA and data from World Bank, for 2015, are considered as reference. Trends for the fuel basket, already incorporated in Module 1, come from EU wide decarbonisation scenarios while the evolution of the value added is modelled by employing functions that correlate the shares of value added in total GDP – for the different economic sectors – with the GDP per capita

2.1.3. Road transport

Future energy demand and consumption for road transport can be quantified considering the projected energy usage for passenger and freight modes. Passenger cars and buses are grouped as part of the Passenger mode subcategory while light and heavy-duty vehicles for the transportation of goods are included in the Freight mode subcategory.

The future energy demand for both modes in DESSTINEE is modelled accounting for: the energy demand for the reference year; the increase in transport demand; and the changes in efficiency. Energy demand for each mode, during the reference year, is automatically calculated on the basis of: the total fuel consumption for the sector; the travel demand for the passenger and freight mode; and associated efficiencies. Default fuel usage within this sector was obtained from the IEA national energy balances (IEA, 2017) whilst data for transport demand and efficiencies, in 2015, came from the EU Baseline Scenario 2016 (EU, 2016).

Future transport demand and efficiency for each mode will depend on the scenario being considered along with the fuel basket. The default efficiency values for each transport mode, associated with the EU 'Baseline' and the '1.5TECH' scenarios (EU, 2018b), were calculated by accounting for: the changes in the fuel disaggregation of the fleet; the future fuel economy per vehicle type; assumptions for vehicle capacity; and national projections for transport demand. Changes in fuel distribution for every vehicle category were based on adapting the information presented, at EU level, by the afore mentioned scenarios into national circumstances. In terms of fleet efficiency, full implementation of the EU Post 2030 standards for fuel per travelled distance (EU, 2019) was assumed when modelling the 2050 time horizon. Default national transport demand was estimated using a mathematical relationship with GDP, adjusting the obtained results to meet the total EU level increase predicted by the scenarios. Total consumption for each fuel type within the road transport sector was obtained by summing up the fuel usage for each vehicle category. The shares in the fuel basket were then calculated as the ratio between the total consumption for each fuel and the total consumption for all fuels.

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2.1.4. Rail transport, navigation, and aviation

Future energy demand and associated fuel consumption for rail transport, navigation and aviation can be quantified on the basis of the estimated future values for passenger and freight modes, following an analogous methodology to the road transport sector. Users need to provide the travel demand and efficiency for both modes, within the different subcategories, in addition to information for trends in the fuel baskets. Default data in DESSTINEE was defined considering: the energy statistics from IEA (IEA, 2017) for 2015; the transport demand from the EU Reference Scenario 2016 (EU, 2016) for the passenger modes for rail, navigation, and aviation; and the World Bank statistics for maritime and air freight transport (WB, 2020c and WB, 2020d). Default values for passenger navigation only include domestic trips while freight accounts for both international and domestic services. In the case of aviation, passenger and freight comprise domestic and international flights. Default demand and efficiency trends, implemented in DESSTINEE for the EU Baseline and the 1.5TECH scenarios, are based on an aggregated sectorial value for passenger and freight air transport.

2.1.5. Hourly profiles for electricity

DESSTINEE's Module 2 can be run to generate hourly profiles for electricity demand using the annual figures estimated by Module 1. For the residential sector, the hourly distributions for power consumption reported by DEFRA (DEFRA, 2012) were considered. These profiles report measured data for households in the UK, distinguishing between different types of appliances and space and water heating. In the case of office buildings, it was decided to develop the hourly profiles for power consumption, for the different final uses, considering the trends in Birmingham.

A flat 24/7 profile for Heavy industries was assumed whilst a 9 to 5 distribution was considered for Light Industries, mirroring the commercial pattern. For electric cars, the charging profile proposed by NERL (NERL, 2011) was used for the hourly distribution of power consumption. Three charging modes were taken into account: fully home charging, alternate home and work, and least-cost charging via the utility directly controlling chargers. Seasonal and hourly distribution for consumed power, by rail passenger, was built using the data from Ireland and for the UK - obtained through personal communication. Freight rail profiles were developed by assuming that these kind of trains were run to avoid conflict with passenger services so there were slightly more services at night rather than at peak times.

For more information about the model's key specifications, assumptions and uncertainties, and a list of the main inputs and outputs see **Appendix A. DESSTINEE**.

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2.2 DREEM

The **D**ynamic high-**R**esolution d**E**mand-sid**E** **M**anagement (DREEM) model 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 to assess the benefits and limitations of demand-flexibility, primarily for consumers as well as for other power actors involved (Stavrakas, and 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 - and modular - based system 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" (**Figure 1**) (Pereverza et al. 2019) . 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. It also provides the ability to incorporate future technological breakthroughs in a detailed manner, such as the inclusion of heat pumps or electric vehicles, in view of energy transitions envisioning the full electrification of the heating and transport sectors. The latter makes the DREEM model competitive compared to other models in the field, since scientific literature acknowledges that there are limitations to how much technological detail can be incorporated without running into computational and other difficulties (Nikas et al. 2017). The model also supports the capability of producing output for a group of buildings and could also serve as a basis for modelling domestic energy demand within the broader field of urban, national, or regional energy systems analysis.

All the modules of the models were developed using the "Buildings" library, which is an open-source, freely available Modelica library for building energy and control systems (Wetter 2011). Modelica is an equation-based, object-oriented modelling language for the simulation of dynamic systems, and has been used in several studies and applications for the design and the simulation of various BES and control systems (Wetter 2009; Zuo et al. 2016; Wetter et al. 2016; Bunning et al. 2017). Alongside to the Modelica models, Python scripts have been developed to model parts of the Demand-Response and control components, and to enable the interface with the Dymola simulation environment.

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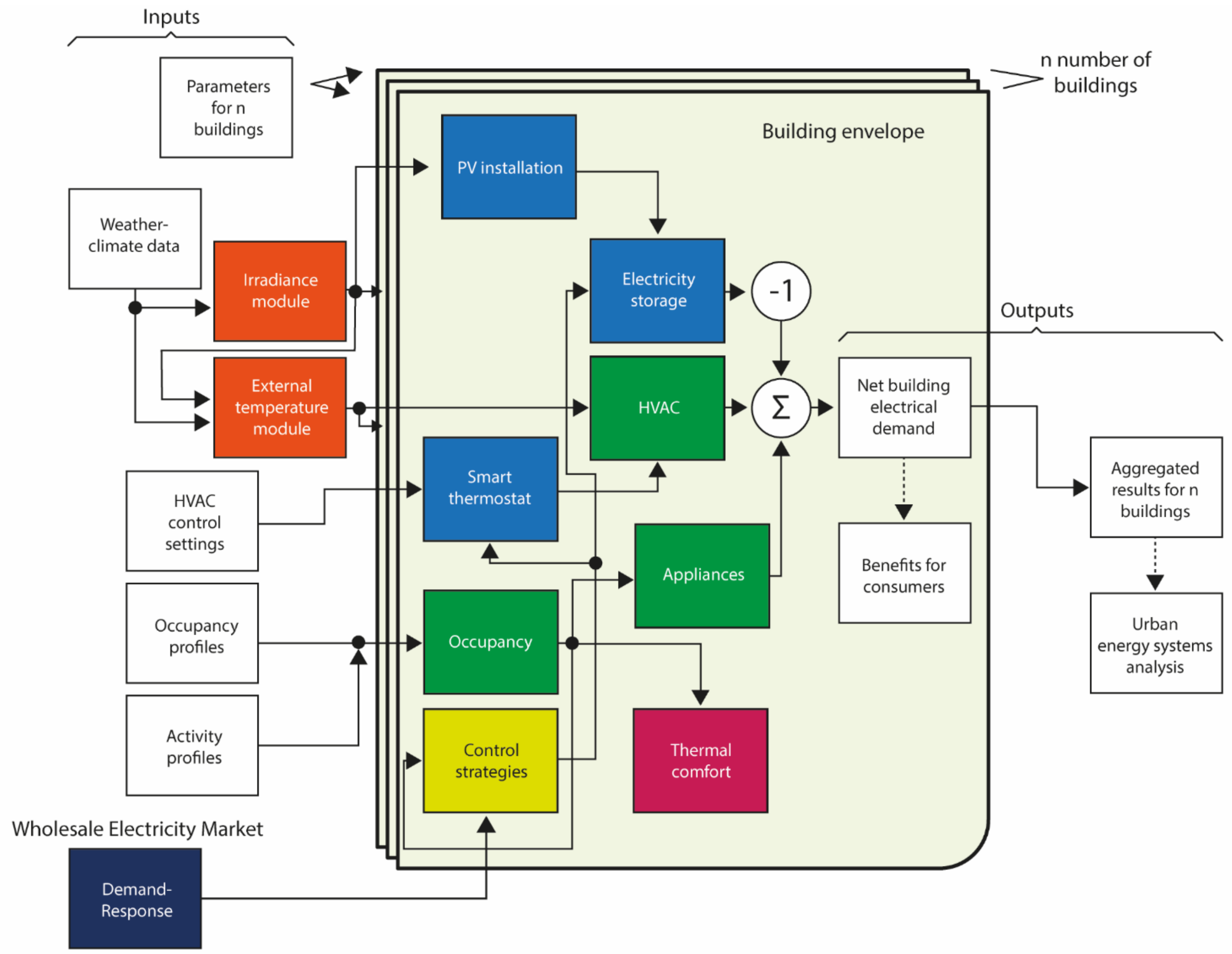

Figure 1. The DREEM model's architecture as it currently stands. Source: Stavrakas and Flamos (2020)

For more information about the model's key specifications, assumptions and uncertainties, and a list of the main inputs and outputs see **Appendix B. DREEM**.

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2.3 BEVPO

The Battery Electric Vehicle Policy (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.

We are given the arithmetic mean of hourly travel time measurements between different zones of a city (Fig 2a) and want to estimate the traffic flow and spatial parking distribution of cars in that city. In a first stage, we estimate the probabilities of car traffic between zones as a function o mean travel time (Fig. 2b). These probabilities exploit the changes in mean travel time between the zones of the city throughout a day to approximate information about when cars would drive and where they would drive to. In a second stage, we sample individual car traffic from these probability distributions and determine the number of cars that are parked in a zone as a function of cars flowing in and out from that zone (Fig. 2c). In a third and last stage, we use validation results to tune the parameters of the probability distributions that we sample from (Fig. 2d). For each model parameter or each set of model parameters that we can freely choose, a set point value is used to make a good choice. A set point value can for instance be the evaluation error between sampled and measured parking densities and traffic activity, or the average number of trips and travel distances.

The Uber Movement project provides statistical data about travel times between different zones of a city. Currently, data is available for more than 50 cities worldwide with one second resolution. The data distinguishes between each quarter of several years. Depending on the city of interest, data is available from the years 2015 until 2021. The sparsity of the datasets plays an important role for the performance of BEVPO. These sparsities depend on the number of Uber users in the provided cities and the provided time periods. Measurements are only given between zones and at times, in which a sufficient amount of Uber rides were undertaken, so as to ensure a sufficiently good representation of overall traffic. Therefore, OD travel time matrices should ideally be retrieved from other sources such as local traffic departments of cities or global scale applications like Google Maps.

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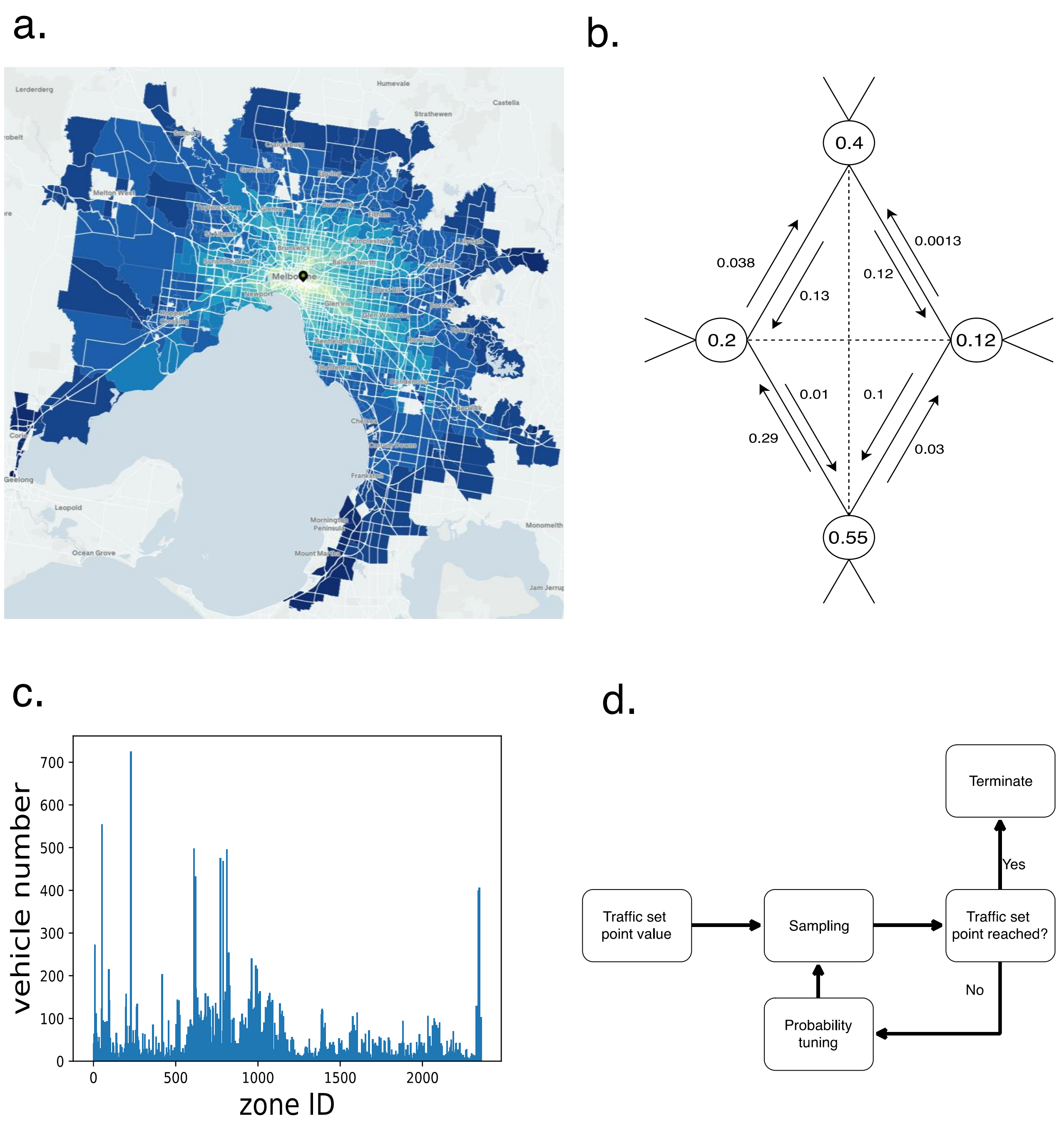

Figure 2: The arithmetic mean of hourly travel time, probabilities of car traffic, and car parking zones of different zones of a city

For more information about the model's key specifications, assumptions and uncertainties, and a list of the main inputs and outputs see **Appendix C. BEPVO**.

