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System Models

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Abstract

This deliverable presents three different models that can be used in the verification of the developed mechanisms for the e-balance system. With the first model the system can be described at a detailed level. It takes into account the physical aspects of the grid, as well as the customer's preferences, which results in accurate results. The model has been built in a simulator that allows the user to configure and evaluate the designed scenarios.

The second model is a high level model that focusses on the energy flows within the e-balance system. The model is well suited for a fast, high level analysis of newly developed ideas.

The third model is a high level, hybrid Petri net model for analysing the resilience of the energy supply. The model allows analysing different strategies to use distributed generation and storage for resilient energy supply in case of grid failure.

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Executive Summary

This deliverable describes three models that can be used in the validation and evaluation of the developed mechanisms for the e-balance system. The three models describe the system on various level of detail, and address different aspects of the e-balance system.

The first model, presented in Chapter 2, describes the e-balance system in high detail. It includes the physical grid aspects, such as cables and transformers, smart consumer devices, as well as the user's preferences. This detailed model allows for accurate analysis of most aspects of the e-balance system, such as the hierarchical grid topology, power quality, balance of energy, etc. The model is implemented in a newly developed simulator. The simulator allows for easy analysis and comparison of the aspects of interest. This simulator will be developed further during task T5.2 and T5.3 to incorporate the algorithms developed within these tasks.

The second model, presented in Chapter 3, is a high level model which focusses on the energy flows within the grid. The model allows for a first, fast analysis of newly developed ideas. An initial basic model of a smart neighbourhood has been implemented in the Anylogic tool. The flexible tool, with its user interface, makes the model easily adaptable and extendable when necessary.

The third model, presented in Chapter 4, is a high level model for the analysis of the resilience of the energy supply. The e-balance system is capable of using the available distributed energy resources, including locally energy storage, to keep up the energy supply when the grid fails. The model allows to estimate the probability that the local energy supply will be sufficient until the grid failure is repaired.

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Abbreviations

CHP	Combined Heat and Power
CMU	Customer Management Unit
DER	Distributed Energy Resource
EV	Electric Vehicle
GHI	Global Horizontal Irradiance
HPnG	Hybrid Petri net with General transitions
LV-GMU	Low Voltage Grig Management Unit
PV	Photo Voltaic
UPS	Uninterruptable Power Supply

1 Introduction

In work package WP5 of the e-balance project an energy management platform is being developed. This management platform balances the electricity consumption within the grid to fulfil several goals: reduce CO2 emissions, defer costly grid investments, reduce transport losses, avoid peak generation usage, improve power quality, improve availability/reliability, etc.

This platform consists of devices and software that control and influence the electricity flows (or streams) within the physical grid to reach these goals. To save time and money, we initially evaluate the effect of our algorithms and measures in several simulation environments. However, a simulation that takes every aspect of the grid into account on a millisecond time scale is infeasible as it takes too long to simulate. We therefore make several specialized models to make a fast simulation possible.

The first model, presented in Chapter 1, is a low-level grid model. The model is very general and can describe many types of energy streams, such as gas, heat and electricity. This makes it straightforward to generalize the results from the e-balance project to a multi-commodity system. Within the context of e-balance, we focus on electricity. The low-level grid model takes low-level aspects like the physical grid (cables, appliances, transformers, etc.), prosumer preferences, etc., into account. During the e-balance project, we develop a simulator which uses this model. Using this simulator, we can evaluate the effect of many algorithms (mainly for balancing and resilience) on the grid. The model and the simulator are used in task T5.2 to evaluate the balancing algorithms, in task T5.3 to evaluate the power quality improvement that results from using the balancing algorithms, and in task T6.4 we compare the simulations with the results from the demonstrators.

The second model, presented in Chapter 3, is a high-level grid model. When the low level simulation takes too much time, or when several high-level ideas need to be evaluated quickly to obtain some first insights, this model is used. It enables fast simulations and is easy to adapt.

The third and last model, presented in Chapter 4, is designed specifically for the resilience of the energy supply when DERs are present. This model is based on a hybrid Petri net. Using this model, the resilience of the energy supply in case of a grid failure can be evaluated. Results of this evaluation will be presented in deliverable D5.3.

