SENTINEL

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

BUILDING A LOW-CARBON, CLIMATE RESILIENT FUTURE: SECURE, CLEAN AND EFFICIENT ENERGY

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Version	Date	Released by	Nature of change
0.1	25.01.2021	Tarun Khanna (Hertie School)	Draft version for peer-review review
0.2	12.02.2021	Jakob Thellufsen (AAU)	Comments on draft version
0.3	22.02.2021	Tarun Khanna (Hertie School)	Final Draft

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1. Introduction

This report discusses the improvements made in the three economic impacts models that are the modeling ensemble of SENTINEL WP 5, namely, the European Electricity Market Model (EMMA), the WEGDYN computable general equilibrium (CGE) model and the Business Strategy Assessment Model (BSAM). EMMA is a techno-economic model, developed to simulate the integrated north-western European power system. It models both dispatch of and investment in power plants, minimizing total costs with respect to investment, production, and trade decisions under a large set of technical constraints. WEGDYN belongs to the class of macroeconomic models, which depict the whole economy, separated into different production sectors and demand agents. At the global level, it can be configured at flexible country/ regional levels. The Business Strategy Assessment Model (BSAM) is an agent-based simulation model which simulates the Day-Ahead Scheduling (DAS) of wholesale electricity markets. It outputs the system marginal price (SMP), the electricity mix, the generation schedule of all resources, the profit/loss of each generator, and the level of curtailment applied to renewable energy sources. It is currently developed and calibrated to model the specificities of the Greek wholesale electricity market. Figure 1provides a snapshot of the models. Together these three models aim to capture micro- and macroeconomic impacts of the energy transition. Under Task 5.2 of SENTINEL, improvements were made to the structure and functioning of these three models to match user needs. These refinements are detailed in the following sections.

Figure 1: The modeling ensemble of SENTINEL WP5.

EMMA

Power system optimization
- Linear optimization problem
- Minimization of *power system* costs which include fixed and variable costs of power supply
- **Main outputs:**
  - Investment in new capacities
  - Decommissioning of existing capacities
  - Dispatch of the power plant fleet

BSAM

Agent-based power dispatch model
- Agent-based simulation of day ahead *wholesale electricity market*
- Machine learning simulation of generators' bidding strategy
- Unit commitment and economic dispatch simulations minimizing electricity generation costs at a system level
- **Main outputs:**
  - Electricity mix
  - CO_2 emissions
  - System marginal price
  - Curtailment

WEGDYN

Computable General Equilibrium (CGE)
- Macroeconomic model of the *global* economy
- Multi-region (focus: EU MS level), multi-sector (input-output), multi-agent (private & public)
- Top-down assessment of policy interventions
- (In)direct effects driven by relative price mechanism
- **Main outputs:**
  - GDP and decomposition
  - Economic welfare
  - Sector turnover
  - CO_2 emissions

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Trends and modelling paradigms

The improvements made to the three models were motivated through work carried out in Task 5.1, Task 7.1, and WP 1 of the SENTINEL project. With Task 5.1, the University of Graz (Uni Graz) and the Hertie School (HSOG) reviewed the literature on observed trends and modelling paradigms in the context of economic impact assessments. The outcome of this research is documented in deliverable 5.1 of the SENTINEL project (Mayer, 2020). In Task 7.1, the University of Piraeus (UPRC) performed stakeholder consultation to co-design the narrative for the Greek case study of SENTINEL. As part of the consultation, information was gathered regarding improvements that could be made to BSAM to improve the simulation results of the Greek wholesale electricity market. The insights gained through the processes influenced the selection and design of the model improvements that are documented in this report. Since these insights are model specific, a summary of the relevant outcomes is included in the respective sections on modelling gaps for the individual models.

Accounting for user needs

To identify the needs of different stakeholder groups, SENTINEL project partners implemented a multi-methods approach including qualitative interviews, an online survey, and a stakeholder workshop (WP 1). They performed 32 interviews with four different stakeholder groups: (i) policymakers, working in the governments/European Commission or governmental organizations; (ii) scientists and analysts, working in academia or consulting; (iii) energy industry representatives, including transmission and distribution system operators; and (iv) representatives of non-governmental organizations. SENTINEL partners also invited these stakeholders to an online "User Needs Workshop" in October 2020 to discuss the expectations of energy modelling for the European energy transition. The workshop's outcome is summarized in deliverable 1.2 (Süsser et al., 2020). As a part of the work on model improvements, WP 5 partners presented the three economic-focused models discussed in this report, as well as their key planned model improvements. Discussion with the stakeholders followed, about the relevance of the model's functionalities, model improvements and model linkages (within WP5) to the work and need of the stakeholders. The stakeholders appreciated our planned improvements and provided us with useful insights which we further incorporated.

Guidance for model improvement

Based on the literature review on modelling trends and paradigms, the expertise of the involved project partners, and considering the user needs, we identified the following key areas for enhancing the capabilities of economic impact models covered in this project.

- Exploration of distributional effects at the level of economic sectors (incl. energy) and private and public households by improving the WEGDYN model.

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- Exploration of the effects of (de)commissioning and (in) flexible energy production at a higher resolved technological level by adding these features to the EMMA model.
- Evaluation of the evolution of the electricity mix as RES technologies' capacity increases in the generation portfolio by using the improved BSAM model.
- Provision of a comprehensive, consistent, and tractable assessment of the trade-offs and synergies related to the energy transition (distributional effects, emission reduction targets, competitiveness, etc.) by soft linking of EMMA, BSAM and WEGDYN (to be covered in deliverable 5.3).

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2. EMMA

Model overview

The open-source EMMA, is a techno-economic model of the integrated North-Western European power system, covering Germany, France, Belgium, the Netherlands, Poland, Sweden, and Norway. During the SENTINEL project, the geographical scope will be expanded to include Greece and perform simulations for the Greek case study. EMMA simulates both dispatch of and investment in power plants, minimizing total investment costs, production, and trade decisions under a large set of technical constraints. In economic terms, it is a partial equilibrium model of the wholesale electricity market with a focus on the supply side. It calculates short-term or long-term optima (equilibria) and estimates the corresponding capacity mix as well as hourly prices, generation, and cross-border trade for each market area. Model formulations are parsimonious while representing wind and solar power variability, power system inflexibilities, and flexibility options with appropriate detail – such as an hourly granularity. Technically, EMMA is a linear program with about two million non-zero variables.