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2.4 HEB

The HEB (High Efficiency Buildings) model calculates energy demand and CO_2 emissions of the residential and tertiary building sector until 2050 under three different scenarios to investigate the potential of the building sector to mitigate climate change through various opportunities. This model is novel in its methodology as compared to earlier global energy analyses and reflects the emerging new paradigm – the performance-oriented approach to buildings energy analysis. The elaborated model is in the framework of the bottom-up approach, as it includes rather detailed technological information for one sector of economy. However, it also benefits from certain macroeconomic and sociodemographic data which include population, urbanisation rate, and floor area per capita. The key output of the HEB model consists of floor area projection for different types of residential and tertiary buildings in different regions and Member States, total energy consumption of residential and tertiary buildings, energy consumption for heating and cooling, energy consumption for hot water energy, total CO_2 emission, CO_2 emission for heating and cooling, and CO_2 emission for hot water energy. The end use demand and its corresponding emission are produced until 2050 at a yearly resolution for 12 key regions which cover the world and 28 member states.

The HEB model uses three different scenarios to understand energy use dynamics and to explore the potential of the building sector to mitigate climate change through various opportunities. The three scenarios of the HEB model are described briefly in the following paragraph:

1. Deep Efficiency Scenario: Deep efficiency scenario demonstrates the potential of state-of-the-art construction and retrofit technologies that can substantially reduce energy consumption of the building sector and hence reduce CO_2 emissions as well, while also providing full thermal comfort in buildings. In this scenario, exemplary building practices are implemented worldwide for both new and renovated buildings.
2. Moderate Efficiency Scenario: Moderate scenario incorporates present policy initiatives, particularly implementation of Energy Building Performance Directive (EPBD) in the EU and building codes for new buildings in other regions.
3. Frozen Efficiency Scenario: This scenario assumes that the energy performance of new and retrofit buildings do not improve as the baseline and retrofit buildings consume around 10% less than standard existing buildings for space heating and cooling, while most new buildings have a higher level of energy performance than in moderate scenario due to lower compliance with Building Codes.

The HEB model conducts scenario analysis for the entire building sector where the building sector is distinguished by their location (namely rural, urban, and slum), building type (namely single-family, multifamily, commercial, and public buildings with subcategories), and building vintages (namely existing, new, advanced new, retrofit, advanced retrofit). These detailed classifications of buildings are conducted for 11 regions and EU-27 countries, furthermore, within each region different climate zones are considered to capture the difference in building energy use and renewable energy generation caused by climate variations. The climate zones are calculated based on four key climatic factors, namely: heating degree days (HDD), cooling degree days (CDD), relative humidity of the warmest month (RH), and average temperature of the warmest month (T). These parameters are processed by means of GIS5 tool - spatial analysis – and performed with ArcGIS 9.3 software. Figure 3 below shows the calculation steps of the HEB model:

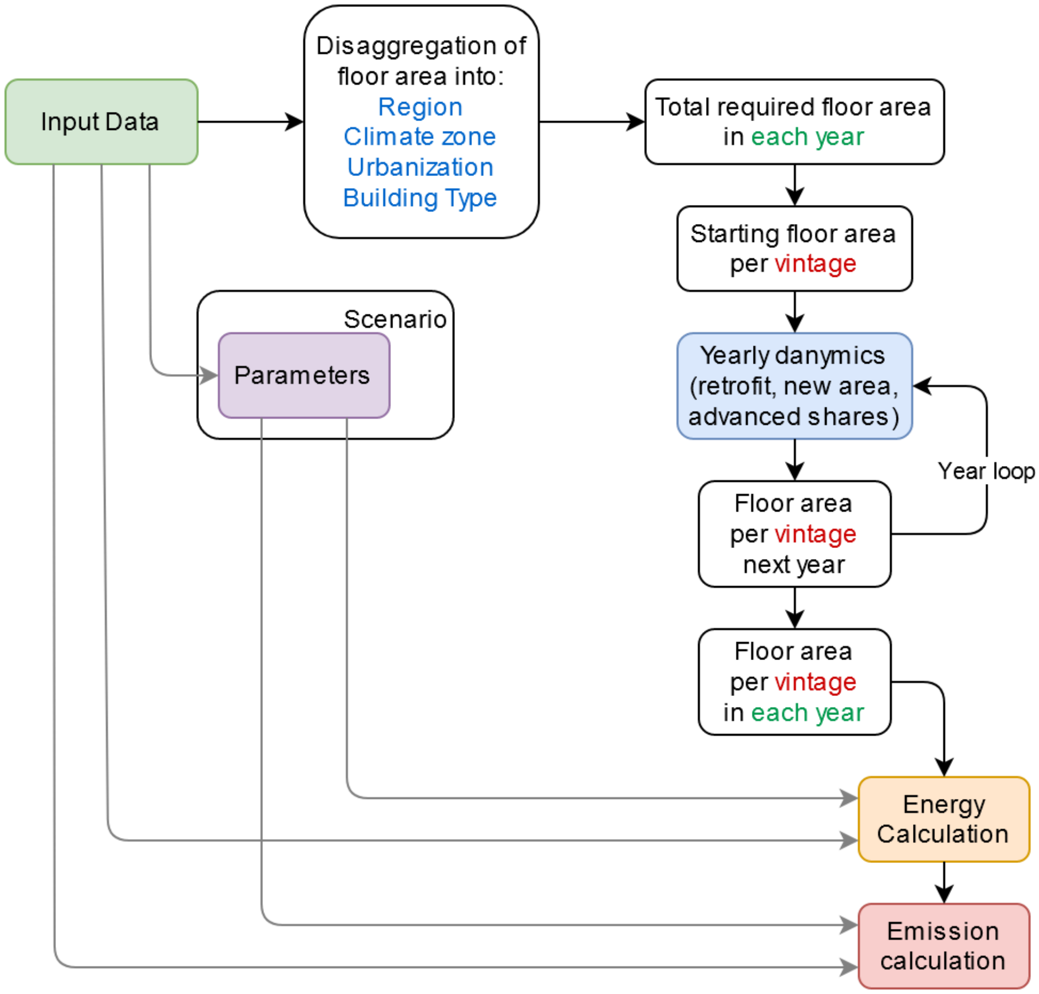

Figure 3: Calculation steps followed in HEB model

The purpose of the detail classifications of building categories and scenario assessments are to explore the consequences of certain policy directions/decisions to inform policymaking. The primary aim of this model is to illustrate the potential of the building sector to achieve ambitious climate change mitigation goals.

The HEB model is developed in MS Access database by using VBA macro coding to calculate various large data sets. Due to VBA MS Access coding this model is not an open access model.

For more information about the model's key specifications, assumptions and uncertainties, and a list of the main inputs and outputs see **Appendix D. HEB**.

3. Knowledge gaps and user needs in energy demand modelling

Energy policies and energy-related GHG mitigation pathways are often incorporated into energy models to estimate the potential outcome of the policies. As discussed in section 1, energy models are used by different users and, thus, the use of energy models, especially energy demand models, varies across different groups. As per the usage, different users have a different set of needs which they want to see in an energy model. Therefore, in the SENTINEL project, all kinds of needs of different users are identified and, accordingly, the SENTINEL energy system models will be upgraded to address these various needs. These user-needs can also be considered as key gaps in energy modelling and, thus, upgrading the SENTINEL models as per these needs would contribute immensely to the science of energy modelling by producing more accurate outputs related to the pathways achieving a European zero-carbon energy system by 2050.

This report presents all the user-needs related to energy demand modelling and this section first presents the methodology of identifying user-needs, while it defines various user-needs that can change the future demand pattern.

3.1 Methodology of identifying the user-needs

To understand and identify the different user-needs we have used a three-tier methodological approach. In the first tier of the methodology, we have conducted a focused literature review to identify the specific knowledge gaps related to energy demand modelling under the SENTINEL D3.1. In the second tier of the methodology, various online interviews and an online EU-wide survey were conducted under the SENTINEL D1.2 where different stakeholders have expressed their needs. Lastly, in the third tier of our methodological approach, the SENTINEL WP3 team has participated in 3 thematic workshops where the consortium directly interacted with various stakeholders to understand and identify different aspects of the demand side that should be considered in the modelling work. Figure 4 summarises the methodological framework applied in this report.

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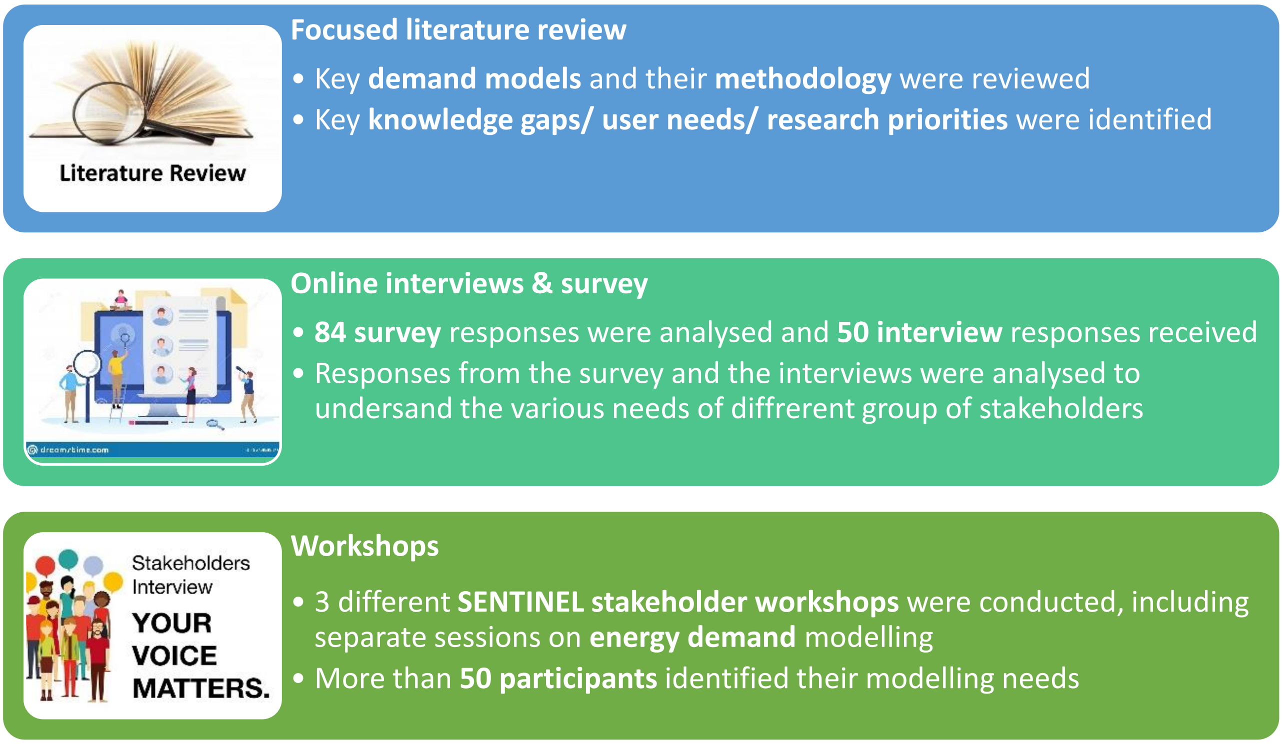

Figure 4: Methodological framework used to identify user needs

To understand the various knowledge gaps/ user needs/ research priorities in the field of energy demand modelling, we based our work on previous insights and findings, namely:

a) **Focused literature review:** Under the SENTINEL Tasks 1.2 and 3.1, a thorough literature review has been conducted to understand key knowledge gaps in energy demand modelling. Further, in D3.1, to gather information about sector-specific demand models, a 'call for evidence' was circulated among the energy community to collect information about both published and unpublished (grey literature) models related to the building and transport sector. From this evidence list, around 25 sector-specific demand models were reviewed to understand the scope of improvement in calculating energy demand for a specific time period. Apart from 'call for evidence', the literature reviews in both tasks 1.2 and 3.1 were conducted by reviewing energy-related peer-review journals found in the scientific databases such as 'Science Direct', 'Google Scholar' and online database of CEU library. More information is presented in the SENTINEL Deliverables D1.2 (refer to Gaschnig et al., 2020) and D3.1 (refer to Chatterjee and Urge-Vorsatz, 2020).

b) **Online interviews and survey:** Under Task 1.1, 32 qualitative interviews from all relevant stakeholder groups in five jurisdictions within Europe (the EU as a whole, Germany, Greece, Poland, and Sweden) representing various geographical, political, and cultural backgrounds, were conducted to receive in-depth insights into arguments and reasons for different stakeholders' modelling demands. More information is presented in the SENTINEL Deliverable D1.1 (Lilliestam et al. 2020).

Under Task 7.1 and the national case study, 18 additional interviews in the format of online meetings and small group sessions with key stakeholders and experts from the Greek energy system were conducted to identify specific contextualised knowledge gaps, user needs, and research priorities. More information is presented in the SENTINEL Deliverable D7.1 (refer to Stavrakas et al. 2021).

Furthermore, under Task 1.2, an online survey was conducted to gain data for statistical analysis and study the urgency of possible current user needs of energy models by different stakeholder groups. The survey addressed the same four stakeholder groups as the interviews, and was distributed among national, European, and international organisations and representatives of politics, civil society, economy/ industry, and science. The 84 respondents that completed the survey can be characterised as energy experts with model experience from across Europe interested in the European energy transition and using models for decision-making in various sectors. More information is presented in the SENTINEL Deliverable D1.2.

c) **Workshops:** Finally, under Task 1.2, a European expert workshop to discuss energy modelling expectations for the European energy transition. was organised. Due to the COVID-19 situation, this was implemented in online format. The workshop's objective was to discuss, verify, and prioritise findings in face-to-face interactions between different stakeholder groups. For example, about conflicting needs (trade-offs) extracted from data collected within previous methods, as well as to receive specific requirements for the development of SENTINEL models and their thematic focus. 26 invitees from the primary SENTINEL stakeholder groups with a background in modelling participated in the workshop. More information is presented in the SENTINEL Deliverable D1.2.

In addition, under Task 7.1 and the regional and continental case studies, two additional workshops with thematic break-out sessions were organised. These were to identify specific contextualised knowledge gaps, user needs, and research priorities for the Nordic and the European case studies, to be answered by the SENTINEL modelling suite, in alignment with the targets set by the most updated policy documents. 35 invitees from the primary SENTINEL stakeholder groups with a background in modelling participated in the workshop. More information is presented in the SENTINEL Deliverable D7.1.