2 Low level energy models and simulation

This chapter is based on a chapter from a PhD thesis [1], and some unpublished results.

2.1 Energy models

This section describes and explains the model of the energy infrastructure, used for a low-level energy simulator, to design optimization algorithms and to verify these algorithms. The goal of the algorithms is to optimize the electricity flows through the grid by influencing individual domestic devices. Therefore, the model consists of multiple levels: the lowest level consists of the devices within buildings, a collection of devices, each with its own behaviour and optimization potential. These devices can convert, buffer and consume energy and are connected to each other in such a way that energy can flow between these devices. Buildings can exchange energy with their outer world and multiple buildings can be combined into a grid. For electricity, the grid itself also has a levelled (fractal-like) structure; it consists of multiple voltage levels. On the lowest voltage level, multiple buildings neighbourhood are grouped behind one transformer. Multiple neighbourhoods can be combined into cities with higher voltage levels, etc. Furthermore, on different voltage levels electricity is typically fed in by different scales of generators.

The model is derived using a bottom up approach. We start with modelling the behaviour of individual devices in the buildings, each with its own energy consumption, production or buffering. Next, connections between these devices are modelled, resulting in an expression for the energy streams within the building. Connections have to specify their type of energy (e.g., heat streams cannot be connected to electricity streams). Also, the interconnectivity has to be defined. For example, heat flows often from the boiler to the heat store and from there to the heating. The set of devices, how they are connected and the connections with their outer world together, form a building.

Multiple buildings are combined into a grid; all connections of the buildings with the outer world are connected to the right type of energy supply. Most types of energy supply can be modelled straightforwardly. Natural gas and district heating are hardly influenced by fluctuation in demand since gas and heat can be stored easily. Next to connections with external energy suppliers, some buildings have their own energy stock (e.g., oil fuel). These energy sources can also be modelled rather easily.

However, the electricity grid is more complicated and has a levelled structure itself. Since it is hard to store electricity, power plants have to deal with fluctuations immediately. Furthermore, to decrease transport losses there are multiple voltage levels and transformers between the voltage levels to transform the voltages. These voltage levels, the capacity of the transformers and the capacity of the grid should be incorporated in the model. Buildings are connected to the lowest voltage level. They can be connected in groups behind one transformer, depending on the power demand of each building. Power plants and renewable sources are connected to different voltage levels. The model should keep track of locality of the electricity; electricity exported by a building might be imported by buildings behind the same transformer. Furthermore, the model should keep track of production patterns of power plants and the electricity streams through the grid.

Summarizing, the model should take into account the complete infrastructure from the behaviour of individual domestic devices up to the grid infrastructure with multiple voltage levels, transformers and generation sites. Furthermore, the model should be generic to be able to also incorporate future technologies and devices.

The model described in this chapter represents the status of the buildings and network at a certain moment in time. Especially the status of the devices, e.g., the energy demand of devices and levels of buffers, changes over time. Therefore, the observed horizon is divided in time intervals; the model describes the status of the buildings and network during a certain time interval, or to be more precisely, at the beginning of the time interval. Based on the choices made and energy streams during a time interval, the status of devices and therefore the parameters of the model for the next time interval can be derived.

In this chapter the complete model is described. The next section starts with a derivation of a model for the building, starting with the underlying idea of the model. In Section 2.3 it is compactly described how multiple buildings can be combined into a grid and the last section ends up with conclusions. Section 2.4 describes how prosumer behaviour, preferences and strategies are used in the model. Finally, in Section 2.5, the application of these models within the simulations is discussed.

2.2 Building model

The model of a building should contain all energy streams within the building and the exchange of energy with its environment. The energy streams need to be modelled up to a device level since optimization algorithms may influence the behaviour of individual devices. In this section we first develop an intuitive notion of the energy streams. In subsequent subsections the notion will be formalized. We have chosen for a model that supports different types of commodities, such as electricity, heat and gas such that our models can be broadly applied. However, our focus within the e-balance project is on electricity.