Gaps identified for improvement

The search into modelling literature performed as part of Deliverable 5.1, highlighted sector coupling as a key aspect of the energy transition and a critical feature of economic impact models (Mayer, 2020). While sector coupling is natively accounted for in top-down approaches (such as the CGE model WEGDYN), this is not necessarily the case for the focused bottom-up models (such as the power system model EMMA). In particular, the link with the heating sector has been selected for a deep-dive because (i) the linkage is already pronounced in today's energy system, (ii) it has large potentials in terms of energy supply, (iii) the available technologies are relatively clearly defined and (iv) the literature on power-heat-linkages is rich when compared to other power-to-X linkages (see section 2.2. of Mayer, 2020). This motivated the overhaul of the way combined heat and power generation units (CHP) are modelled in EMMA.

Another key aspect of modelling electricity future is flexibility. Technological progress and policy interventions will increase the share of variable renewable energy (e.g., wind and solar). This will make the residual load more volatile and increase the need for flexibility. Baseload plants are typically unable to quickly adjust their output due to restrictions on how fast these plants can ramp up or ramp down their output. These restrictions also differ with respect to technology (e.g., are stricter for coal compared to gas-fired power plants) than for gas-fired power plants. Accurate simulation of the system thus required the EMMA model to be updated to consider cycling costs and restrictions for each technology.

The EMMA model was also updated to represent not only the various technologies for electricity production and their flexibility but also the vintages of these technologies. Older vintages of the same technology tend to be less efficient and less flexible. Incorporating the vintages thus enables us to understand the utilization and economic viability of the existing technologies of various vintages to present a more fine-grained version of the distribution of the impacts of the energy transition across technologies.

Finally, considering the scenario frameworks developed as part of the SENTINEL project and, in particular, the role of investigating carbon neutrality, EMMA is going to be complemented with key features to allow for a representative outlook.

Improvements implemented in the model

CHP generation

One of the major inflexibilities in European power systems is combined heat and power (CHP) generation, where heat and electricity is produced in one integrated process. This configuration can force plants to generate electricity, even if the electricity price is below their variable costs (e.g., when heat demand is high whilst residual load is low). The CHP must-run constraint represented by equation (1).guarantees that the electricity generation of each of the five coal- or gas-fired CHP technologies h does not fall below a minimum level $g_{t,r,h,v}^{min}$, derived from the heat demand. This minimum electricity generation is a function of the amount of electric CHP capacity of each technology and vintage $\hat{k}_{r,h,v}$, the minimum electricity generation profile $\psi_{t,r,h}^{min}$, and the technical availability $\alpha_{t,r,h}$. The minimum electricity generation profile is derived from the heat demand profile $\varphi_{t,r}^{heat}$, considering the design[1] power-to-heat ratios σ_h^{CHP} of different CHP types, namely backpressure turbines (BP), extraction-condensing turbines (EC), and exhaust heat recovery (EH), which are weighted by their technology-specific shares in electric capacity χ_h^{CHP}. The heat demand profile is based on ambient temperature and captures the distribution of heat demand over time, relative to the peak demand. The equation (2) accounts for CHP constraints on the maximum power generation by $g_{t,r,h,v}^{max}$. The maximum generation is a function of the amount of CHP capacity of each technology $\hat{k}_{r,h,v}$, the maximum electricity generation profile $\psi_{t,r,h}^{max}$, the non-CHP capacity $\hat{g}_{r,h,v} - \hat{k}_{r,h,v}$, and the technical availability $\alpha_{t,r,h}$. The maximum electricity generation profile captures the characteristics of the different CHP types: the maximum electricity generation of backpressure turbines is proportional to the heat production, according to the fixed power-to-heat ratio σ_h^{BP}; the maximum power production of extraction-condensing turbines is inversely proportional to the heat production, according to the power-loss coefficient β_h^{EC}; and exhaust heat recovery has negligible

[1] The operational power-to-heat ratio can be larger than the design power-to-heat ratio for extraction-condensing turbines and exhaust heat recovery.

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implications for the maximum power output. The operational constraints for backpressure and extraction-condensing turbines as well as a combination of these are illustrated in Figure 1.

$$g_{t,r,h,v} \geq g^{min}_{t,r,h,v} = \hat{k}_{r,h,v} \cdot \psi^{min}_{t,r,h} \cdot \alpha_{t,r,h} \qquad \forall\, t,r,h,v \quad (1)$$

s.t.

$$\psi^{min}_{t,r,h} = (\chi^{BP}_h \cdot \sigma^{BP}_h + \chi^{EC}_h \cdot \sigma^{EC}_h + \chi^{EH}_h \cdot \sigma^{EH}_h) \cdot \varphi^{heat}_{t,r}$$

$$g_{t,r,h,v} \leq g^{max}_{t,r,h,v} = \left(\hat{k}_{r,h,v}\, \varphi^{max}_{t,r,chp} + \left(\hat{g}_{r,h,v} - \hat{k}_{r,h,v}\right)\right) \alpha_{t,r,h} \qquad \forall\, t,r,h,v \quad (2)$$

s.t.

$$\psi^{max}_{t,r,h} = \chi^{BP}_h \cdot \sigma^{BP}_h \cdot \varphi^{heat}_{t,r} + \chi^{EC}_h \cdot \left(1 - \beta^{EC}_h \cdot \varphi^{heat}_{t,r}\right) + \chi^{EH}_h$$

Where,

$g_{t,r,h,v}$ is electricity generation of the five coal- or gas-fired CHP technology h,
$\hat{k}_{r,h,v}$ is amount of electric CHP capacity of each technology and vintage,
$\psi_{t,r,h}$ is electricity generation profile,
$\alpha_{t,r,h}$ is technical availability,
$\varphi^{heat}_{t,r}$ is heat demand profile,
σ^{CHP}_h is design power-to-heat ratios of different CHP types,
χ^{CHP}_h is technology-specific shares in electric capacity.