3.2 Identifying the user-needs

Based on the literature review, the online survey, the interviews, and the stakeholder workshops, two categories of user-needs have been identified for energy demand modelling. The two categories are namely generic/transversal user-needs and sector-specific user-needs. The generic user-needs

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are those needs that apply to all the energy demand models despite their methodology, objective, or research question. These generic user-needs are identified and validated with literature, interviews, and workshop responses, to ensure that incorporating these needs would contribute significantly in generating more precise estimates of energy demand profiles. Unlike the generic user-needs, the sector-specific user-needs are only valid of demand models aiming at a particular sector. For instance, some of the user-needs such as the 'potential for heating and cooling' or 'digitalisation of buildings' are only valid for the building sector energy demand models, and hence demand models concerning the building sector would only be relevant for them. In SENTINEL, there are three main sectors considered (namely buildings, mobility/transport, and industry) for which the demand profile will be calculated. Thus, sector-specific user-needs are identified for all these three sectors. Similar to the generic user-needs, sector-specific user-needs are also identified and validated with literature, interview and workshop responses. In the section below, each category of user-needs is discussed.

3.2.1 General/ transversal user needs

1. **Energy demand transition between 2030-2050**

The transition towards a climate-neutral society is an absolute necessity in order to limit the global temperature rise within 1.5 degrees. The EU aims to be climate-neutral by 2050 for which demand for fossil fuels such as coal, gas, and oil, needs to be reduced by 80% by 2050[3]. Therefore, it is important to understand how the sector-specific reduction of demand in the EU can contribute to the transition towards a climate-neutral society by using different energy demand models. Most of the energy demand models project/forecast data until 2050. However, to understand the demand pattern in 2050, understanding the demand pattern for the next 10 years will be pivotal, especially by realising different emission reduction pathways. Hence, modelling demand for 2030 is as important as 2050 (IEA 2020). For instance, in order to be climate neutral by 2050, the European Commission has proposed to reduce the emission by at least 40% by 2030[4] which would shape the pathway to achieve climate neutrality in the EU by 2050.

2. **Role of renewable electricity to meet demand**

Renewable energy sources (which include energy sources from solar, wind, tide, and geothermal) play a pivotal role in reducing energy-related GHG emissions. As per the EU renewable energy directive, by 2030, 32% of the energy supply must be met by energy generated from renewable

[3] https://www.mckinsey.com/business-functions/sustainability/our-insights/how-the-european-union-could-achieve-net-zero-emissions-at-net-zero-cost

[4] https://ec.europa.eu/clima/policies/strategies/2030_en

energy sources (European Commission 2018). Furthermore, the directive prescribes to all EU countries to generate at least 20% of their total energy needs with renewable energy by 2020. Figure 5 below presents the trend of the overall share of energy from renewable sources in EU28.

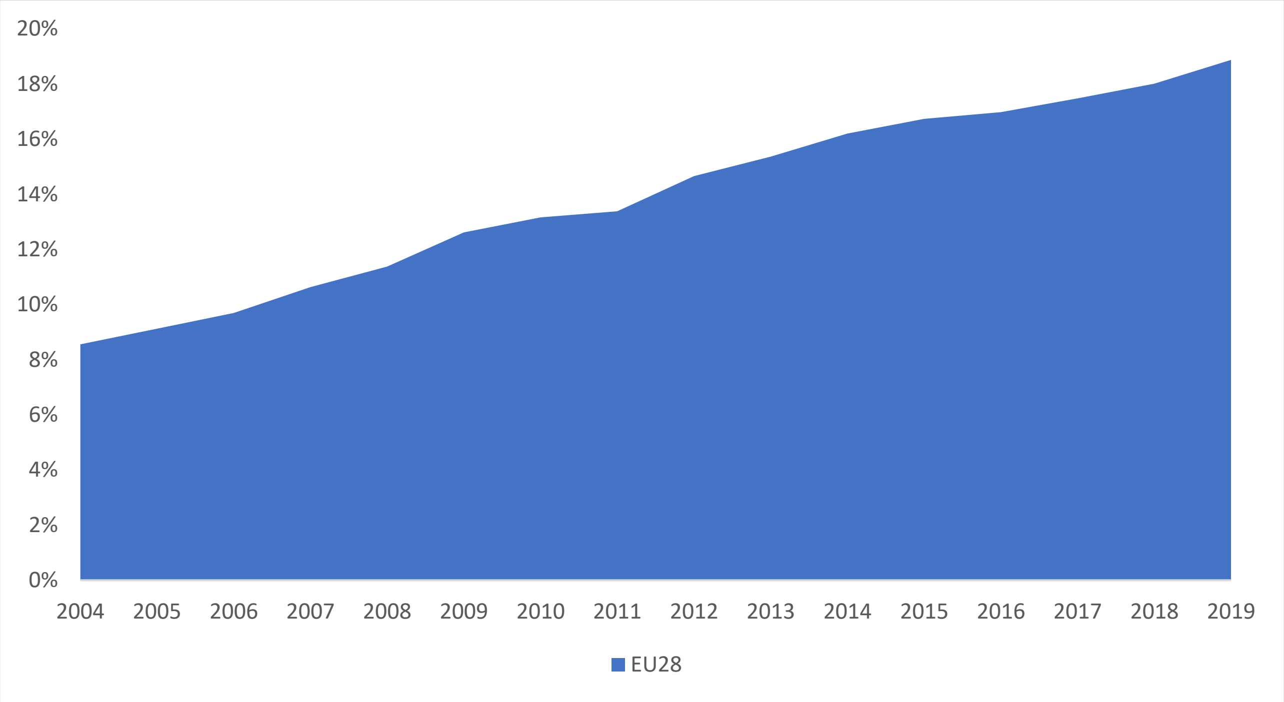

Figure 5: Overall share of energy from renewable sources with IN EU28, 2004-2019 (%). Data source: Short Assessment of Renewable Energy Sources 2019 database, Eurostat

Figure 5 clearly shows an increasing share of renewable energy production over the years until 2019. This increasing trend of renewable share further shows the importance of modelling different renewable energy options to reduce GHG emissions and to achieve climate neutrality. Within the renewable energy share, different sources of renewable energy need to be incorporated in the model. Figure 6 below presents the trends of different renewable energy sources used in the EU:

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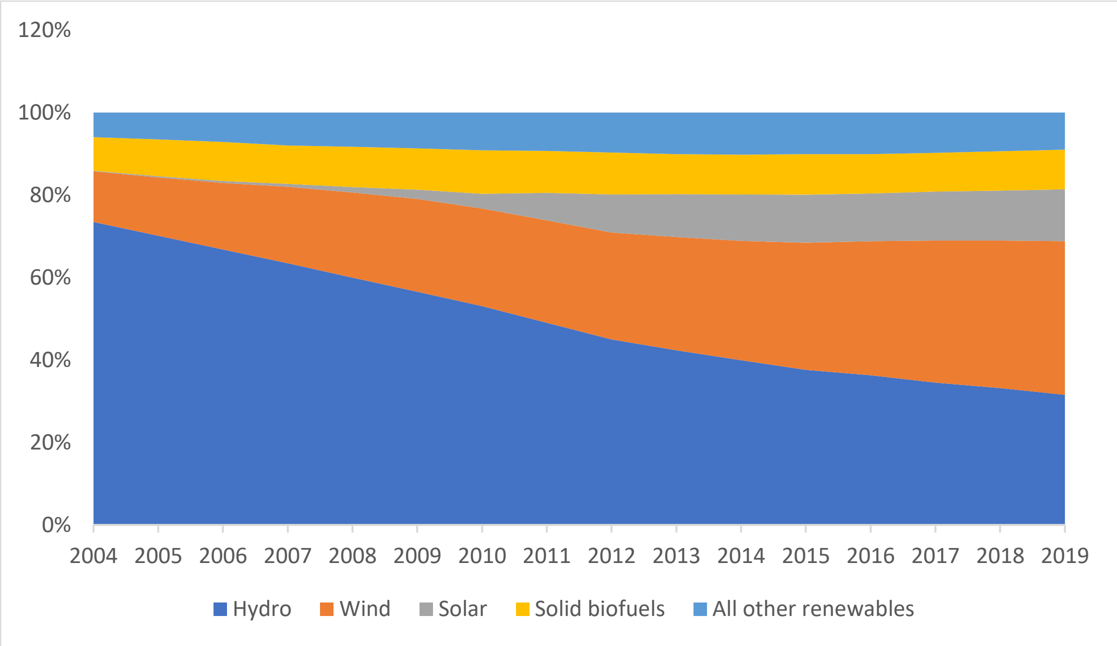

Figure 6: Share of different renewable energy sources among total renewable energy produced in EU. Data source: Short Assessment of Renewable Energy Sources 2019 database, Eurostat

The data reported in the 'Short Assessment of Renewable Energy Sources' (SHARES) database clearly indicate the increasing trend of wind and solar sources to generate energy. More precisely, among the renewable sources, solar and wind together have a 50% share, meaning 50% of renewable energy was produced from these two sources in 2019. The share of wind and solar has been steadily increasing in the EU since 2010. Until 2016, hydro sources used to be the largest renewable source, but since 2007 onwards the share of hydro sources has been steadily declining, and it was reported to be 32% in 2019. Thus, modelling of different renewable energy sources needs to be as precise as possible in order to understand whether it is possible to achieve the EU renewable energy target, and hence the EU climate neutral objective, by 2050.

3. Incorporation of green and e-gases

The incorporation of green and e-gases is key to fulfil emission reduction targets, especially in those scenarios that aim for stricter emission caps (EU, 2018b). Green gases include biogas and biomethane – mostly obtained through anaerobic digestion of organic waste streams – and H_2 – from biomass and waste gasification or steam methane reforming processes (IEA, 2019 and IEA, 2020a). E-gases or power to gases (P2G) are fuels being produced via H_2 from water electrolysis using renewable electricity (Staffell et al., 2019). H_2 reacts with CO_2 at high temperature and high

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pressure (between 10 and 30 bar) producing methane (Wulf et al., 2018). These fuels are envisaged as a way to store electricity and allow CO_2 utilisation. Scenarios aiming for well below 1.5-degree targets forecast that e-gases and green gases will account for 18% of the final energy consumption, therefore playing a significant role in the industrial and transport sector (EU, 2018b).

4. Changes in demand profiles (shapes in load curves)

Sector coupling, fuel switching in final energy uses, and modifications in efficiency will lead to changes in the demand profiles. These will not only affect absolute demand, but also the shape (profile) of this demand through the year (Boßmann and Staffell, 2015; Pfenninger et al., 2014; Toktarova et al.,2019). Understanding the impacts that these changes may have in the future energy system is essential, particularly in terms of supply security. With power demand becoming more volatile and supply largely relying on renewable intermittent sources, especially when aiming for climate neutrality by 2050, the analysis of load curves for the design of the future energy system is crucial.

5. Sector coupling and extra electricity

Reaching net zero emissions by 2050 (EU, 2020 a) and the fulfilment of the newly approved emission cuts for 2030 (EU, 2020b) rely on the electrification of large emitting energy uses - such as road transport, heat supply and some processes in heavy industries. Scenarios presenting results for climate neutrality in 2050 forecast increases in power demands between 40-80% in comparison with 2015. Electricity is expected to become the most used energy carrier in the road transport and the residential sector, and to significantly account for the final energy consumed in industries.

Electrification, using renewable sources for power generation, will not only help towards decreasing the carbon intensity of the supply, but it will also be useful to reduce the energy intensity of the economy. This is because electrification enables the fulfilment of sectorial energy demand by employing a lower final energy consumption due to efficiency improvement. For example, battery and plug-in diesel hybrid passenger cars consume respectively 51 and 37 % lower energy per unit of travelled distance in comparison with an average size petrol car (EEA, 2018). Heat pumps, due to their coefficient performance, enable to satisfy heating and cooling demand by consuming less power than resistance based devices and employing lower primary energy than thermal based heat production technologies (IEA,2020b).

6. Digitalisation

Although, in the past, electricity, heat, transportation, and the industrial sector were considered separately as part of the energy transition, getting an overview of all areas and integrating them into an energy system has become increasingly important. In this context, over the coming decades, digital technologies are set to make energy systems around the world more connected, intelligent, efficient, reliable, and sustainable. Stunning advances in data, analytics and connectivity are enabling a range of new digital applications such as smart appliances and shared mobility. In addition, smart solutions based on the concept of "Internet-of-Things" (IoT) are expected to reduce CO_2 emissions by improving energy efficiency, optimising energy management, coordinating supply and demand in an increasingly decentralised electricity distribution network, and improving operational process efficiency across industry sectors. However, on the other hand, digitalisation is raising new security and privacy risks, while policymakers and stakeholders increasingly face new and complex decisions, often with incomplete or imperfect information. Adding to this challenge is the extremely dynamic nature of energy systems, which are often built on large, long-lived physical infrastructure and assets.

According to stakeholders, with the wider implementation of digital technologies, a bigger part of the additional electricity demand stemming from the electrification of the heating and transport sectors could be covered through RES-generated electricity. However, further research is still needed to quantify the potential benefits of digital solutions towards an efficient, intelligent, and sustainable sector coupling. More specifically, models should look into the potential to optimise the use of renewables and integrated energy systems through the integration of digital technologies that could increase security of supply, higher efficiency, and lower operating costs.

In this context, energy models should further assess how digitalisation could support the optimisation of the energy mix based on pre-defined targets and demand/ supply patterns, switching accordingly between electricity from source-specific power supplies. Digitally-enabled demand forecasting and supply planning for coordinating supply and energy storage and discharging in a decentralised renewable-based power system is also another important need that was highlighted by stakeholders.

Models should be also able to explore the potential of digitalisation in the transport sector, focusing on the prediction of transportation patterns and peak demand, as well as App and IoT-based supply/demand balancing from communication between transport vehicles and suppliers/ grid/ electric vehicle virtual power stations. New business models in which car batteries serve as an energy resource when the vehicle is stationary, providing services to the grid, is one of the major needs that stakeholders expressed.

In addition, digital technologies will be instrumental in industrial applications, supporting planning, process automation, predictive maintenance, flow surveillance and control systems for

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operational efficiency, safety, and profitability. For example, digital technologies could contribute to the management of carbon capture and storage (CCS) and the conversion of fossil fuel-based transportation to electrified and automated transportation. To this end, energy models should reflect more on the value that digital solutions could have for different entities along the value chain, also focusing on transactional aspects and logistics planning.

Finally, the specific drivers for different aspects of the energy transition are diverse in nature and the use of digital technologies and the digital transformation will therefore vary. Trusted data and digital workflows will be instrumental to ensure flexible, digital-assisted, and automated decision-making and coordination of activities. As a result, the development of nuanced algorithms that could ensure regulatory compliance, data privacy and cybersecurity in the new decentralised network of energy trading among several entities (including private and industrial prosumers and utilities) will be imperative.

3.2.2 Sector-specific user-needs

3.2.2.1 User-needs related to mobility sector

1. **Fleet distribution, electrification and renewable fuels**

Road transport currently accounts for 26.3% of fossil CO_2 emissions in the EU27 and the UK (Crippa et al., 2020 and Oreggioni et al., 2020). It is the only final energy use for which emissions have gone up since 2000 to nowadays. Such increase is mostly consequence of larger transport demand (EU, 2016) despite reductions in specific fuel consumption per unit of travelled distance (Enerdata, 2019).