In most (European) buildings electricity and (possibly) gas are imported and heat is produced inside buildings. However, it should also be possible to model a district heating system. Furthermore, for the stability and reliability analysis it is required to model phase shifting in the electricity network (both real and reactive power). Finally, the amount of sun and wind imported and the conversion efficiency should be incorporated in the model. Therefore, a generic model of the considered types of energy, the available devices and the energy exchanged with the direct environment is required. A sketch of a possible house is given in Figure 1.

In the remainder of this section the complete model for the building is derived, from a device level via the connections between devices up to energy import and export.

2.2.1 Building model

The model of a building is built on the notion of energy-carriers and devices. All devices in the building consume, convert or buffer one or more types of energy carriers. For example, a fridge consumes electricity; a boiler converts gas into heat and a hot water tank stores heat. Devices are interconnected via streams that transport energy-carriers. However, some devices are connected to multiple other devices, for example all electrical devices consuming electricity from the same source (e.g., imported electricity). Therefore, devices are interconnected via pools, i.e., every stream of a certain type of each device is connected to a pool. Since pools are abstract elements only introduced for modelling purposes, it cannot contain any energy and the sum of energy streaming in and out of a pool has to be zero at every moment in time. The model corresponding to the house sketched in Figure 1 is given in Figure 2. In the following subsections the four elements, energy-carriers, devices, energy streams and pools, are explained more detailed.