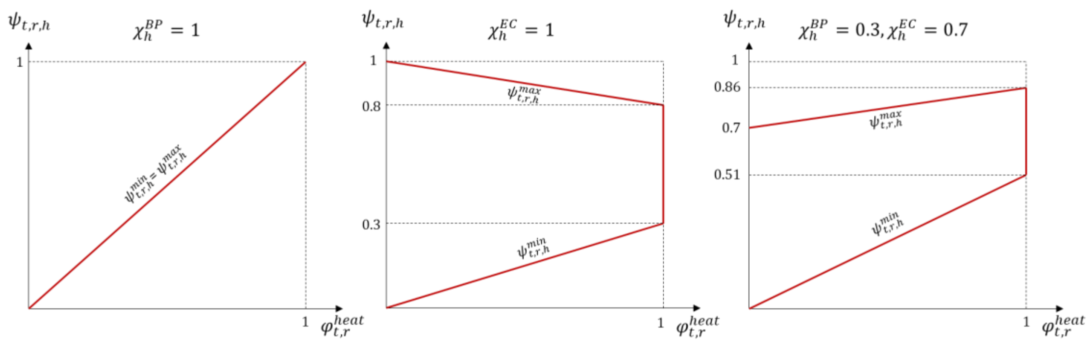

Figure 2: Operational CHP constraints for backpressure turbines (left), extraction condensing turbines (center), and a combination of these (right).

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Cycling costs and constraints

Cycling restrictions and costs are typically faced by thermal generation units when varying their power output. These variations are driven by the need to meet fluctuating residual demand. The decreasing levelized cost of energy (LCOE) of variable renewable energy (VRE) and policy targets will increase the share of installed VRE. Because of this, the volatility of the residual load is expected to increase as well, causing the need for conventional technologies adjusting their power output more frequently (and faster). This can be interpreted as an increasing requirement on system flexibility.

The variation on generation between a point in time $(t-1)$ and its succeeding (t) is represented by two positive defined variables $(g^{+}_{t,r,k,v}\text{: generation increase},\ g^{-}_{t,r,k,v}\text{: generation decrease})$. Specific ramping cost (rc_k) and ramping constraints (rr_k) are input parameters that characterize a technology. These inputs parameters paired with the calculated variations on generation are the used to calculate ramping costs $(RC_{t,r,k,v})$ and ramping constraints $(RR_{t,r,k,v})$ as shown in Equation(3). Finally, the ramping costs are added to the system costs i.e., the objective function to minimize. This implementation adapts the work of (Traber & Kemfert , 2009) to the EMMA model, in terms of ramping specification as well as of mathematical formulation.

$$
\begin{aligned}
& g^{+}_{t,r,k,v} - g^{-}_{t,r,k,v} = g_{t,r,k,v} - g_{t-1,r,k,v} \qquad \forall\, t,r,k,v \qquad (3)\\
& RC_{t,r,k,v} = rc_k \cdot g^{+}_{t,r,k,v}\\
& g^{+}_{t,r,k,v} \leq RR_{t,r,k,v} = rr_k \cdot \hat{g}_{r,k,v}\\
& g^{-}_{t,r,k,v} \leq RR_{t,r,k,v} = rr_k \cdot \hat{g}_{r,k,v}
\end{aligned}
$$

Simplifications and limitations. We assume that ramping constraints are symmetrical (i.e., similarly affect ramp-up and ramp-down activities). This formulation does not differentiate between operating a unit below or above the point of stable export load nor does it differentiate between hot and cold start. Finally, although the formulation itself captures ramping activities, we envisage this formulation to be paired with a linear parametrization of cycling costs.

Technology vintages

During the past decades, significant progress on power generation technologies has been made. This does not only refer to renewable generation but also conventional thermal generation technologies which had to adapt to changing market conditions (such as increasing commodity prices and requirements on flexibility) and regulations (such as emission standards). Since newer generation units coexist aside those that have been built in the past decades, not all power plants of a specific technology are alike the current thermal unit fleet. To account for this diversity, EMMA features up to four vintages v per technology. Power generation capacities are assigned to a vintage depending on the installation year. The choice of modelling vintages rather than individual plants is motivated

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by the trade-off between accuracy and computational tractability. In fact, although modelling individual plants is arguably more accurate, this also implies a higher number of equations and variables to the solver to be optimized.

Carbon neutrality features

Carbon neutral pathways play a key role in the scenario framework of the SENTINEL project. Some aspects of power systems (must) change radically to approach the zero-emission target. In the context of the power system model EMMA, this translates into the requirement to model dispatchable technologies with carbon capture as well as technologies capable of using VRE generation surpluses when these occurs (generating value rather than forcing power curtailment). Furthermore, the model is complemented to capture the political constraint on emissions. Hence, the following features are planned to be integrated into the EMMA model:

- **Emission constraints:** To allow for modeling scenarios compliant to the emission target, emissions are defined as model-endogenous variables. They are calculated based on technology-specific emission factors and their respective fuels consumption, which is a consequence of their dispatch. Total emissions in a year are then constrained to be lower than the target.
- **Dispatchable technologies:** Although VRE play a key role in the transition towards carbon-free electricity system, their firm capacity is comparably low. To ensure security-of-supply, they need to be complemented by other dispatchable technologies. Under the condition of carbon neutrality, alternative technologies that can replace conventional fossil-based generation units have to be considered. Because of this, the set of modelled technologies is complemented by carbon capture and storage.
- **Power-to-Hydrogen:** The steep learning curve of PV and wind turbines make these technologies economically attractive instruments to reach carbon neutrality. Nevertheless, at higher penetration rates, periods where their generation exceeds demand become more frequent. To mitigate the necessity to curtail power it is required to consider technologies capable of making use of the electricity surplus. The option to invest in electrolyzers is added to the EMMA model to enable this.

Transparency

To improve accessibility and transparency of the work done in the SENTINEL project and the EMMA model, the model documentation and code is now available on GitHub: EMMA model documentation.

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3. WEGDYN

Model Overview

WEGDYN belongs to the class of macroeconomic models, which depict the whole economy, separated into different production sectors and demand agents. Specifically, WEGDYN is a computable general equilibrium (CGE) model of the global economy. The basic idea behind CGE models is that all markets are in equilibrium (i.e., supply is equal to demand) and this "general equilibrium" can be disturbed by local interventions (e.g., by an enforced switch to a new technology, or by a policy intervention), triggering relative price changes as well as demand (quantity) adjustments until a new general equilibrium emerges. From the difference between new and old equilibrium we draw conclusions on how the economy reacts to the intervention.