As previously mentioned, electricity will play a key role to enable emission reductions for the road transport. Particularly, an expansion of plug-in hybrid and battery passenger cars is forecasted to take place between nowadays and 2030 - afterwards most of the fleet is predicted to be constituted by battery (80%) and H_2 fuel cell equipped units (15%) when considering carbon neutral scenarios (EU, 2018b). In the case of heavy-duty vehicles, fossil, diesel, and oil fuelled trucks are expected to be replaced by hybrid (electric and diesel), natural gas, biofueled, and power to liquid units. A growth in the production of second-generation biofuels, produced thanks to biomass gasification and Fischer Tropsch process for converting syngas to alkane and alkene fuel types, is forecasted alike the widespread use of power to liquid and gas vectors, obtained using H_2 from excess renewable electricity (EU, 2018b).

The pace for deployment of these low carbon technologies will determine the pathway for emission reductions for this key sector, however, as afore described, there are constraints to be considered. Some of them are related to renewable intermittent power supply, the development of storage

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technologies, and the improvement of electrolysis processes, in addition to the widespread availability of charging stations both for electricity and H_2. In terms of biomass, first generation biofuels are well established energy vectors within the transport sector (IEA, 2017); however, they are produced using crops and raw materials which are feedstock for the food industry. Research in optimising, upscaling and prototyping secondary biofuel production, using waste gasification and or woody biomass, is currently being conducted (Hirani et al., 2018).

2. Overall efficiency changes and CO_2 emission standards for circulating units

Reaching emission reductions for the road transport sector is possible not only due to the decrease of the fossil intensity of the fuel basket but also thanks to a more efficient fleet. Standards for fuel economy – applied to newly manufactured units – and fossil CO_2 emissions are expected to be strengthened in the coming years - including the limits set in the Post 2020, Post 2025 and Post 2030 EU standards (EU, 2019). Depending on the vehicle and fuel type, caps between 20-40% for fuel consumption per travelled distance or in fossil CO_2 emissions, in comparison with 2020 values, are prescribed in the case of Post 2025 and Post 2030 standards (EU, 2019). These new targets will not only apply to liquid fuelled units but also to battery and fuel cell equipped vehicles. Consequence of these standards and the widespread use of electric vehicles, the final energy demand for road transport is forecasted to be between 50-60% lower by 2050, in comparison with 2005, when considering the most ambitious decarbonisation scenarios (EU, 2018b).

3. Impact of vehicle charging infrastructure

The electrification of the mobility sector makes it important to know where cars are parked at what times. At times and locations where large numbers of cars are parked with high density and must charge simultaneously for their upcoming trips, their additional electricity consumption can cause stresses to the local grid (Muratori 2018). On the other side, the batteries of parked electric cars can be valuable storage capacities that can be used for balancing grid operation with large shares of intermittent renewable energy sources (Clement-Nyns et al. 2011; Leemput et al. 2012; Traube et al. 2012). For an efficient placement, sizing and grid connection of charging stations, it is therefore important to know the spatio-temporal distribution of car parking densities on the scale of entire cities (Lam et al. 2014; Sadeghi-Barzani et al. 2014; Zhu et al. 2016). A key user need and something that we are currently not able to do is to create the spatio-temporal distribution of car parking densities for times and locations for which we do not have OD travel time matrices available.

4. Smart driving and other possible ways to reduce travelled distance

Reducing emissions from road transport does not only involve decreasing the fossil and energy intensity of this key sector but also developing technologies and policies aimed at optimising traffic

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flow. Some of these measures could focus particularly on urban traffic, for passenger cars and light duty vehicles, such as smoother traffic flow - due to the implementation of "green traffic lights – and guided parking systems, providing information on available parking slots to avoid parking search traffic. A better use of the freight capacity would also contribute to reducing the amount of travelled ton.km (Krause, 2000).

3.2.2.2 User-needs related to building sector

1. **Standardisation/ labelling of buildings, energy efficiency and isolation**

Standardisation of the building sector is a critical need that was raised during the engagement activities with stakeholders, with "*How can the standardisation of the building sector be further pushed*" being one of the major questions that was raised by them. In addition, stakeholders questioned whether "*the zero-carbon energy supplies can be a cheaper way of decarbonising buildings that deep retrofit and what is the isolation level of buildings*."

On the other hand, while energy renovation of buildings is perceived as an important way to reduce energy consumption, preserving indoor comfort was considered as important by most of the stakeholders, who highlighted that "*having a warm and comfortable home is as important as achieving energy savings through renovation measures*."

Another important user need that was raised by the stakeholders, is studying the relationship between energy efficiency and RES in buildings, with many of them focusing on "*the optimal energy efficiency investments in buildings in order to achieve cost effective synergies between RES and the electrified heating and cooling sector*." For example, in the context of the Greek case study, stakeholders questioned "*What should be the level and the timing of financing in combined RES and energy efficiency measures in different types of buildings in the residential sector with the least possible costs*." The importance of studying the RES-energy efficiency nexus in the building sector becomes more apparent when considering that in Greece an increase of 37,400 jobs (22,000 full-time jobs) on a yearly basis is estimated due to the impact of RES penetration and energy renovation of buildings until 2030. Modelling exercises should focus on assessing specific incentives and financing mechanisms, accounting also for "big" consumers (e.g., from the industry and the tertiary sectors).

In this context, another important user need that was raised by stakeholders is exploring "*what are the potential costs, and barriers for nearly zero energy buildings (NZEB)*.", as for example, in the case of the Nordic case study where stakeholders acknowledged that the Nordic region "*does not emphasise the need for international building certifications like passive houses or nearly-zero energy buildings*."

Finally, modelling exercises should streamline the use of data inputs/ assumptions, as stakeholders acknowledged that the level of available information, especially on residential buildings, is considered as 'not very high' or 'scarce'; there "*is a lack of information about residential buildings and their energy performance details*", as no obligation exists to collect data about the residential building stock, and building owners are not requested to inform the municipality about implemented energy efficiency measures.

2. Building integrated renewable production

Renewable energy sources and energy efficiency measures to meet building energy demand are essential to curb global temperature rise. Although many of the energy models do show the potential of different energy efficiency measures and renewable energy use to meet the energy demand from the building sector under different scenarios, there is almost no model which investigates the potentiality of the integrated system (meaning the combination of both energy efficiency measures and renewable energy use to meet building sector energy demand). However, it is crucial to explore the feasibility of the use of renewable energy- more precisely, to explore the possibility of whether a sufficient amount of renewable energy is available to meet the building energy demand. Furthermore, in the building sector, the importance of smart grid or smart buildings has gained interest recently, but until now, the majority of the building sector-related energy models have projected energy demand by using a component-oriented approach which means energy models often consider building as a sum of separate components. This approach lacks the complexity of the building systems and hence, ends up delivering an over-simplified analysis of the energy demand (Urge-Vorstaz et al. 2012). Thus, the feasibility of the integrated approach of incorporating both renewable energy sources and energy efficiency measures to meet energy demand is required to project the building energy demand more accurately.

3. Lock-in effects

The lock-in, more precisely carbon lock-in, limits technological, economic, political, and social efforts to reduce carbon emissions (Seto et al. 2016). Carbon lock-in possesses several challenges towards limiting global warming at 1.5 degrees. There are three major ways by which lock-in can limit the potential of a mitigation strategy: (a) technological and infrastructural lock-in - this type of lock-in is associated with the technologies and infrastructure which influence energy supply and hence, indirectly or directly emits CO_2. For instance, investment in long-lasting built infrastructure such as buildings and land use patterns, influence the energy demand patterns as the components of the built environment determine energy demand for a considerable length of time after their development (Seto et al. 2016). This way, investment in long-lasting built infrastructure, which is not energy efficient by design, would result in carbon lock-in. (b) Institutional and governance lock-in - institutional and governance type of lock-ins affect energy production and energy demand. Institutional and governance lock-in is a characteristic of institutions and type of governance that

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arises through the coevolution of multiple systems such as 'technological, economic, scientific, political, social, institutional, and environmental spheres' (Könnölä et al. 2006; Seto et al. 2016). For instance, the government often reduces the unit prices of electricity and formulate policies to expand coal-based electricity (Foxon 2002). As a consequence, the demand for electricity increases and, hence, carbon emission from electricity consumption would also increase. (c) Behaviour lock-in - Individual behaviour and habits often influence energy consumption. Habits such as heating and cooling habits - use of heater/cooler when it is required and the use (or misuse) of appliances (for example switching off the appliances after use) - have significant energy and emissions implications by locking-in the rate and magnitude of any mitigation measure (Shove and Walker 2014; Seto et al. 2016). The socio-technical structure of society often shapes consumers' choices towards more energy-consuming ways of life (Maréchal 2010). Thus, in other words, it is safe to conclude that institutional and governmental lock-in can result in a behavioural lock-in. These existing technologies, institutions, and behavioural norms together often compel the rate and the scale of carbon emissions reductions. Understanding the nature of lock-in would help in identifying the alternative paths and strategies to achieve full mitigation potential (Seto et al. 2016). However, until now, most of the building models do not incorporate lock-in rigorously and thus, as a result, the projection of future energy demand may not provide a comprehensive picture of the future energy demand. Moreover, the potential climate change policies may be seen as under-achievers due to these lock-in effects and hence would result in underinvestment.

4. Consumer/ prosumer behaviour

Integrating socio-technical transitions in energy demand models (for example, behaviour, social risks and opportunities, transition dynamics, and heterogeneity across and within societies) is an important aspect raised by both the literature and stakeholders.

In particular, our findings showed that energy demand models should address more social and behavioural aspects (including behavioural aspects of heating/ cooling) of the energy transition that could create opportunities for active consumer participation, as prosumers. According to stakeholders, key modelling issues for scenario development and model inputs'/ outputs' definition should be resolved to improve modelling of human behaviour, including the role of attitudes, preferences, and acceptance.

"*Behaviour, lifestyle, and heterogeneity of consumers*" are critical aspects of the energy transition that existing models have not addressed that much so far. More specifically, the online survey conducted under WP1 highlighted that the top three social aspects that should be further analysed by energy models are: **1.** "Co-benefits of prosumerism and community energy", **2.** "Drivers and barriers of social innovations' diffusion", and **3.** "Dynamics of social acceptance and individual attitudes." This was further validated during bilateral interview meetings and an online workshop,

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where stakeholders raised as critical the improved integration of different aspects of citizens'/ consumers' behaviour and of social acceptance of energy technologies into energy models, with a special focus on understanding "*how policy changes can trigger behavioural changes*."

All these needs are strongly related to demand modelling, as one of the key gaps identified related to energy demand modelling was the need to model the "*human factor*." In particular, stakeholders acknowledged a high demand for modelling behavioural aspects, such as consumer and prosumer, and their relation to demand-side management and demand-response practices and options. There was also the suggestion of including energy communities as investors in the models. Indicative user needs/ research questions expressed by stakeholders in this area, also in the context of the case studies, were:

- *What are the rebound effects due to behavioural consumption patterns?*
- *Do prosumers and community energy groups accelerate the energy transition? Should we think nationally or at a continental level? How do these options influence the common energy targets?*
- *How do individual consumption patterns influence each other and what impact does that have on energy savings? Would energy sufficiency be a viable option?*
- *What types of policy measures would be better suited to lead to behaviour/ lifestyle changes (incentivise consumers) to take effective actions?*
- *Which business models could incentivise people to invest in the necessary technological infrastructure?*

5. Potential for heat pumps

Future technological developments and their costs is a very important need for stakeholders, especially when it comes to heat pumps, as there are still a lot of knowledge gaps and uncertainties regarding their potential in the building sector. Energy demand models should explore their performance more and also in combination with devices that enable demand-flexibility and demand-response functionalities. In addition, models should look into the contextual opportunities for heat pumps to increase energy efficiency in buildings without the thermal comfort of the occupants being compromised. Indicatively, in the context of the Nordic case study, one stakeholder from Sweden stated that, "*assessing the performance of heat pumps should be combined with studying the different ranges of the acceptable indoor temperatures and heating setpoints towards finding the optimal balance between increasing energy efficiency and preserving thermal comfort*."

6. Potential for district heating and cooling

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District heating plays a key role in several EU Member States, particularly in Scandinavian countries and in Latvia and Lithuania, where a large fraction of their heat demand is supplied using this kind of energy conversion plant (JRC, 2012). In Nordic countries, these plants tend to be operated using waste or woody biomass as feedstock and recently, in Norway, one of these facilities has incorporated post combustion CO_2 capture units (Fortum, 2021), enabling negative CO_2 emission energy generation.

Despite that these technologies may be a very useful way to supply heat and cooling demand, by taking profit of both material and thermal waste streams (low quality heat in industrial process), there are also several limitations for their deployment. One of them is the distance between the customers and the plants, which may lead to significant financial investments for the construction of the distribution network in addition to pumping costs and heat losses/ gains (IEA ETSAP, 2013). Another key concern for investment is related to heat demand variability and the impact that improvement in building envelope efficiency may have on future demand. Both could lead to a very low load operating capacity for the plants and consequently affect their techno-economic performance (IEA, 2019).

While these aspects are more related to energy supply models, the tools in SENTINEL's demand Work Package – such as DESSTINEE – enable the exploration of the effects of the incorporation of these technologies in the fuel basket for heating, analysing how they can contribute to reduce the stress on the consumption of other vectors and the trade off with building envelope efficiency measures.

7. Meteorological impacts of modern technologies for energy supply in buildings

Installed power of wind and PV in Europe is constantly increasing. Over the years more energy is generated through these sources, making power systems more weather dependent. For this reason, in order to be able to face the high impact of weather in power systems, the need of detailed, high resolution in time and space, modelling of wind and PV generation is more and more important.

So far, current research work has made some improvements in the simulation of weather impact on power systems. However, it faces some limitations so long as it only accounts for the impact of weather on wind and PV generation and not on the whole system, considering the interactions between generation and demand, and the effect of different renewable generation on total system cost, etc.

Stakeholders stated that some existing energy and power models have tried to increase their resolution to catch-up with the weather variability, considering the renewables' generation. This offers them the capability of capturing detailed correlations between weather and generation, but due to high computational requirements, they are limited to one year or less than ten year projections. Therefore, longer-term weather variability is required.

Furthermore, another important lack of existing work is the inclusion of substantial changes on future demand patterns due to weather impacts. The majority of the existing studies do not take into consideration the possible changes to the shape of consumption, making their projections just by scaling the existing profiles. Stakeholders concluded that most of the existing work focuses only on the weather impacts of considering supply-side changes, without taking into account the weather impacts on the changing shape of future demand.

Finally, especially for the European case study, stakeholders stated that weather differences between different regions are expected to affect the way technologies (e.g., heat pumps) operate in the building sector, and, thus, models should address this issue when studying diffusion patterns of such technologies.

8. Digitalisation and widespread of smart appliances

Literature review acknowledged that, regarding model content, one of the main user needs linked to energy transition is digitalisation. This was also validated by results from our online survey, where one-third of the respondents selected digitalisation as one of the most important aspects of the energy transition.