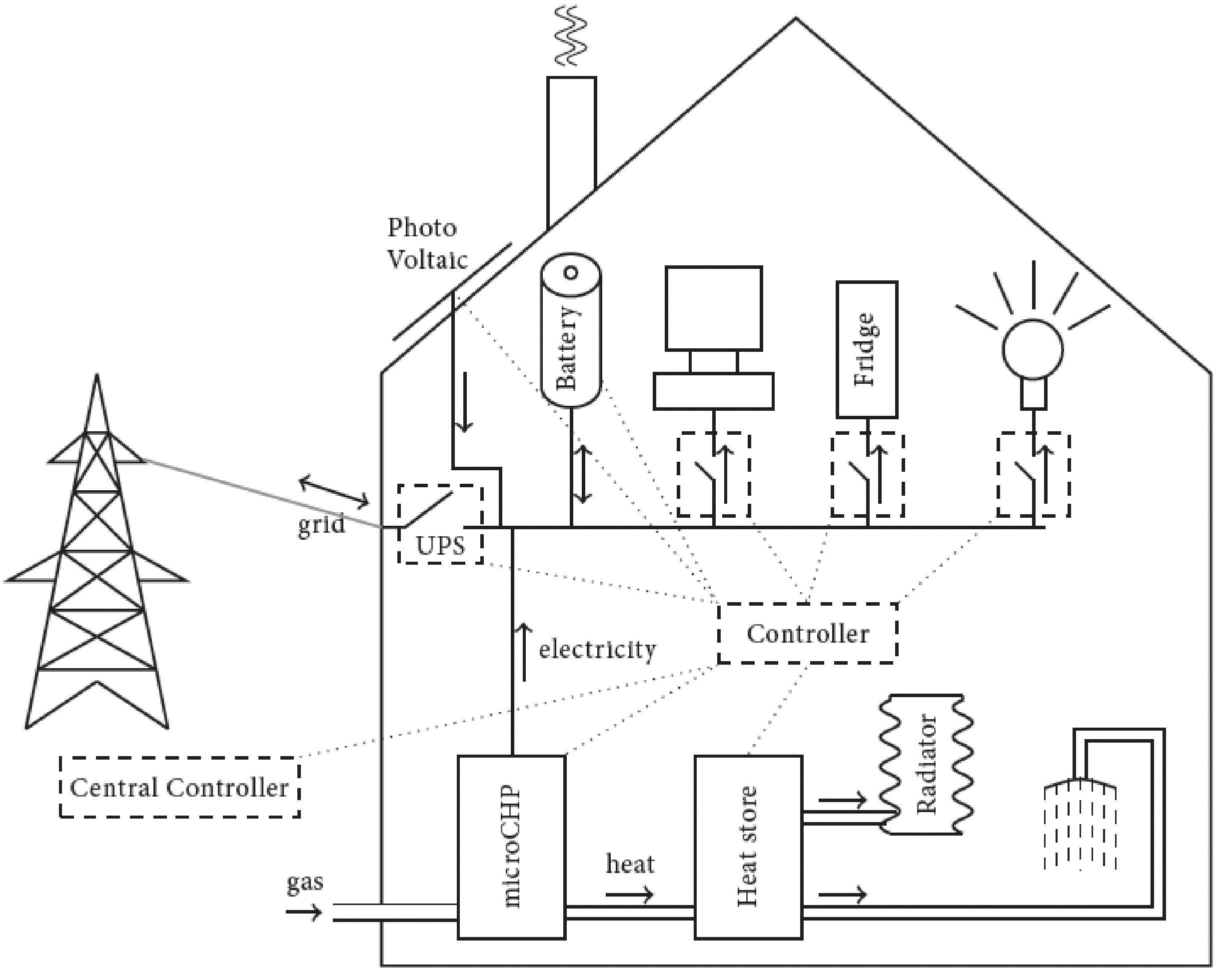


Figure 1: Schematic of the foreseen house

2.2.2 Energy-carriers

The developed model is based on a set of energy-carriers. An energy-carrier is defined as an elementary manifestation of energy, i.e., a medium or substance that contains energy. Most used energy-carriers in buildings are electricity, heat and natural gas. But also sunlight and wind can be seen as energy-carriers. All energy streams within a building and the energy sources used from outside are seen as streams of these energy-carriers: streams of heat, electricity and gas, but also sunlight, wind, etc. Electricity streams can be split up into a real and a reactive stream to observe the phase shift. Each stream consists of a flow of a single energy carrier (e.g., only electricity).

Within a building energy is exchanged with its environment, converted (change of energy-carrier type), (temporarily) stored and consumed by devices. In this context, e.g., a hot water tap is assumed to be a heat consuming device just as a TV set is an electricity consuming device. The model distinguishes four different types of devices within the building: 1) exchanging devices, 2) converting devices, 3) buffering devices and 4) consuming devices, as follows.

2.2.3 Devices

At the basis of the model there are devices and energy streams between these devices: energy of a specific type flows from device to device. A device does something with the energy-carriers (exchange, convert, buffer, consume). So, a device is an entity where energy flows in and/or out and where the type of the energy flows is specified.