In SENTINEL, we deploy the global multi-regional version (WEGDYN, calibrated to the GTAP Database (Aguiar et al., 2016)), which can be run in a static-comparative as well as in a recursive-dynamic mode (see Bednar-Friedl et al., 2012, for the model documentation of the static version and Mayer et al., 2019, for the recursive-dynamic one). Moreover, WEGDYN is a multi-sector model, which incorporates up to 57 economic sectors[2]. Regarding energy, the representation of electricity supply in the WEGDYN CGE model is based on the GTAP Power Database (Peters, 2016), which distinguishes various fossil and renewable electricity generation technologies, as well as nuclear. The supply of fossil energy differentiates between coal, natural gas, crude oil, and refined oil products. Energy demand is depicted through monetary input-output flows based on the globally consistent use of region-specific social accounting matrices. The temporal resolution of CGE models is yearly, constraining the model's ability to capture intra-annual specificities of individual technologies (e.g., intermittency, seasonality) or behavior (e.g., demand profiles). This weakness can be overcome by linking WEGDYN to other (more detailed) energy models.

Gaps

The energy transition involves the introduction of new and the adjustment of existing policy measures. It includes instruments such as taxes, subsidies, direct transfers but also command-and-control regulation like fuel efficiency standards or portfolio standards. Such an introduction or adjustment of policies spurs distributional effects, possibly also in a non-intended way. The distributional effects are in turn co-determined by the underlying tax and transfer system of a country as well as income patterns across societal groups, ultimately affecting their ability to afford goods and services. Inclusivity ("leaving no one behind") is a cornerstone of the EU's *Green Deal* to get broad public acceptance. Stakeholders in the SENTINEL user needs workshop also stressed the importance of a distributional lens.

[2] https://www.gtap.agecon.purdue.edu/databases/contribute/detailedsector57.asp

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The WEGDYN model's ability to capture the direct and indirect economy-wide income and expenditure effects of targeted policy intervention (particularly in a consistent and tractable way; see Figure 3) comes, however, with a relevant shortcoming, when the model is applied in its standard version. Macroeconomic (top-down) tools. like the WEGDYN model, typically represent private consumers as a single representative household. This weakness masks potential heterogeneous effects at the household level.

For the case of the energy transformation ahead, the problem states as follows: The energy supply sector is part of long economic value chains, depicted with input-output relations in the model. Local policy interventions (e.g., RES portfolio standards) trigger relative price changes of income components (e.g., wages, capital rents), as well as on the households' expenditure side, via changed market prices for consumption goods. The net-effect of the income and expenditure channels working at the same time is unclear and renders an extended income decomposition of households' characteristics crucial (e.g., by income levels).

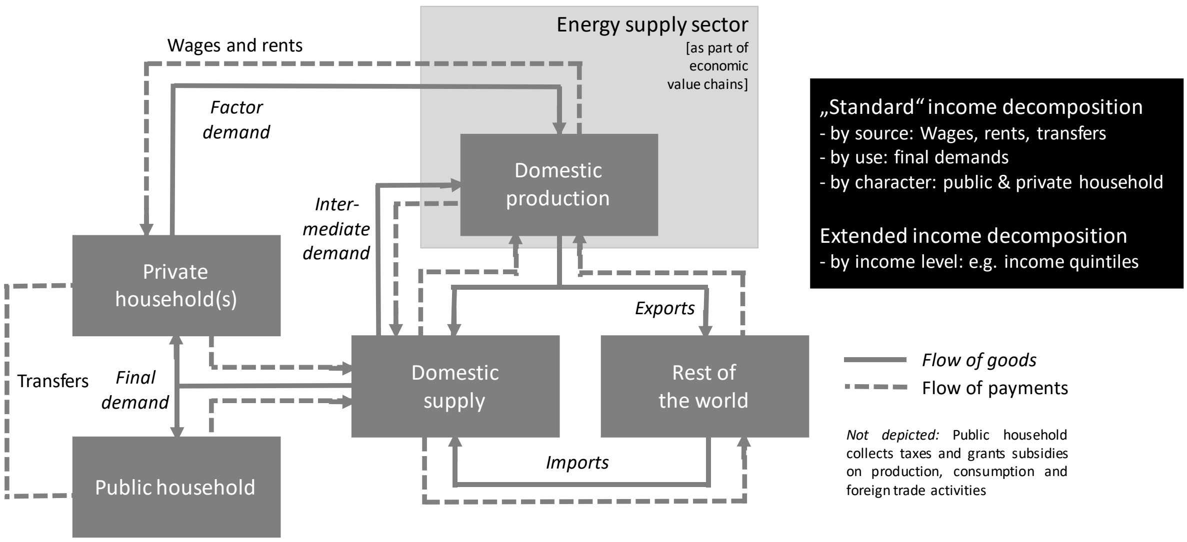

Figure 3: Flow chart of the WEGDYN model.

Improvements

Distributional impact of energy transition

Usually, individuals' budgetary balance requires that total income (Y) equate total expenditures (X) (equation (4). This warrants that everything produced is consumed by someone and payments of an economic agent mirror income streams of others. Income streams can be decomposed, as shown in equation (5, into wage earnings W and rents R (both being market income streams), as well as transfer payments TR from the public agent (e.g. child support). These components determine

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disposable income taking also into account eventual factor taxes. Expenditure streams split into consumption *C* and savings *S* (equation (6). Note that *C* is a vector of goods and services, which in the model is determined by the sectoral resolution (up to 57 sectors in WEGDYN). While the standard version of WEGDYN features the budgetary balance from two representative agents (i.e. one private household and one public household), the improvement taken in SENTINEL is adding an index *hh* to equations 4-6 in order to capture distributional effects within different groups of private households differentiated by their income level and expenditure structure.

$$Y = X \tag{4}$$

$$Y = W + R + TR \tag{5}$$

$$X = C + S \tag{6}$$

Based on the households' budget, and here for the example of Greece, we split household groups into quintiles. Figure 4 summarizes the income distribution in Greece (households' share of national equivalized national income) and Figure 4 shows the consumer basket of each household group. Top 20% income group earns 41% of national income, while the bottom 20% income group earns only 6% (Figure 4). Greek households use income largely for consumption of goods and services in the categories of nutrition and housing (Figure 5). This micro data on Greek consumer baskets reveals, for instance, that the share of expenditures for energy (electricity, gas, heating fuels) falls with income levels and the share of transport-related expenses rises with it. The energy transition impacts citizens in manifold ways, the here described economic channels are certainly a crucial dimension.