More specifically, stakeholders questioned the role of digital technologies (e.g., their pros and cons, impacts and opportunities, etc.) in the context of the upcoming energy transition and highlighted that one of the most important digitalisation-related aspects that should receive further attention from energy models is "how *new, digital technologies and services*" can contribute to the further decarbonisation of the building sector, also supporting sector coupling and system flexibility, as stakeholders are not yet convinced that these aspects are addressed by existing models. For example, one representative from the European case study highlighted the need for models to be able to assess the role of digitalisation in relation to electric vehicles' charging/ discharging patterns, especially in the residential sector.

In addition, policymakers especially stated that models should further evaluate "*the footprint and the rebound effects of digitalisation*" and "*whether low-tech options are sometimes better, particularly when factoring in resource/ material demand*," while representatives from NGOs questioned the role of energy models in optimising digitalisation processes.

Furthermore, although some of the key effects of energy efficiency measures, such as digitalisation, are partly considered by the existing demand models, further needs were identified. The "Internet-of-Things" and smart buildings are notions related to digitalisation and through it to demand-side management options. In particular, stakeholders highlighted that digitalisation of demand-side management is an important innovation that should be included in energy models, along with

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assessing "*how information-rich smart system technologies can facilitate decentral concepts in order to become more beneficial to the overall energy system*." Smart features like smart appliances are another aspect that should be incorporated in energy demand models.

In addition, with the wider implementation of digitalisation, a bigger part of the additional electricity demand stemming from the electrification of the heating and transport sectors could be covered through RES-generated electricity. Demand-side flexibility, smart microgrids, and energy blockchains are developed allowing the maximum utilisation of the RES-generated electricity. To this end, demand models should further include such digitalisation aspects such as smart meters, RES aggregation, and virtual power plant management that could enable better system management and create opportunities for active consumer participation (e.g., prosumers, demand-response, etc.). Digitalisation in relation to demand-response applications and time-of-use incentives should also be explored. Finally, new business models should be developed to assess the potential for Pay-for-Performance (P4P) schemes in Europe, exploring incentive mechanisms from different third parties.

3.2.2.3 User-needs related to the industrial sector

1. **Fuel switching for heating in industry**

The penetration of electricity, H_2 and power to fuel carriers is key to meeting the emission reduction targets for the secondary sector (EU, 2018b). Heat supply electrification is expected to contribute to decarbonising the pulp, paper and chemical production. These industries consume a large amount of energy for water heating and for steam generation (IEA, 2017), the first could be undertaken using heat pumps while the latter could be supplied using electric boilers (EU, 2018b). Some studies (EPRI, 2018) also suggest the widespread use of electric arc furnaces, infrared and induction heating techniques. Nonetheless, further research is still needed for exploring commercial uptake (EU, 2018b).

2. **Role of CCUS**

Carbon capture, storage and utilisation technologies are also envisaged as a way to reduce both direct combustion and process CO_2 emissions. CO_2 is sequestrated from the flue gases, using physical or chemical driven separation processes, and subsequently the obtained high purity CO_2 stream can be transported to be geologically stored (IPCC, 2005). The separated CO_2 can also be used as feedstock chemicals production, and fuels or can be pumped in agricultural greenhouses to increase productivity (IEA, 2014; Oreggioni et al (2019)).

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Carbon capture technologies require a significant amount of energy, heat or power for CO_2 removal and for the regeneration of the separation agents. Amine based chemical absorption-desorption units are the most widespread technologies for CO_2 separation. They are currently employed for gas sweetening and are being commercially upscaled for CO_2 capture in power plants and large coal combustion sources (IPCC, 2005; NETL, 2011; NRG, 2020). CO_2 is chemically absorbed and later recovered, at high purity, in a stripping column as a top product of the partial condenser. Steam, as a heat supplying fluid, is needed for the operation of the reboiler of the stripper and its generation constitutes the largest energy consumption of the process (Ahn et al., 2013). Other CO2 capture techniques include physical and chemical separation processes using sorbents and membranes (IPCC, 2005). Since the purpose of CO_2 capture technologies is to produce a rich CO2 stream, the energy penalty and costs are lower when higher CO_2 concentration flue gases are being treated (NETL, 2011). That is why it is convenient to operate these units in industries for which direct CO_2 combustion and process emissions are generated - such as: steel manufacturing, chemical and petrochemical industries and cement production. Particularly for cement industries, calcium looping technologies are envisaged as a carbon capture method which would also allow higher production of clinker and power generation (IEAGHG, 2008). The application of CCS technologies in industries using biomass, as fuel or feedstock, leads to "negative CO_2 emissions" required to compensate for fossil CO_2 emissions from other sectors with the aim of reaching climate neutrality (EU, 2018b).

The deployment of CCS technologies also rely on transport and storage infrastructure. In terms of transport networks and storage hubs, different Member States and the UK are exploring business models for enabling commercial upscale (Element Energy, 2018; Norwegian Ministry of Petroleum and Energy, 2021). Built gas pipelines currently not in use and end of life, or nearly end of life, gas and oil wells could also be employed for geologically storage. In particular, CO_2 injection could enable enhanced oil recovery, increasing productivity in aged wells (IEAGHG, 2016).

When CO_2 transport or injection were economically unfeasible, CO_2 utilisation routes could be used as a final CO_2 deposition method, contributing as well to reduce climate and environmental impacts associated with the production of certain goods - mainly chemical industry feedstocks and fuels (IEA, 2014). CO_2 tends to be quite a non-reactive molecule and a significant amount of H_2 and energy may be required, thus, environmental trade-offs should be carefully analysed (Fernandez D'Acosta et al., 2018; Schakel et al., 2016a).

3. Heat recovery and industrial co-generation

Heat recovery and industrial co-generation contribute to decreasing fossil fuel and electricity consumption. This can be accomplished by a better process integration of energy streams such as taking profit of exhaust flue gases to preheat process feedstocks, generate steam or operate organic Rankine cycles (TURBODEN, 2021) or gas engines (INNIO, 2019). Industrial co-generation and on site heat production is currently incentivised by different policies in the EU Member States and the UK

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(CHPQA, 2019), aiming at reducing energy consumption within the industrial sector and meeting efficiency targets prescribed in the Energy Efficiency Directive (EU, 2012). Hot exhaust gases could also be used for running ammonia absorption chilling processes, combining ammonia absorption and desorption cycles with refrigeration technology, avoiding the power consumption associated with the compression stages of the refrigeration cycles (Darwish et al., 2008).

4. Hydrogen(H_2)

H_2 is envisaged as a key vector to meet emission reductions, especially in scenarios aiming at climate neutrality or early climate neutrality (EU, 2018). H_2 could be combusted in fuel cells, boilers, gas engines and turbines. "Green" H_2 can be produced through the gasification of woody biomass and waste or via water electrolysis, using renewable electricity. "Blue H_2" can be obtained through the methane reforming process and the associated carbon footprint may be reduced by deploying a downstream CO_2 removal process (IEA, 2019). Nonetheless, there are several challenges associated with the use of H_2 as fuel. Rich H_2 fuel mixes could lead to malfunctioning of combustion devices - such as knocking, preignition and backfiring at higher loads in gas engine and high flame temperatures in boilers or furnaces (IEA, 2019). That is why it is expected that H_2 will be mainly used in innovative production process, replacing fossil feedstock in steel production and in chemical industries and later on as energy vector for combustion processes (E4tech, 2015). Particularly, blends with a small fraction of H_2 and a large amount of natural gas are forecasted to be considered as a way to avoid the afore mentioned issues (E4tech, 2015).

The deployment of H_2 transport networks is also a limiting factor for a significant H_2 uptake as energy carrier, thus several alternatives are being considered such as enabling H_2 transport in unused natural gas pipelines or injecting H_2 in active natural gas pipelines, formulating H_2-natural gas blends (E4tech, 2015). Investments are forecasted to take place in the coming years and several business models are currently being explored in different EU countries and the UK (E4tech, 2015).

5. Net zero steel and cement production

Steel and cement production currently accounts for 2.7% and 2.5% of fossil CO_2 emissions at European level (Crippa et al., 2018; Oreggioni et al., 2020). These emissions include CO_2 from fuel combustion in these facilities as well as by product CO_2 emissions - from the calcination of limestone for clinker production and from the reduction of iron ore for iron manufacturing. Clinker and pig are, at posteriori, upgraded to obtain cement and steel respectively.

Conventional blast furnace based steel and cement production processes rely on coal as energy carrier and reduction agent. Decarbonising these industries will comprise the use of low carbon feedstocks in addition to the deployment of CCS (EU, 2018b).

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In the case of cement, research is conducted for the operation of kiln systems - using solid biomass, waste and low carbon gases - considering not only the thermodynamics and flame conditions but also the optimisation of limestone and energy consumption (Schakel et al., 2016b). Regarding CCS, CO_2 can be captured using solvent based technologies - as currently being explored for upscaling in several industrial projects- or else considering calcium looping processes (IEAGHG, 2008). The latter involve the reaction of CO_2 with CaO to produce limestone, which is converted downstream into CO_2 and CaO, enabling a pure CO_2 stream to be obtained while avoiding the need of additional CO_2 removal units. This also increases clinker production as well as heat recovery for power and heat generation (Romano et al., 2014; Ozcan et al., 2013). This technology is also being prototyped for commercial uptake in pilot projects like the one funded by the EU at the Buzzi Unicem plant in Italy (CLEANKER, 2021).

Several technologies could be considered for the decarbonisation of the steel production, some of them are analogous to the ones described for cement industries while there are some options that are very sectorial specific or that can be more economically feasible in the context of steel manufacturing. Most of the steel in Europe is currently produced using the blast furnace and basic oxygen furnace route. This involves the reduction of iron ore, due to the oxidation of coke in a blast furnace, to obtain pig iron which is downstream processed in a basic oxygen furnace for the production of steel. Direct fossil CO_2 emissions can be reduced by replacing coke with woody biomass or waste (Mc Kinsey &Co, 2020). Emissions could also be cut by deploying CCS technologies such as solvent based processes. If the blast furnace were operated using biomass and CO_2 removal units were installed, negative CO_2 emission steel making could be reached.

Steel can also be produce using the direct reduced iron (DRI) technique in combination with an electric arc furnace - using iron ore and, mostly, steel scrap as raw material respectively. The DRI process generally employs a gaseous fuel as a reduction agent, mainly natural gas, which thermically convents into CO and H_2 reacting with the oxygen present in iron ores. The resulting iron and the steel scrap are molten in the electric arc furnace and the product is downstream refined. This route also offers potential for decarbonisation such as: using e-gases, biogas, biomethane or H_2 in the DRI. In addition, electric arc furnaces are expected, in the coming years, to be operated using renewable electricity (Mc Kinsey &Co, 2020).

Scenarios aiming for climate neutrality foresee that most of the afore described technological changes will be implemented. Reductions of up to 83% of direct fossil CO_2 emission from cement industries and 97% from steel production, in comparison with 2015, are forecasted by 2050 for the EU27+UK (EU, 2018b).

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4. Upgrading SENTINEL demand models to address the user-needs

In section 3 both the methodology and definition of the user-needs are discussed. This section now discusses how energy demand models used in SENTINEL would upgrade themselves in order to address these user-needs. As is discussed in section 2, each of the energy demand models has its own methodology, assumption, and data constraints. Thus, to address both categories of user-needs, each of the models follow a different approach. The approach varies as per the type of user-needs. In the section below, these different approaches are discussed for each category of user-needs.

4.1 Addressing generic user needs through SENTINEL demand models

Some of the key generic user-needs, such as modelling energy demand for both the 2030 and 2050 time period, incorporate the usage of renewable energy, or energy efficiency, and are already accounted for in most of our demand models. Thus, addressing these user-needs would be possible without any further modification of the models. However, some of the generic needs such as 'incorporation of green and e-gases' or 'generating demand profiles at an hourly resolution' require further development of our models. For instance, DESSTINEE is upgraded by developing auxiliary routines to account green and e-gas related user need. The consumption of gaseous fuels – for all the final energy uses – can now be disaggregated into natural gas, biomethane, biogas, e-gases or power to gases and H2. This is done by processing the results of Module 1 in an external Excel file containing the shares of the afore mentioned energy carriers within the gaseous fuels for different sectors in the EU27 Member States and the UK. These shares will depend on the assumptions of the scenarios being modelled. As default, the routine has implemented the fractions associated with the 1.5 scenarios, presented by the EU in the context of the 2050 Long Term Strategy (EU, 2018). The routine quantifies the annual demand for these vectors as well as the associated emissions. This will also enable cross-checking against the amount of excess renewable electricity required for the production of the e-gases.

A similar approach is followed for calculating demand profile for each sector. The electricity demand-supply patterns are envisaged to undergo significant modifications - consequence of the widespread of electricity as energy carrier for heating supply, transport and industry. Such changes have the potential not only to lead to variations in the total yearly power demand but also in the hourly distribution. As afore described, DESSTINEE Module 2 can be used for generating hourly power and final energy demand profiles on the basis of the yearly figures estimated in Module 1. Simulated load curves for 2015 are being validated against actual load curves and some parameters

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- such as night storage and charging profiles for electric vehicles - are currently being revised to better fit real hourly power profiles informed by national electricity grid statistics.

For some of the user-needs such as 'lifestyle change' or 'sector coupling and digitalisation', it is difficult to address them generically or for each sector. Issues such as lifestyle changes are quite broad when it comes to modelling them. More precisely, each of the demand models requires specific input data to model any parameter, and lifestyle change needs to be defined more narrowly in terms of a particular change in lifestyle which mostly can be related to any specific sector. Therefore, when the lifestyle gets narrowed down then it is much more appropriate to model it with sector-specific models than trying to capture it with all the demand models. Similarly, sector decoupling varies as per sector and in a way, they are interlinked. Therefore, modelling them on an overall demand basis may not provide an appropriate result, and thus, modelling these needs for each sector would be much more appropriate.

Table 1 below summarises the discussion with colour codes to specify which generic user-needs can be addressed by which model:

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Table 1: Generic user-needs addressed by different energy demand models

	Demand models			
Generic user-needs	**BEVPO**	**DESSTINEE**	**DREEM**	**HEB**
Energy demand transition between 2030-2050	Green	Green	Green	Green
Role of renewable electricity to meet demand	Green	Green	Green	Green
Incorporation of green and e-gases	Grey	Green	Grey	Grey
Changes in demand profiles	Grey	Green	Green	Green
Sector coupling and extra electricity	Grey	Green	Grey	Grey
Digitalisation	Grey	Grey	Green	Grey

Index: Green- addressed by the model

Grey- not addressed by the model

4.2 Addressing sector-specific needs through SENTINEL demand models

4.2.1 User needs - related to the building sector

User-needs identified for the building sector can be considered as a comprehensive list of actions that any energy demand model dealing with the building sector-related energy demand must address. User-needs such as 'standardisation of buildings', 'consumer behaviour', 'potential of heat pumps', and 'digitisation and smart appliances' can influence the total energy demand immensely. That is why three of our demand models in SENTINEL (namely DESSTINEE, DREEM, and HEB) used for the building sector, will be upgraded and in some cases modified accordingly in order to be able to address some of the user needs. None of the demand models can address all of the user-needs identified for the building sector- more precisely, for each of the user-needs, different models are used. For instance, for the standardisation/labelling of buildings both the DREEM and HEB model can be used- in other words, both the DREEM and HEB models can incorporate standardisation/ labelling of buildings in order to calculate energy demand of the building sector. Concretely, the HEB model assumes three scenarios with different building vintage types - such as existing, new, advanced new (such as nearly zero buildings and passive houses), retrofit, and advanced retrofit – and the share of each type of building vintage changes in each scenario. For example, the deep efficiency scenario (refer to section 2.3) has the highest share of advanced new and deep retrofitted buildings compared to the other two scenarios in HEB and, accordingly, the total energy demand of the building sector changes across different scenarios. Thus, the HEB model accounts for the

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potential of high-efficiency buildings in reducing energy demand and accordingly the emission-related to the building sector.