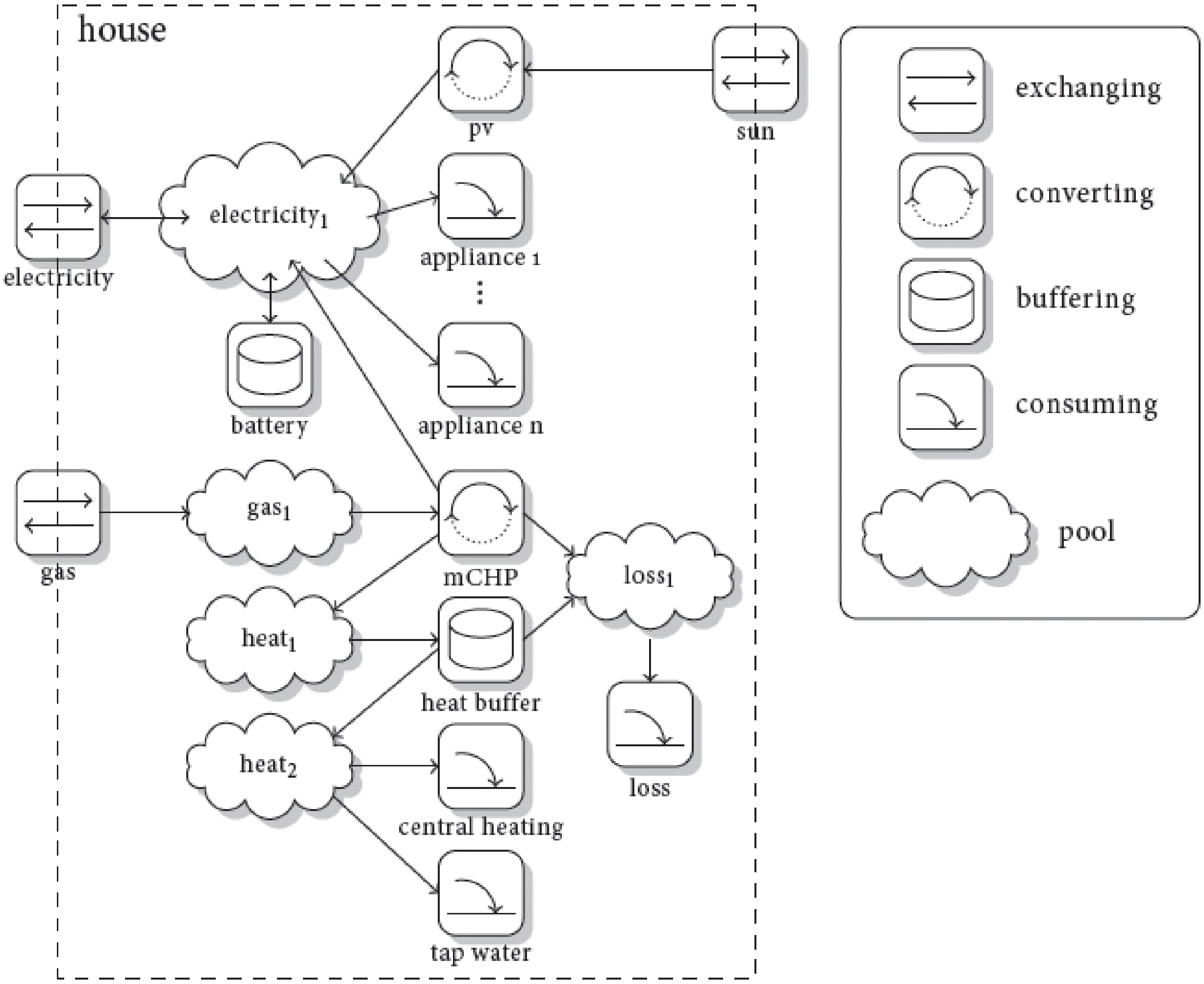


Figure 2: Modelled house

All devices within the building are modelled separately. We chose for this granularity, since the optimization algorithms to be tested with the model influence the behaviour of individual devices. Such behaviour can for instance be the decision when to run a converting device or when to temporarily buffer the electricity, e.g., in order to shave peaks. Similarly, by decoupling the heat production and consumption using a heat buffer, shifting the runtime of a microCHP may become possible. Furthermore, demand side load management of consuming devices builds on managing individual devices. However, also not manageable devices can be used. Since these devices have no optimization potential and just consume the energy they need, they can be modelled as one or a few big devices, i.e., these devices can be aggregated into one single device. Furthermore, import and export of energy is also modelled as a device, an exchanging device. By introducing an exchanging device the number of different elements stays limited and the model stays simple, generic and extendable.

In the following paragraphs, the specific characteristics of the four different types of devices are discussed.

Exchanging devices exchange energy with the environment. From a building point of view, a building exchanges energy with its environment. For most conventional buildings this is only electricity that can be imported and exported and gas that can be imported, but some buildings also may import heat from district heating. Furthermore, in recent years also sunlight and wind play a role and these are modelled as energy imports connected to exchanging devices. We model exchanging devices such that they exchange only one energy-carrier with the environment. Exchanging devices typically have a bound on the power that is exchanged. An example of an exchanging device is the connection of a household to the electricity grid (with a current limitation).

Converting devices convert one or more energy-carriers into one or more other energy-carriers. In our model, we assume that the amount of energy streaming into these devices is equal to the amount of energy streaming out of these devices. However, energy conversions (often) have a certain amount of loss during conversion. This is modelled as a separate energy stream out of the device (loss streams). So, a microCHP for example has a gas stream in (100%) and a heat stream (80%), an electricity stream (15%) and loss stream (5%) out. Other examples of converting devices are heat pumps and PV panels.