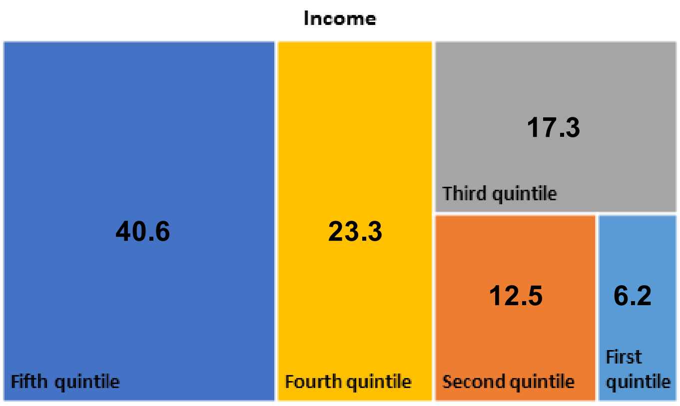

Figure 4: Income distribution in Greece (2015; based on EuroStat data; [ILC_DI01]).

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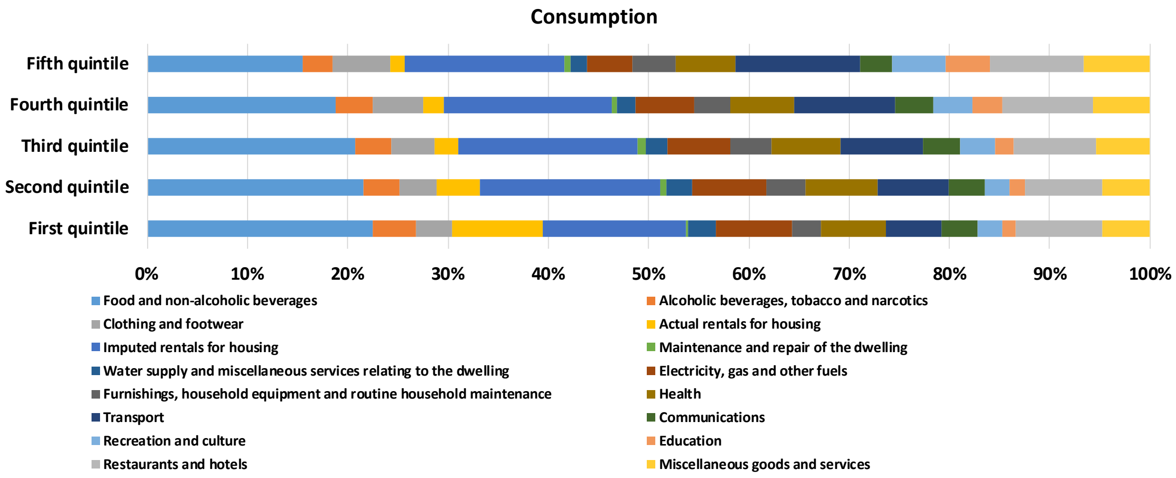

Figure 5: Income by use in Greece (2015; based on EuroStat data; [HBS_STR_T223]).

Further data collection and processing is work in progress to connect household-level information with macroeconomic accounts of the WEGDYN model for all EU member states (where micro data is available and accessible). If required, other household characteristics besides income and expenditure patterns (e.g., urban-rural) may be included depending upon the specific research question. Another remaining issue – at the time of this report – is whether household heterogeneity will be integrated directly in the WEGDYN model or distributional effects derived from the analysis *ex post*. While the former option is more appealing in terms of integrating distinct preferences (i.e., different consumption patterns and savings rates), it is also a much more data-intensive calibration task with some observations possibly not available at the intended granularity level of household characteristics.

Some further background, here focusing on the Greek case study in SENTINEL, indicates our way forward. Currently, the public system in Greece uses taxes to reduce market income inequalities rather than transfers according to empirical evidence provided by Guillaud et al. (2020). Furthermore, macroeconomic simulations show that carbon pricing in Greece (without recycling back the tax revenues to private households) would already be progressive (Landis et al., 2021), because low-income groups are "protected" by (inflation-indexed) transfers from the public hand keeping disposable income comparably stable. By contrast, disposable income of high(er)-income groups is much more subject to changes in market income and, thus, reacts much stronger to changes in policy and framework conditions. There is similar evidence for other countries (Mayer, et al., 2021, Landis et al., 2021, Beck et al., 2016). In SENTINEL, we go beyond carbon pricing, looking at the effects of energy-sector specific measures such as shutting down fossil-fueled power plants. To be precise, we couple various quantitative models (e.g., for the Greek case study, to be covered in Deliverable 5.3, the ensemble of BSAM-EMMA-WEGDYN) to explore *inter alia* income distributional effects and changes in patterns of consumption.

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Co-benefits of energy transition

A further improvement of WEGDYN modelling is to incorporate an *ex-post* analysis of the co-benefits of the energy transition. These include, for instance, changes in congestion time due to structural changes in transport or changes in other air pollutants due to less fossil-based residential heating and the connected health benefits. By that, we aim at complementing impacts on traditional economic indicators such as gross domestic product by a diverse set of sub-proxies measuring human wellbeing.

Transparency

The core functionalities of the WEGDYN model are already accessible through peer-reviewed publications (Bednar-Friedl et al., 2012; Mayer et al., 2019). To improve accessibility and transparency of the work done in the SENTINEL project, processed data and model code will be shared through online repositories (GitLab and/or Zenodo).

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4. BSAM

Model Overview

BSAM simulates the Day-Ahead Scheduling of the Greek central dispatch wholesale electricity market in an agent-based manner. Specifically, BSAM (i) simulates the generators' progressively accumulated knowledge relevant to the bidding strategy they follow for their electricity generation aiming at maximization of their profit, (ii) simulates operational market rules (e.g., price caps, demand, and reserve requirements), and (iii) uses the generators' bids to solve in an hourly resolution the Security Constrained Unit Commitment and Economic Dispatch problems with the objective to minimize system-wide electricity generation costs (Wood, Wollenberg, & Sheblé, 2013).