Similarly, DREEM can also incorporate the effects of standardisation/ labelling of buildings. In particular, the DREEM model was developed based on the concept of 'reduced (low)-order' modules that represent adequately building thermal dynamics for the purposes at hand. Reduced-order thermal network modelling represents a thermal zone by thermal resistances and capacities (RC-network), using the electrical circuit analogy. This approach allows for high discretisation, without relying on extremely detailed input data requirements and excessive computational runtimes. The parameters for heat transfer coefficients, and thermal resistances and capacities, are determined using historical data and standards for the geographical context of interest. The DREEM model builds on realistic building typologies and standards using data from the EU online webtool TABULA[5], which synthesises data and building specifications according to EU energy performance of buildings standards (EPB standards, Energy Performance of Buildings Directive (EPBD) 2010/31/EU). The model's structure allows also for the inclusion of the newest building specifications (such as nearly zero buildings and passive houses) that are foreseen under the Green Deal's renovation wave. In addition, the model allows for exploring the effects of buildings' standardisation/ labelling in reducing energy demand, through energy efficiency retrofits and deep renovations and, accordingly, emissions related to demand in the residential sector.

Since both demand models can incorporate the effects of standardisation/ labelling of buildings, the HEB model will be used to show the potential of this particular user-need for each EU member state and DREEM will be used to calculate the effects of standardisation/ labelling for residential buildings in Greece and the Nordic Region, as the geographical coverage of the DREEM model, at this point, is limited to specific European countries. The two models' results can be, then, compared and discussed accordingly to enable more meaningful country-specific perspectives.

In addition, according to stakeholders' insights, preserving indoor thermal comfort is as important as achieving energy savings through renovation measures. The DREEM model will address the issue of thermal comfort as it includes a whole modelling component dedicated to determining appropriate indoor thermal conditions and temperature ranges that result in thermal satisfaction of the occupants based on the "DIN EN ISO 7730", "ASHRAE 55" and "EN 15251" international standards. This exercise will take place for different standardised building typologies in the residential sector in Greece and the Nordic countries, providing further insights on the effects of buildings' standardisation/ labelling in reducing energy demand.

Furthermore, regarding digitalisation, potential for heat pumps, and consumer profiles, the DREEM model can incorporate these needs as modelling inputs to explore the impact on total energy

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

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demand which is the final modelling output. Its modular and bottom-up structure provides the ability to incorporate future technological breakthroughs in a detailed manner. Regarding digitalisation aspects, the model includes a whole component that focuses on supervisory control systems, as high-level controllers, that allow complete consideration of the system's characteristics and interactions among all elements and their associated variables, using different types of heuristic and optimisation algorithms. In the context of the Greek and the Nordic case studies, the model will explore scenarios towards the achievement of energy savings and cost-effectiveness accounting for digital technologies as smart thermostats and automated energy control/ management systems in the residential sector. These scenarios will be also linked to behavioural aspects of consumers, as the DREEM model will be used to explore the potential for energy savings through the setback analysis of thermostat setpoints. This analysis refers to the notion that energy savings can be achieved if consumers are willing to setback their thermostat setpoint without compromising their thermal comfort. This exercise will also allow us to shed light in behavioural aspects of heating and cooling, a need that was especially raised by stakeholders especially in the context of the Nordic case study.

In this context, shedding more light on the potential of heat pumps in the residential sector, the DREEM model will be used to assess their performance in combination with studying the different ranges of acceptable indoor temperatures and heating setpoints towards finding the optimal balance between increasing energy efficiency and preserving thermal comfort. This exercise will be also linked to the setback analysis.

Furthermore, the DREEM model will be used to explore additional applications relevant to both digitalisation and behavioural aspects by bringing together all important aspects of end-use with a demand-response modelling framework, that builds on the concept of time-based demand-response methods. Time-based demand-response methods are considered the most effective demand-side management strategies as their inherent characteristics are more suitable to the real-world unsteady and fluctuating energy consumptions. In particular, the model will be used to explore the potential of "real-world" scenarios which assume a central planner, that attempts to maximise flexibility value by issuing demand-response signals. This entity learns the optimal policy that maximises its revenues through an optimisation approach based on reinforcement learning theory. This exercise will aim at exploring the decision-making framework and solve the dynamic pricing problem in a hierarchical electricity market that considers both service providers' profits and consumers' costs/ benefits. Consumers' decision-making behaviour will be modelled via different probabilistic methods to explore different levels of benefits according to consumers' probability to comply with these demand-response signals (i.e., their intention to shift loads to the next hours without compromising energy needs and thermal comfort).

In addition, the DREEM model will be used to address different aspects of prosumerism in the residential sector, assessing in parallel potential costs and benefits, and explore business models that could incentivise consumers to invest in technological infrastructure as small-scale PV and battery storage systems towards energy sufficiency in the residential sector in Greece. Finally, the DREEM model could address limited rebound effects due to behavioural consumption patterns, focusing only on the quantification of direct rebound effects associated with the switch from incandescent lamps (ILs) or halogen bulbs to more energy efficient compact fluorescent lamps (CFLs) or light emitting diodes (LEDs) using representative data from literature.

To understand the potential of lock-in effects in the building sector, we use the HEB model. Precisely, lock-in effect shows the potential loss in energy savings due to moderate technological improvements and policy efforts instead of ambitious ones. The HEB model calculates lock-in effect as the difference in the thermal energy use levels achieved under two scenarios – Moderate Efficiency and Deep Efficiency – in relation to the base year. In practice, the lock-in problem originates when a refurbishment or new construction, does not follow a holistic optimisation of building envelope and technologies and, thus, the moderate energy practices become standard. Consequently, it becomes almost impossible to further reduce energy consumption in such buildings for many decades to come and in some cases, for the entire remaining lifetime of the building (Urge-Vorstaz et al. 2012).

Lastly, none of the demand models used in SENTINEL are able to address integrated energy production needs. Thus, HEB model collaborates with another model developed at CEU, namely BISE model, to explore the potential of the role of solar energy produced on site in Europe (Petrichenko 2014). BISE model estimate solar thermal and electric output from advanced building-integrated hybrid technologies by taking into account many geographical, architectural, morphological, and climatic parameters. By using BISE model, the total solar thermal and electric production from the buildings can be calculated for different EU regions at an hourly resolution.

4.2.2 User needs - related to transport

The user needs and modelling gaps that we have identified for the transport sector are quite diverse. To address most of the identified needs, the demand models which are used for calculating transport demand, namely BEVPO and DESSTINEE, would upgrade themselves. BEVPO can be addressed with machine learning [9]. For instance, as explained in section 3, nationally dependent widespread of more efficient and low carbon intense technologies are expected to occur within the road transport sector. To model these changes, a new auxiliar routine supplementing DESSTINEE Module 1 for road transport has been developed. This routine estimates the fuel consumption for each energy carrier, at EU27+UK level, on the basis of: fuel penetration for each vehicle type, fuel economy standards, and travel demand projections. The total usage for every vector, for the time horizon of interest associated with the scenario being modelled, is calculated as the share in the

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total energy consumption for the road transport. A ratio, between these shares and the ones for 2015 at EU27+UK level, is quantified and applied to 2015's nationally defined fuel baskets.

Similarly, for needs such as fleet distribution, electrification, and vehicle charging infrastructure, the BEVPO model is upgraded to address these needs. More precisely, for times and locations for which we do not have OD travel time matrices available, but a series of other data such as satellite imagery and meteorological conditions that we call features, we can infer these OD values. We can learn a functional relationship between OD matrices of times and locations with available data and our features using, for example, advanced deep learning techniques. Next, we can predict OD matrices for any time period and city for which we do not have OD travel time data available using the functional relationships that we learned purely from our data, free from any assumptions. Users of BEVPO can then create models of city-scale car traffic and parking for any period of time into the past or the future and for any city of interest, without having to collect additional data beyond what is processed and saved in the BEVPO neural network prediction models that we train and provide to the public.

4.2.3 User needs - related to industry

Energy consumption, fuel basket and CO_2 emissions from the industrial sector are challenging to model, requiring a detailed bottom-up approach and accounting for the different sub-categories that are part of this sector. It is of great interest to have accurate, nationally and sectorial based estimations, especially for the production of cement, chemicals and steel given their contribution to total energy consumption and associated emissions. To accomplish this objective, an auxiliar routine was developed in DESSTINEE, aimed at providing inputs to Module 1. The routine enables the definition of country level future fuel baskets, energy usage, and combustion and process emissions for the three afore mentioned subsectors. This is undertaken by considering current energy demand and fuel baskets in addition to national projections for good production and EU27+UK targets for energy consumption and emission reductions – accounting as well for the penetration of CCUS technologies. These results provide the incremental/decremental coefficients, in terms of efficiency and energy carrier penetration, which are required for the calculation of final energy consumption for the "Heavy Industry" subcategory in DESSTINEE. Quantified process CO_2 emissions supplement the emissions from fuel combustion, enabling a more comprehensive picture of the carbon budget.

To summarise the discussion, figure 7 presents the interaction between the different user-needs and the SENTINEL energy demand models.

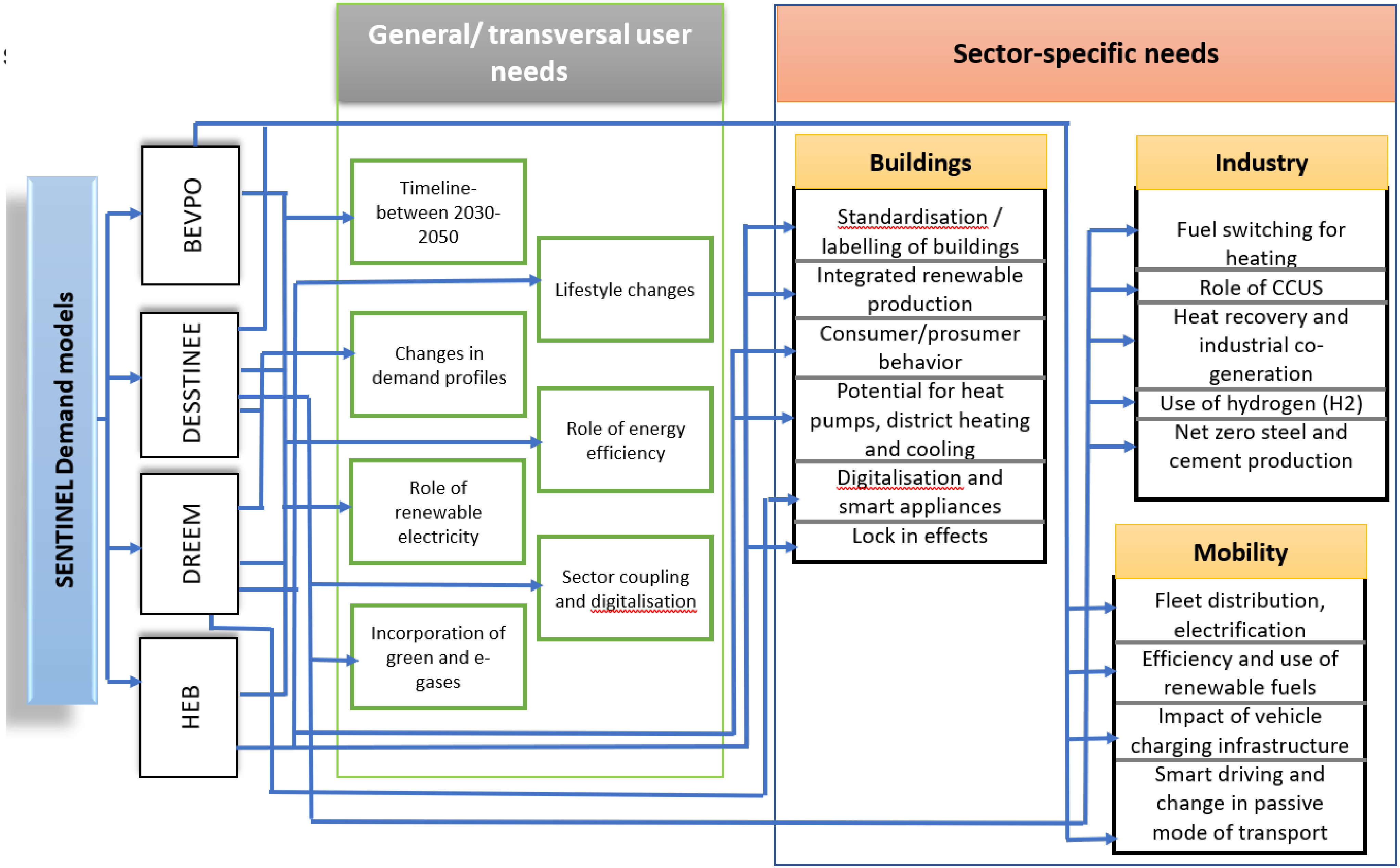

Figure 7: Different categories of user-needs addressed by different energy demand models

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Figure 7 summarises the interaction between two categories of user needs and demand models. Here, it is important to understand that each of the demand models have some limitations in terms of data or methodology and, hence, it is not possible to address all the needs by a single demand model - this is also not the objective of SENTINEL. The SENTINEL demand models are quite diverse in nature and all four demand models use different methodologies to calculate sector-specific energy demand. Since these models use a different set of methodologies, the demand models complement each other, especially when it comes to addressing different user-needs. For instance, to calculate the demand profile of the building sector at an hourly resolution, the HEB model feeds in total demand data for both residential and tertiary buildings to DESSTINEE and DESSTINEE calculates the hourly demand profile of the building sector. Similarly, BEVPO and DESSTINEE can be soft-linked in order to address fleet distribution and electrification-related user-need. Although some of the user-needs, such as digitalisation of buildings or potential of heat pumps in the building sector, can only be addressed within a limited geographical scope due to constraints-related to data and resources, all the demand-related needs are quantified within WP3 even for a limited geographical scope. The needs quantified for a limited geographical scope can provide a fair estimation of the magnitude of the need. More precisely, the impact of the needs on final energy demand can be understood, and accordingly, the consortium will discuss how to quantify these needs for each of the EU Member States. In the following section, the conceptual framework of soft-linking methodology is discussed.