The model has an hourly resolution. Input data are inserted in CSV format and are grouped in two categories: (i) the constantly changing historical data and projections containing the electricity demand, RES generation, hydro generation, electricity import prices, fuel prices (i.e., lignite and natural gas), and EU Emissions Trading System (EU ETS) carbon prices, and (ii) the un-/slowly-changing data containing technical and economic characteristics of thermal resources, interconnection capacities with neighboring countries, and market-related data (e.g., price caps, system reserves, etc.). Using this data BSAM simulates the Day-Ahead Scheduling (DAS) problem and outputs in an hourly resolution the system marginal price (SMP), the electricity mix, the generation schedule of all resources, the profit/loss of each generator, and the level of curtailment applied to RES generation.

To do so, BSAM features a **Unit commitment module**, which solves the Security Constrained Unit Commitment and Economic Dispatch problems. The constraints considered are:

(i) System constraints

- Total electricity generation must be equal to demand.
- Committed generating resources must be capable of generating electricity within the upper and lower electricity demand thresholds (considering spinning reserves).

(ii) Generating resources' constraints

- Resources should operate between their technical minimums and maximums.
- 'Must run' resources should always be online.
- Resources' operation should also comply with their minimum uptimes and downtimes as well as with their start up times.

To solve these constraints, the Enhanced Priority Listing algorithm (Delarue, Cattrysse, & D'haeseleer) is applied. This algorithm ranks agents' price bids in an increasing order and then iteratively commits units and clears the respective bids considering both the system and generating resources' constraints. Agents' bids are modelled within an **agent module**, which models generators as competitively interacting agents who learn to bid their generation, towards profit maximization,

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while being competitive enough to enter the market. Finally, market variables, such as residual load (i.e., the remaining electricity demand after subtracting the demand covered by RES generation), system reserves, price caps, and shutdown decisions for low-utilized plants are managed by a **wholesale electricity market module**.

Although the model is currently calibrated for the Greek wholesale electricity market, it can simulate any day-ahead market if all necessary data is available. The only exception is the hydro generation which is regulated for the case of Greece, and the current implementation of BSAM is based on the respective regulations. Detailed features of the model will become available in (Kontochristopoulos, Michas, & Kleanthis, under review).

Subsections 4.2 and 4.3 present the identified gaps and respective improvements, mainly targeting the **Unit Commitment module**.

Gaps

In the context of the SENTINEL project, electricity market experts from the Public Power Corporation (PPC), the Greek Independent Power Transmission Operator (IPTO), and a development agency collaborating with the Greek Ministry of Environment and Energy provided feedback regarding BSAM capacities and modelling gaps. These gaps include the need for (i) updated and accurate input data for conventional generators and system reserves, (ii) calculation of carbon emissions of conventional power plants and their respective costs as part of the units' variable costs, (iii) an updated methodology for the calculation of electricity generation from hydro plants according to national regulations, and (iv) simulation of storage systems.

Regarding data accuracy, experts highlighted the need for accurate data for conventional power plants (i.e., lignite and natural gas power plants), which are the ones participating in the unit commitment and economic dispatch problems (RES are modelled with priority dispatch). Conventional power plants' participation to the electricity generation mix is expected to decrease, however, they will still play an important role in the current decade. BSAM, as a perfect-foresight model, does not account for uncertainty. Therefore, uncertainty in the outputs of BSAM should be mitigated by using as accurate data, as possible. For this reason, one significant need has been the collection of data for the main characteristics of conventional units, which are: **(i) standing data**, namely the type of their technology, the used fuel's data (e.g., heating values, carbon content, cost, etc.), their generation capacity, their technical minimum uptimes, downtimes, start-up and transition times and their heat rates, as well as **(ii) status and availability** (i.e., scheduled commissioning, shutdown, etc.).

Another critical aspect of the unit commitment module of BSAM lies in the hourly satisfaction of both upwards and downwards reserve requirements. According to the reserve requirements, committed dispatchable units (e.g., hydro plants and thermal power plants) must be capable of generating electricity between a lower (i.e., residual demand minus reserves) and an upper (i.e., residual demand

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plus reserves) threshold. A key gap that was mentioned by experts regarding the unit commitment module was that the reserve capacities were initially assumed to be equal to a user-defined percentage of demand. However, in Greece specific reserve capacities per hour of the day are procured (HEnEx (Operator of the Hellenic Electricity Market) , 2019). Therefore, there has been a need for updating the specific reserve capacities' simulations using data from official sources.

Another gap concerning conventional power plants has been the fact that the original version of BSAM did not account the carbon emissions' costs to the calculation of power plants' variable costs. Carbon prices and thus carbon emissions' costs have rapidly increased over the last years, while scenarios foresee a further increase in the future (Hellenic Ministry of Environment and Energy, 2019). Therefore, updating the calculation of the conventional units' variable costs, considering carbon emission costs, has been considered an important modelling need to be implemented within the unit commitment module.

In contrast to conventional power plants, whose variable costs are associated with fuel and emission costs, hydro plants have very low operational costs. However, there is an indirect cost of water usage, related to cost savings, due to the substitution of conventional power by hydro generation. This cost determines the unit price of electricity generation from hydroelectric generators as a substitute of other fuels. Specifically, the unit price of each hydro plant's generation is calculated using the cost of displaced energy from conventional sources as well as the energy availability (water level) at the respective dam. The above calculation methodology complies with that daily used by the Electricity Market Operator (HenEx) to calculate the variable cost of the hydro plants, which considers rules that set the conditions for fair competition without introducing barriers to the optimal use of water stocks (Regulatory Authority for Energy, 2016). This methodological gap was identified by IPTO experts, and along with the gaps identified for conventional power plants, have been considered important to make the Unit Commitment module of BSAM more precise in terms of the contribution of hydro and conventional power plants to the electricity mix.

Finally, in case of an electricity system with high penetration of non-dispatchable RES plants, the residual load will become more volatile, due to the intermittent nature of RES, which can put at risk uninterruptible supply and increase the electricity system's complexity as well as its flexibility needs (Hermans, Bruninx, & Delarue, 2020). To achieve high levels of RES-generated electricity penetration with acceptable levels of curtailment, energy storage is needed (Nanaki & Xydis, 2018; Mir Mohammadi Kooshknow & Davis, 2018). By utilizing storage technologies, such as battery storage, which has developed rapidly over the last years and is applicable both to large and small installations, electricity supply can be better matched with demand (Energy, Ministry of Environment and, 2019). With storage, RES plants can become a dominant source of power in the transitioning Greek electricity market, which is a focal target of the Greek NECP. For this reason, a need to model battery energy storage systems (BESS) has emerged.

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Improvements

To perform the necessary improvements, we reviewed literature of scientific articles and policy documents, and consulted with experts.

Accurate data for conventional power plants

The main characteristics of conventional units (i.e., standing data as well as status and availability), as described in the previous section, were found by reviewing the Ten-year network development plan of IPTO (Operator, Independent Power Transmission, 2018) and a relevant study from RAE (Regulatory Authority for Energy , 2011). The requirements for minimum uptimes and downtimes as well as start-up and transition times were retrieved from the System Operation Code for the Greek Transmission System (I.P.T.O. , 2019), and were verified by other literature sources (Delarue, Cattrysse, & D'haeseleer; Wood, Wollenberg, & Sheblé, 2013). Stakeholder consultation with the Greek Public Power Corporation (PPC) has proven to be key for the validation of necessary data regarding conventional power plants. Specifically, PPC provided efficiencies, capacities, minimum levels for stable generation, minimum uptimes/downtimes of PPC-owned power plants, and scheduled commissioning, de-commissioning, fuel change and shutdown of power plants.

Update of system reserve requirements in hourly resolution

After calculating the residual demand (i.e., demand minus RES generation), the upwards and downwards system reserve requirements should be satisfied in each trading period (i.e., each simulated hour). The system reserve requirements are the following (Gubina, 2019):

- Primary or Frequency Containment Reserves (FCR) which are active power reserves used to restrict frequency deviations from the system's nominal value and thus continuously keep the power grid in balance.
- Frequency Restoration Reserves (FRR) which are active power reserves, which can be used for restoring the frequency of the system to its nominal value. FRR are divided into Secondary or automatic Frequency Restoration Reserves (aFRR), which operate constantly, and their activation is triggered automatically, and Tertiary or manual Frequency Restoration Reserves (mFRR), which operate discretely and in an almost continuous manner, and can be activated manually.
- Replacement Reserves (RR) or Tertiary Reserves which are mainly utilised as a means of replacing FRR, when disturbances last longer than usual, or complementing their activations. RR are modelled in BSAM, however, they are not needed for a case study regarding the Greek electricity system, as for Greece the procurement requirement for RR equals zero (HEnEx (Operator of the Hellenic Electricity Market) , 2019).

The hourly reserve requirements are provided by HenEx (HEnEx (Operator of the Hellenic Electricity Market) , 2019).

Calculation of power plants' CO2 emissions and EU ETS emission costs

The variable costs of a conventional power plant (€) can be calculated as a sum of its fuel cost and carbon (CO2) emissions' cost (equation 7):

$$Variable\ cost\ =\ Fuel\ cost\ +\ CO2\ emissions'\ cost \tag{7}$$

The fuel cost (€) can be modelled as a quadratic function, considering the cost coefficients of different electricity generation technologies (a, b, c) (Wood, Wollenberg, & Sheblé, 2013; Delarue, Cattrysse, & D'haeseleer), which are affected by the heat rates (HR) of the units, the lower heating value of their fuels (LHV) in (KJ/kg) or (kWh/kg), and costs related to fuel type (€/MWh), and the net electricity generation (MWh) of each power plant (P) (equation 8):

$$Fuel\ cost = a \cdot P\hat{}2 + b \cdot P + c \tag{8}$$

The carbon emissions' cost (€) is related to actual generation P, and depends on projections for the EU ETS carbon prices (€/tCO2) and the carbon emissions per unit of electricity generation (tCO2/MWh) (equation 9):

$$CO2\ emissions'cost\ =$$

$$EU\ ETS\ carbon\ price\ \cdot\ CO2\ emissions\ per\ MWh\ generated\ \cdot\ P \tag{9}$$

The data needed to find the carbon emissions per unit of electricity generation for each conventional power plant (equation 10) are the HR of each plant, the LHV of its fuel, and the carbon content (CC) of the fuel (%), which were found through literature review.

$$CO2\ emissions\ per\ MWh\ generated\ =\ HR\ /\ LHV\ \cdot\ 44\ /\ 12\ \cdot\ CC \tag{10}$$

Updated hydroelectric generation calculation methodology

The price of electricity generation from hydro plants is calculated according to Greek regulations, and specifically the decision 207/2016 of the Regulatory Authority for Energy (RAE) (Regulatory Authority for Energy, 2016). According to this regulation, the unit cost of hydro generation is the sum of the cost of displaced energy from conventional sources and a cost component representing the energy/water availability at each dam. The first variable is calculated using historical data for electricity generation from conventional power plants. To calculate the second variable, we assume that:

- The water availability of a dam belonging to a drainage basin is correlated with the water availability of all the other dams of the same basin and thus each basin can be represented by only one dam.

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- Electricity generation is correlated with the water levels on each dam of each hydro plant.
- A normal distribution describes the annual water availability. To define this distribution per drainage basin, historical data of electricity generation from hydro plants is utilized.
- Historical data of electricity generation for each hydro plant are used to determine the expected monthly and annual electricity generation, which is scaled using the expected annual water availability.

Considering these assumptions, for each hydro power plant and on an annual basis, unit prices can be calculated by comparing the monthly and annual projections of electricity generation from hydro plants with the total simulated electricity generation. Unit prices increase (i.e., move towards the upper market price cap) when simulated hydro generation is larger than expected, and decrease (i.e., move towards the lower market price cap) otherwise.

The updated methodology for the calculation of the unit price for electricity generation from hydro power plants has been back tested and has proven to provide results that are on average (e.g., in annual resolution) close to reality. Consequently, the accuracy of the proposed methodology can be considered sufficient and facilitates modelling dams with no historical data on electricity generation based on the heavy correlation within a basin.

Modelling battery storage systems

To model battery energy storage systems (BESS), the battery dispatch algorithm presented by (Quoilin, Kavvadias, Mercier, Pappone, & Zucker, 2016) is used, adapted to the scope of BSAM. This algorithm aims to maximize self-consumption and thus RES integration in the electricity mix, and is developed as a standalone BESS module, which is soft linked to BSAM.

The inputs required by the BESS module consist of (i) the demand timeseries projection for the simulated period in an hourly resolution, (ii) the electricity generation timeseries of each renewable technology for the simulated period in an hourly resolution, and (iii) the technical specifications of the modelled BESS (Table 1).