5. Discussion

The user-needs specific to energy demand modelling are quite diverse and, hence, incorporating them into the SENTINEL demand module would certainly provide a precise estimate of the future energy demand of Europe. As can be seen, user-needs vary as per sector and no single model can address all the user-needs due to methodological challenges. For some of the user-needs, the existing demand models need to be upgraded and only then can the user-needs be incorporated into calculating total energy demand. To identify these user-needs a three-tier methodological approach is used and after identification, each of the user-needs is validated by reviewing literature to understand the potential and magnitude of the user-need. The discussion about user-needs unfolds many other aspects of energy demand modelling in the SENTINEL project which are discussed below:

1. **Limitation of the demand models:** Each of the energy demand models have their own limitations/barrier in terms of their methodology, coverage, or modelling objective. For instance, the modelling objective of BEVPO is not to calculate the total demand of the transport sector but rather to explore the potential of electric vehicles. Thus, total energy demand-related user-needs or, in other words, user-needs impacting the total demand of

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the transport sector, will not be useful to be addressed with BEVPO. Similarly, some of the user-needs related to the building sector (such as the potential for heat pumps, consumer behaviour, and the digitalisation of buildings) are addressed by the DREEM model. However, the coverage of DREEM is only limited to Greece and the Nordic region. Thus, some of these needs will be addressed only at a limited coverage instead of at an overall EU level. Here, it is noteworthy that the objective of demand modelling is to understand the magnitude of the needs and, for that country, specific results would give us sufficient perspective about the magnitude. Therefore, even some of the needs will be quantified for a limited geographical coverage as it would be enough to discuss further about their magnitude and importance in energy demand modelling. Apart from geographical limitations, demand models also have certain methodological limitations that mostly occur due to data unavailability. For example, it is difficult to find a detailed split of building end-use data, such as separate share for space heating and cooling in total energy demand, and hence, in the HEB model, the results for space heating and cooling are presented together.

Similarly, DESSTINEE aims at covering the most relevant sectors and end uses as far as energy consumption and emissions are concerned. This is done through a simplified and medium level detailed approach. Whilst this can be advantageous - in terms of availability of input data, model complexity and informatic implementation - it can also lead to a less accurate sectorial calculation for the service demand, the final energy usage and the hourly profiles. Sectorial service demands are modelled on basis of variables which, in DESSTINEE, are function of the evolution GDP per capita and population. The employed correlations between sector specific variables and GDP per capita evidence have well proven relationships when applied at global level. Nevertheless they may not provide the most suitable fit when being used in areas where there is not a high disparity of income level. Other models may estimate the increase of service demand considering the trends for the amount of workers – for the commercial and industrial sector – or for family disposable income and geographical and behaviour constraints in the case of the transport and building sector. For modelling energy demand within the latter, indicators such as the space, water heating and cooling indices have been included in the calculation of the sectorial incremental factors. DESSTINEE would benefit from a more elaborate definition for these indices so that they could automatically be quantified on the basis of socio-economic, technology penetration, climate indicators and behavioural aspects. Whilst this was partially achieved for the default values in the EU climate neutral scenario, more effort should be invested in the future. The same applies to the appliance intensity coefficients and building envelope efficiency related indicators.

Hourly profiles are simulated using energy consumption distribution patterns from the UK, at household and office level, information from railways based on data from Ireland and charging profiles for EV considering data presented by NREL (NREL, 2011). The distribution patterns have been updated and/or fitted, when possible, to identify monthly variation in some EU countries. However, this has been a quite ad hoc activity, mostly because confronting the DESSTINEE's simulated load curves against the officially reported hourly power dispatch data research is currently being undertaken to review and partially update the hourly and season distribution of sectorial power consumption in Module 2, aiming at country level or macro-region representativeness as well as considering the incorporation of storage technology and further details regarding EV charging regimes.

2. **Overlap between modelling output:** Overlaps between modelling outputs, especially while addressing the different user-needs, should be considered as a positive outcome of SENTINEL structure. Overlaps between output would provide a valid ground to compare the results produced by different models and would further help us understand the strength of each of the modelling tools. With these different sets of results, SENTINEL can conduct a sensitivity analysis to provide a range of demand profiles. During the process of developing demand modelling and addressing user-needs, most of the overlaps have been identified (some of them are discussed in section 4) and, since for the final demand module calculation we will soft-link three different demand models, the chance of an overlapping output is minimum. Even in some cases where the overlapping occurs, for example, in the case of addressing standardisation/labelling of buildings, it would not result in double-counting as only results of the HEB model would be used in final output due to the limited coverage (both in terms of geographical and sectoral) of DREEM. However, results of DREEM for standardisation/ labelling of buildings would provide a ground for comparing the magnitude for the residential building sector. Similarly, DESSTINEE uses a quite high-level methodology for the quantification of energy demand within the building sector, in comparison with the other models in SENTINEL. Comparing its results against HEB and DREEM will be useful to better define indicators that are related with building envelope efficiency, thermal comfort levels and appliance uses.

3. **Transparency of the demand model:** One of the key objectives of the SENTINEL project is to provide an open modelling platform that can ensure full transparency about the models used in this project. During all types of interactions (such as interviews, online surveys or workshops with the stakeholders) it is clear that the most prominent user-need is transparency of the models. Particularly, the lack of publicly available detailed assumptions and intermediate results for key final energy uses – such as space heating, appliances and lighting in buildings, and different vehicle categories for road transport - in EU official

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reference scenarios (EU, 2016 and EU, 2018) has been highlighted. Thus, all the SENTINEL demand models will be open sourced, and the codes of the models will be made available. Moreover, the documentation of the demand models will also be made available in order to make these models easily accessibility and usable.

The objective of the demand module is to calculate the total annual final energy consumption and corresponding greenhouse gas emissions until 2050, for each sector and end use, in addition to producing hourly power demand profiles. The latter will be used for 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. Thus, the main questions for the SENTINEL's Demand Work Package are:

1. How will the energy demand profile of the building, transport and industry sector look like in 2050 if no further actions/policies are taken?
2. What is the potential of the Member States to reduce energy demand and accordingly energy-related GHG emissions that best-practice policies can deliver by 2030 and 2050?

These two key research questions consist of further sector-specific research questions which will be discussed and answered in D3.3. In order to answer these two research questions, four different demand models are used. For instance, to calculate the total energy demand of the building sector, the HEB model will be soft linked with the DESSTINEE model. Since the HEB model has a detailed classification of both residential and tertiary buildings, the output of the HEB model that is the annual final energy demand of the residential and tertiary building sector will be used as an input to the DESSTINEE model in order to calculate the hourly energy demand and GHG emissions related to the energy demand. In this way, the WP3 models are complementing each other to calculate both hourly/annual energy demand and demand-related emissions. However, for the industry and transport sector, the energy demand and demand-related emissions will be calculated mostly by using DESSTINEE.

Figure 8 below presents the conceptual framework of the soft-linking methodology:

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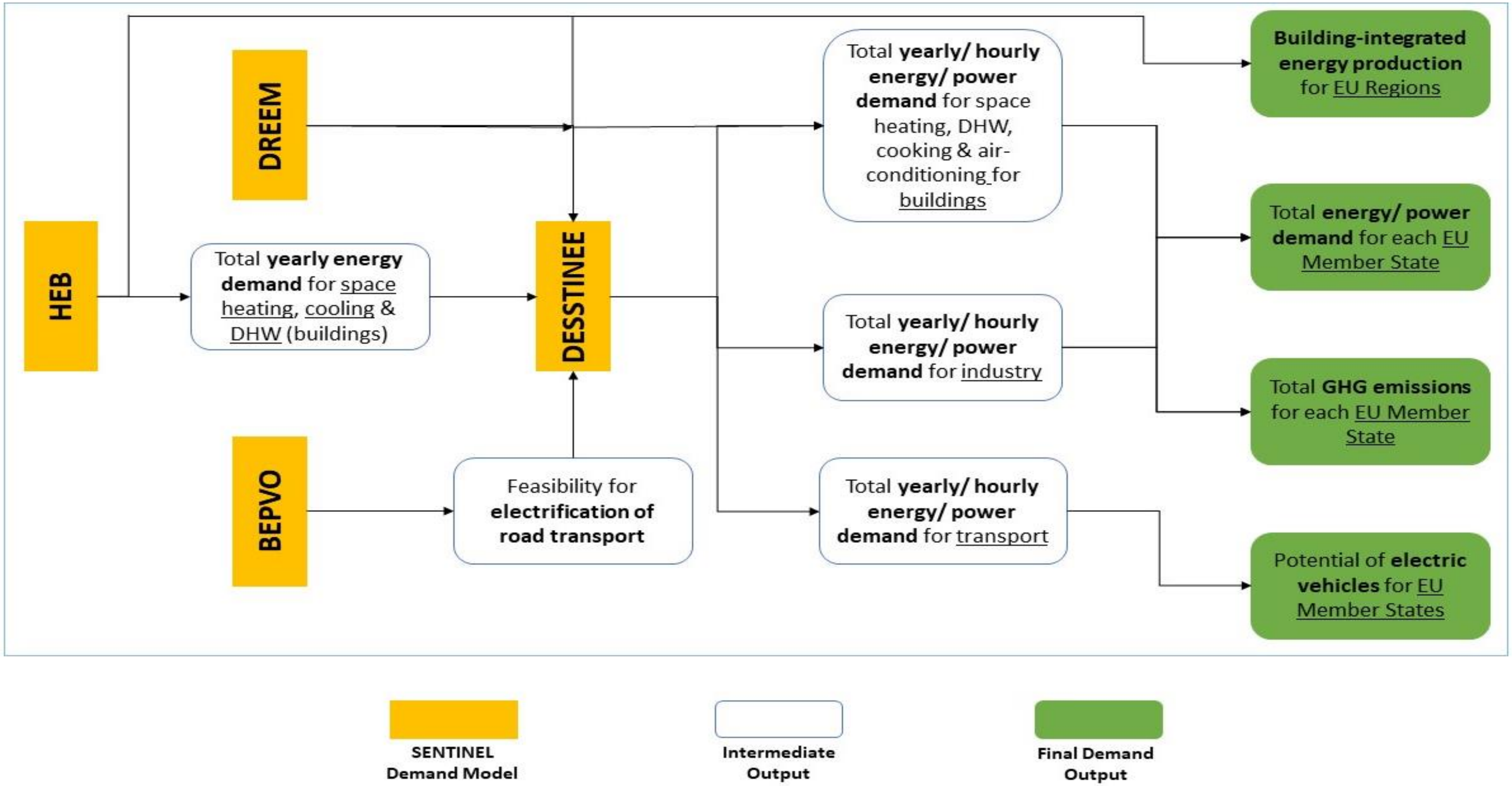

Figure 8: Conceptual framework of the soft-linking methodology of different energy demand used in SENTINEL

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In the next step, we will start producing results by following this conceptual framework of soft-linking demand models. The final outcome of the demand module will then be fed into the system module. The conceptual framework presented in **Figure 8** is only for WP3. **Figure 9** below shows the conceptual framework of work package interlinkages in SENTINEL.

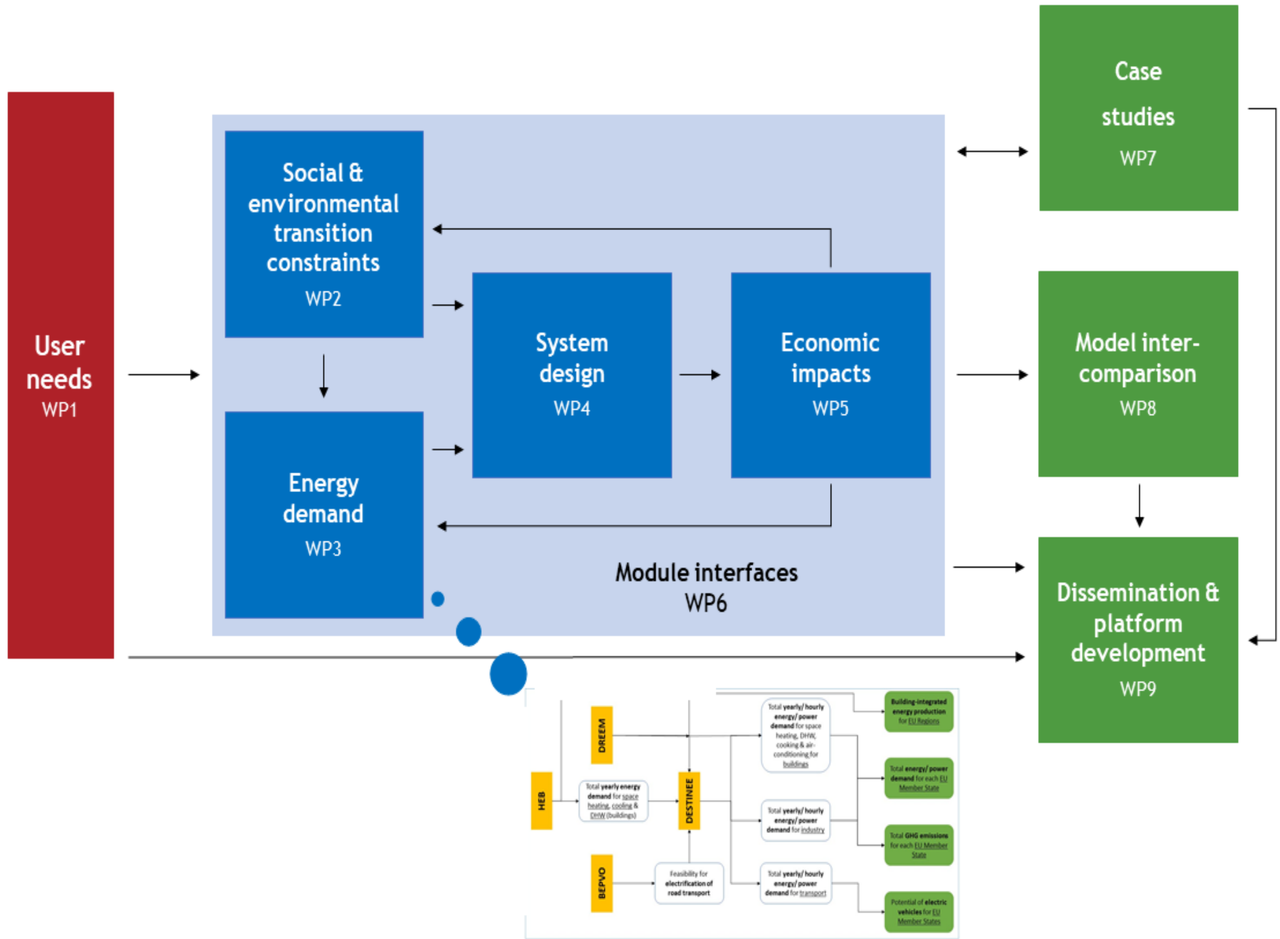

Figure 9: Conceptual framework of work package interlinkages in the SENTINEL project

In WP3, we will produce results under different scenarios which would enable the potential of ambitious energy efficiency and renewable energy policies. However, for each of the case studies, different approaches will be taken as per the case study specifications and research questions that will vary for each case study.