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Table 1 Technical Specifications of BESS

BESS Technical Specifications	Description
C-Rate	Maximum charge/discharge power with reference to the BESS nominal capacity (e.g., ¼ C-rate means that the BESS can fully discharge in 4 hours)
Depth-of-Discharge (DoD)	The lower level of battery discharge
Round-trip efficiency	The percentage of stored energy that can be retrieved (used to model stored energy losses)
Maximum cycling duration	The maximum duration a BESS can remain in charging/discharging state to avoid stationary energy losses

Sources: (MIT Electric Vehicle Team, 2008; HOMER Energy, 2020)

Since BSAM is a wholesale market simulation model, BESS is modelled as an aggregated storage unit at a system level. The BESS dispatch algorithm runs in an hourly resolution and considers only the hourly demand and RES generation (at this point conventional generators' generation and technical constraints are not considered).

At each hour of the modelled period, electricity is stored in the BESS when RES generation is higher than demand and electricity is discharged when demand is higher than RES generation. Since in BSAM the storage system is modelled as an aggregated unit, the restriction usually mandating BESS to continue charging until they are full and discharging until they reach their DoD before reversing their charging/discharging state, is not imposed. This is because, the aggregated BESS corresponds to many decentralised BESS systems, and statistically there are always systems charging and discharging at the same time. To avoid underutilization of BESS, the maximum periods (i.e., hours) the BESS is allowed to remain in a "charging" or "discharging" state equals 24, which according to (Le Varlet, Schmidt, Gambhir, Few, & Staffell, 2020) corresponds to a low BESS utilization rate with one cycle per two days. When demand is lower than RES generation, and the excess generation cannot be stored, curtailment occurs.

Simulations start with the BESS at its DoD, ready to be charged. This State of Charge (SOC) is described by equation 11.

$$SOC_{t=0} = nc * (1 - DoD) \tag{11}$$

where:

- t corresponds to the modelled hour,
- nc corresponds to the nominal electricity capacity of the BESS, and
- DoD corresponds to the depth-of-discharge of the BESS.

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Then, at each simulation hour t the BESS is charged following the algorithm presented above and its SOC as well its charging/discharging power ($P_{ch,t}/P_{dis,t}$) are updated as follows:

$$P_{ch,t} = \min\left(\frac{nc}{C\_rate}, nc - SOC_{t-1}\right) \tag{12}$$

$$P_{dis,t} = \min\left(\frac{nc}{C\_rate}, round\_trip \cdot SOC_{t-1}\right) \tag{13}$$

$$\begin{aligned} SOC_t &= SOC_{t-1} + P_{ch,t}\text{ , if state = 'Charging'} \\ SOC_t &= SOC_{t-1} - \frac{P_{dis,t}}{round\_trip}\text{, if state = 'Discharging'} \end{aligned} \tag{14}$$

where:

- C_rate corresponds to the C-rate of the BESS, and
- $round\_trip$ corresponds to the round-trip efficiency of the BESS

As it can be seen from equations (12-14), stored energy losses are modelled during discharge, by reducing the useable amount of stored energy and by reducing the available energy after each discharge event.

During simulations, each time a charge event occurs, the amount of electricity that is stored in the BESS is added to the demand timeseries at the specific timeframe. Similarly, each time a discharge event occurs, the amount of electricity that is dispatched from the BESS is subtracted from the demand timeseries at the specific timeframe. That way, a new demand timeseries is produced, which is the main output of the BESS module, simulating storage as a demand modifier.

This new demand timeseries is given to BSAM along with the original electricity generation timeseries of each renewable technology to simulate the electricity mix also considering the conventional generators' generation and technical constraints. BSAM models RES with priority dispatch, therefore, the additional demand that has occurred due to BESS charging, only allows additional RES generation (i.e., RES generation to cover demand **and** charge the BESS) to be injected to the electricity mix before calculating the residual demand to be met by conventional generation units. Similarly, the decreased demand that has occurred due to BESS discharging, only reduces the residual demand that needs to be covered by conventional generation units. The only case that curtailment in BSAM during a simulation hour t can be larger than that simulated with the BESS module, is when the minimum uptimes of the conventional generation units committed in simulation hour $t-1$ are violated. This means that if (i) in simulation hour $t-1$ the committed units have minimum technical aggregated power, which is higher than the residual demand in simulation hour t, and (ii) there are not enough committed units that can stop generating in simulation hour t due to minimum uptime violation, RES generation has to be curtailed in order to increase the residual demand to the level of the minimum technical aggregated power of committed units that need to continue operating.

After simulations with BSAM have been completed, the level of RES penetration, the level of curtailment and the entire electricity mix is outputted, considering availability of RES generation, storage capacity, and technical constraints of conventional power plants. A last check is performed in the levels of curtailment. In every simulation hour t, if curtailment in BSAM is lower or equal to the actual RES generation at simulation hour t minus any stored energy at the same hour (equation 15) only renewable energy has been stored.

$$Curtailment \leq RES - stored\ energy \tag{15}$$

If this is the case, this means that the only curtailment simulated in BSAM is due to excess generation that could not be stored, and generation that needs to be curtailed so that conventional generation units cover part of the actual demand at simulation hour t. This check is graphically illustrated in Figure 6.

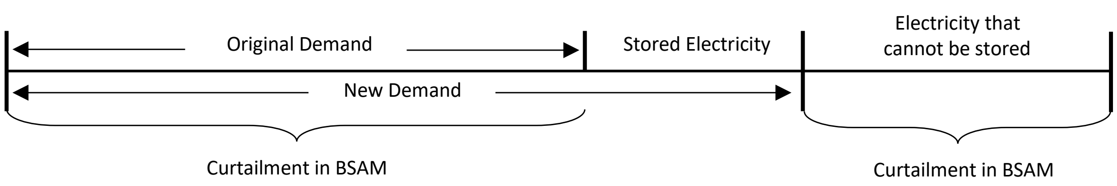

Figure 6: Curtailment check in BSAM

If equation 15 is not satisfied, this means that renewable energy that could be stored is curtailed, and electricity generated from conventional power plants is stored to avoid violating some unit(s)' minimum uptimes.

Transparency

To improve accessibility and transparency of the work done in the SENTINEL project and the BSAM model, the model documentation and underlying data is will soon be published as a research paper (Kontochristopoulos, Michas, & Kleanthis, under review) .

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