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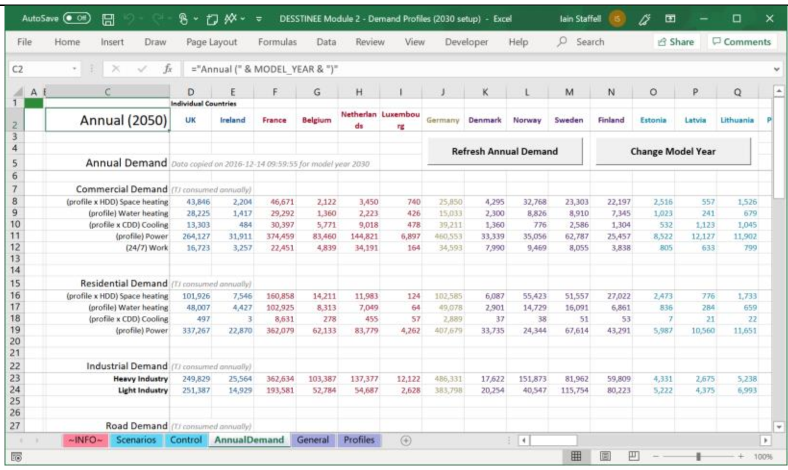
Appendices

A. DESSTINEE

A1. Demand Module

A1.1. Key model specifications (Status Quo)

Type	
Resolution: Spatial	Europe at country-level
Resolution: Temporal	Hourly
Resolution: Sectoral	Electricity, heating, transport, industry
Technical implementation	Excel & VBA. Spreadsheet interface. Works on Windows (possibly on Mac)
Availability: Type of licence	Creative Commons Attribution Share-Alike 3.0 (CC-BY-SA-3.0)
Availability: Software download	https://tinyurl.com/desstinee
Availability: User manual	https://tinyurl.com/desstinee
Screenshot of the model interface	

A1.2. Mathematical model formulation, key assumptions, and uncertainties

Key assumptions and uncertainties
Electricity demand is built up from sample profiles (24-hours profile for a typical summer and winter day) for each sub-sector.

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These profiles are the key source of uncertainty, but extensive validation has been used against actual demand profiles across Europe.

A1.3. Model inputs and outputs

Key inputs	Dimensions (Space/Time)
Population growth	Region
GDP per capita	Region
Fuel and carbon prices	Region, Sector
Efficiency improvement	Region, Sector, Technology
Fuel switching	Region, Sector, Technology
Service demands (Demand for energy services (rather than energy itself), for example transportation (measured in person-kilometres) or thermal comfort)	Region, Sector
Typical-day profiles	Sector, Technology
Heating & Cooling thresholds	Region
Key outputs (decision variables)	
Electricity demand	Region, Sector, Time
Demand for other energy vectors	Region, Sector

A2. Supply Module

A2.1. Key model specifications (Status Quo)

Type	
Resolution: Spatial	Europe at country-level
Resolution: Temporal	Hourly
Resolution: Sectoral	Electricity
Technical implementation	Excel & VBA. Spreadsheet interface. Works on Windows (possibly on Mac)
Availability: Type of licence	Creative Commons Attribution Share-Alike 3.0 (CC-BY-SA-3.0)
Availability: Software download	https://tinyurl.com/desstinee

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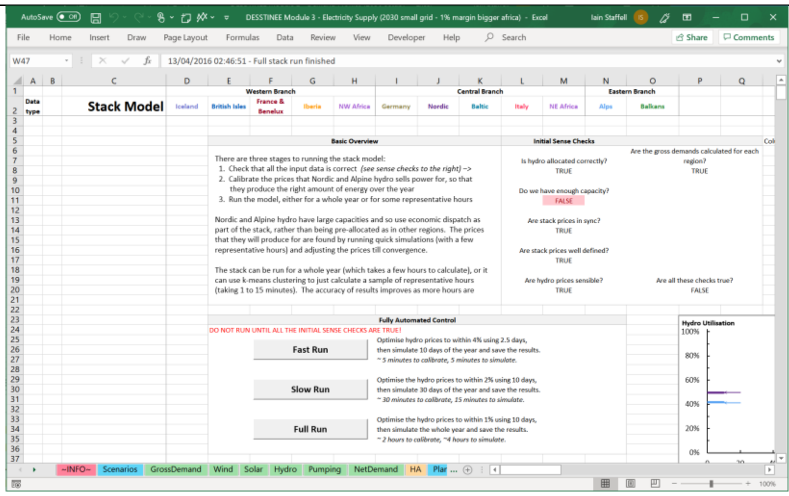
Availability: User manual	https://tinyurl.com/desstinee
Screenshot of the model interface	

A2.2. Mathematical model formulation, key assumptions, and uncertainties

Key assumptions and uncertainties
There are competitive markets with no monopolistic behaviour.
There are no inter-temporal constraints on generator operation (e.g., start-up times and ramping rates are ignored).
The only form of electricity storage is pumped hydro (something to be improved on during SENTINEL).
Future prices for fuels and carbon are known.

A2.3. Model inputs and outputs

Key inputs	Dimensions (Space/Time)
Generation capacity	Region, Technology
Transmission capacity	Region, Technology
Efficiency	Technology
Fuel cost	Technology
Operating costs	Technology
Carbon intensity	Technology
Availability	Technology
Carbon Price	Region

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Electricity demand	Region, Time
Renewable generation	Region, Technology, Time
Key outputs (decision variables)	
Energy production	Region, Technology, Time
Transmission flow	Region, Technology, Time
Key outputs (derived)	
Cost	Region, Time
Carbon emissions	Region, Time
Capacity factors	Region, Technology, Time

B. DREEM

B1. Key model specifications (Status Quo)

Type	
Resolution: Spatial	Country
Resolution: Temporal	1-minute data
Resolution: Sectoral	Building, Electricity
Technical implementation	Python 3, Modelica (runs on Dymola environment)
Availability: Type of licence	To be made available under a free and open license during the project
Availability: Software download	To be uploaded at https://github.com/ during the project
Availability: User manual	To be developed during the project
Screenshot of the model interface	Outputs are CSV, txt, Excel files and python figures. **Dymola interface**

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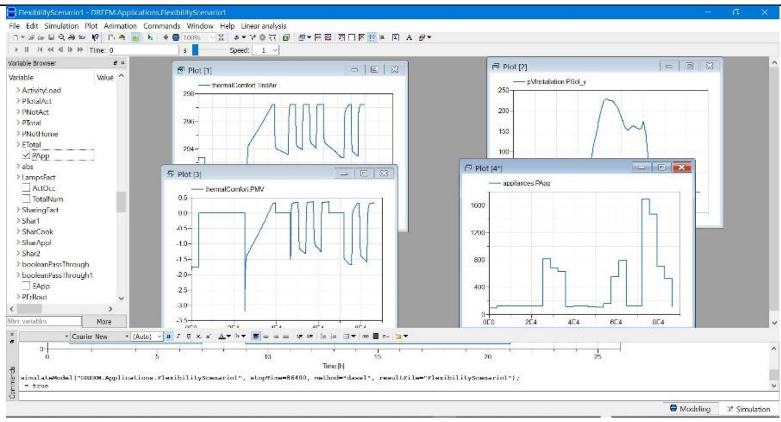
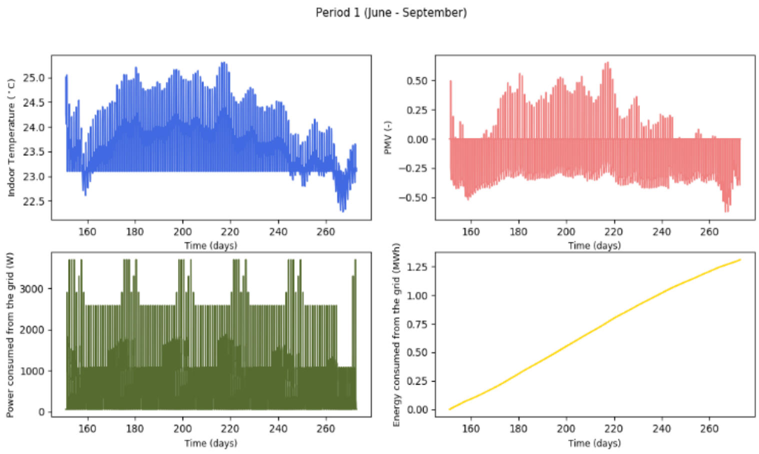


Python figures



B2. Mathematical model formulation, key assumptions, and uncertainties

Key assumptions and uncertainties
The model uses Typical Meteorological Year (TMY) weather data format (i.e., TMY3). To address limitations of existing models (i.e., detailed input data requirements, high discretization, and excessive computational runtimes) the model builds on the concept of 'reduced (low)-order' modules that represent adequately building thermal dynamics for the purposes at hand. At this version, the model focuses only on single-family houses. The model uses many simplified assumptions to simulate various aspects of energy demand (i.e., occupancy and occupants' behaviour, sharing of appliances, etc.) focusing on a minimal set of easily obtainable parameters and statistics (such as from surveys or census data), without relying on historical data.

The "Thermal comfort" module of the model builds on the Fanger approach (Fanger 1970), using the characteristic numbers Predicted Mean Vote and Predicted Percentage of Dissatisfied to compute the thermal comfort of occupants based on the "DIN EN ISO 7730", "ASHRAE 55" and "EN 15251" standards.

At this version, the model focuses on the inclusion of technologies that enable demand-flexibility, as PV installations and electricity storage (i.e., batteries), and devices as smart thermostats and energy management control systems.

The model simulates Demand-Response mechanisms as derived through: (i). considering Hourly Electricity Prices and a Limiting Price, and (ii). a more "real-world" situation, in which a central planner, that attempts to maximize flexibility value by issuing Demand-Response signals, is assumed. This entity learns the optimal policy that maximizes its revenues through an optimization approach based on Reinforcement Learning theory.

The model builds on the concept of rule-based control strategies. The algorithm used uses the minimum and normal indoor temperature setpoints, the indoor temperature of the building and the state-of-charge of the storage. The algorithm controls the operation of the HVAC system and the PV and storage installations, and regulates the temperature setpoints for space heating/ cooling and the storage charging/ discharging. The indoor air temperature is generally maintained at a constant setpoint that allows thermal comfort during occupied periods, while the control strategy provides proper setpoints for minimum energy use, without jeopardizing thermal comfort. The proposed changes to setpoints are made by increasing or decreasing the indoor air temperature setpoint by small, fixed values to achieve further energy savings, while respecting thermal comfort of the occupants. The algorithm allows, also, for considering Demand-Response events.

B3. Model inputs and outputs

Key inputs	Dimensions (Space/Time)
Weather data	Region/ Minute
Building typologies & envelope specifications	Country-Region/ Monthly
Occupancy & activity profiles	Country/ Daily
Appliances (traits, power ratings and use characteristics)	Country/ Daily

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Thermal comfort parameters/ Thermostat setpoints	Country/ Monthly
Competitive electricity consumption tariffs and other regulated charges	Country/ Yearly
System Marginal Prices	Country/ Hourly
HVAC, PV & storage installations, smart-thermostat	Technology-specific: Settings assumed by the user- specifications depending on the technological option selected
Key outputs (decision variables)	
Demand-Response policy that optimize supplier's benefits	Country/ Hourly
Key outputs (derived)	
Net building energy demand	Country/ Hourly
Self-consumption/demand-flexibility benefits for consumers	Country/ Monthly-Yearly
Aggregated results for a number of buildings	Country/ Hourly
Benefits/losses for suppliers	Country/ Monthly-Yearly

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C. BEPVO

C1. Key model specifications (Status Quo)

Type	
Resolution: Spatial	Zones of a city defined in terms of arbitrary polygon planes
Resolution: Temporal	1-hour for the spatial distribution of cars. 1-second for the undertaken trips of cars
Resolution: Sectoral	Transport
Technical implementation	Python Linux, MAC OS and Windows will be supported
Availability: Type of licence	Creative Common License
Availability: Software download	To be uploaded at https://github.com/ during the project
Availability: User manual	https://github.com/ArsamAryandoust/CarParkingMaps https://github.com/MMWeb87/BEVPO
Screenshot of the model interface	Not available yet

C2. Mathematical model formulation, key assumptions, and uncertainties

The key assumptions are that the probability of driving and choosing a trip destination for individuals is a function of changing travel times between the zones of a city throughout an entire cycle of a circadian rhythm.

C3. Model inputs and outputs

Key inputs	Dimensions (Space/Time)
Mean of measured OD travel times	seconds
Standard deviation of measured OD travel times	seconds
Key outputs (decision variables)	
Number of OD trips undertaken at different times of a day/ week/ season/ year	unitless (positive integer or zero) resolution in time: 1h

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	resolution in space: polygons of different sizes, each of several km^2
Number of cars present/parked in each zone of a town at different times of a day/ week/ season/ year	unitless (positive integer or zero) resolution in time: 1h resolution in space: polygons of different sizes, each of several km^2
Key outputs (derived)	
Distribution of cars among city zones	Unitless (real value between zero and one) resolution in time: 1h resolution in space: polygons of different sizes, each of several km^2

D. HEB

D1. Key model specifications (Status Quo)

Type	
Resolution: Spatial	European Union-28 at country level along with the data for US, China, and India
Resolution: Temporal	Yearly data
Resolution: Sectoral	Building
Technical implementation	Python 3
Availability: Type of licence	Creative Common License
Availability: Software download	N/A
Availability: User manual	Diana Urge-Vorsatz, Ksenia Petrichenko, Miklos Antal, Maja Staniec, Michael Labelle, Eren Ozden, Elena Labzina:

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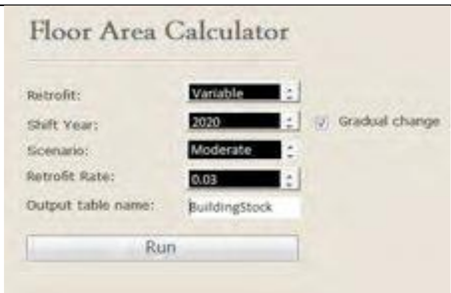
	Best Practice Policies for Low Energy and Carbon Buildings. A Scenario Analysis. Research report prepared by the Center for Climate Change and Sustainable Policy (3CSEP) for the Global Best Practice Network for Buildings. May 2012
Screenshot of the model interface	

D2. Mathematical model formulation, key assumptions, and uncertainties

Key assumptions and uncertainties
Retrofit buildings consume 30% less than standard buildings in Moderate & Deep Efficiency Scenarios and 10% less in Frozen Efficiency Scenario for the regions in general. **Space heating & cooling in commercial and public buildings are determined by real case data and design alteration between building types for the missing data points (Hotels & Restaurants: 1.0, Education: 0.9, Hospitals: 1.3, Offices: 0.7, Retail: 0.8, Others: 0.6).** **Values for EU–27 are the averages for each climate zone among EU countries.** **Fixed emission factors. This assumption is made in order to evaluate the effect of energy demand reduction in buildings and does not take into account changes on supply side, thereby, not considering its potential decarbonisation.**

D3. Model inputs and outputs

Key inputs
Specific energy consumption intensity (for space heating & cooling)
Retrofit rates
Regions
Socio-demographic, macro-economic data

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Scenario (Deep Efficiency Scenario, Moderate Efficiency Scenario, Frozen Efficiency Scenario)
Key outputs
Final energy consumption
CO_2 emission

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