Buffering devices can temporarily store an energy-carrier. These devices have an energy-carrier stream in and the same energy-carrier stream out. This separation of the stream in and out is necessary since these streams are not always shared, e.g., most currently installed heat stores have separated in and out flow circulations. When the in and out stream are shared, this can be enforced by the characteristics of the device. Next to the in and out stream, a separate energy-carrier stream out can be used for modelling loss. Examples of buffering devices are batteries, heat stores and flywheels.

Consuming devices consume one or more energy-carriers in a certain ratio. For most devices, the amount of energy consumed in a certain time interval (the consumption profile) is a characteristic of the device and is therefore defined beforehand. A special type of consuming device is a loss device. For this device it is not defined how much energy it consumes, it simply consumes all loss based on the loss streams connected to this device.

2.2.4 Streams between devices

As mentioned before, at the basis of the model are devices and energy streams between these devices. Every device has certain energy-carrier streams in and/or certain energy-carrier streams out. Input streams for one device are coupled to output streams of other devices, so energy-carriers can flow from one device to another. For example, in most buildings all electricity producing and consuming devices are connected to one grid in the building. Electricity can flow from every electricity output stream to every electricity input stream. On the other hand, hot water flows from the boiler via a pipe to the hot-water buffer and via another pipe to the consuming devices.

2.2.5 Pools

To manage these flows in a proper way, all devices are interconnected through pools. A pool can only transport one energy-carrier and has no loss. This means that a pool has to be balanced: the amount of energy flowing in has to be equal to the amount of energy flowing out at every period of time. Every stream of every device is coupled to one pool and all streams connected to a pool must have the same energy-carrier. Finally, the amount of energy flowing from and to a pool can be limited due to limits in the transportation medium. In the house depicted in Figure 2 there are e.g., two heat pools present.

Summarizing, within every pool one energy-carrier is transported and every stream is connected to one pool. This introduces a lot of expressive power. For example, we can model the situation that (a part of) the building is protected with an Uninterruptable Power Supply (UPS) system.

2.2.6 Limitations and flexibility

Every device has certain physical limitations, e.g., the amount of energy it can import, the amount of energy it can convert, etc. Furthermore, within the limitations of the device, often some kinds of flexibility or operation modes are possible. Examples for such flexibility in options are the timestamp a microCHP is switched on to fill a heat buffer or the decision whether to store energy in a battery and how much. The amount of every energy-carrier flowing in and out, as well as the limits, is defined in Watt (W). Every device has a set of possible options to act (microCHP on/off, buffer charge or discharge and how much, etc.). Based on the state of the device (e.g., State of Charge of the buffer) there can be several valid options. A control algorithm needs to decide which option to choose.

2.3 Smart grid

In the previous section a model for the energy streams in a building has been derived and described in detail. To analyse energy streams in a grid, caused by domestic usage, multiple buildings can be combined into a grid. To combine buildings into a grid, every exchanging device of every building is connected to a pool in the grid. In this way, the buildings can drain the required energy out of the grid (pools). These global pools also need to be in balance, so the net energy demand needs to be delivered to the pools by energy-suppliers. It is possible that there are multiple energy-suppliers per global pool, for example a wind turbine (with a fluctuating amount of production) and a conventional power plant. This total picture of a grid is shown in Figure 3. Such a grid model makes it possible to analyse the impact of optimization algorithms and renewable sources on the production pattern of a power plant. Optionally, global storage devices can be connected to the pools (e.g., flywheel backup as grid frequency regulation [2]). The electricity grid is complex, it consists of multiple voltage levels and generated electricity is fed in on different voltage levels. To model a complete electricity grid including multiple voltage levels, multiple pools can be used. Each pool models one voltage level. Between the pools converting devices convert electricity from one to another voltage level. These converting devices model the transformers between the voltage levels. These transformers have one stream in (a voltage level) and two streams out (another voltage level and loss, not shown in the figure). Within these devices the maximum capacity, the losses and whether they are bi-directional can be modelled with the valid options. Furthermore, multiple neighbourhoods can be modelled to analyse how much electricity is used locally, i.e., how much electricity streams via two transformers to another low voltage pool. This is shown in Figure 3.

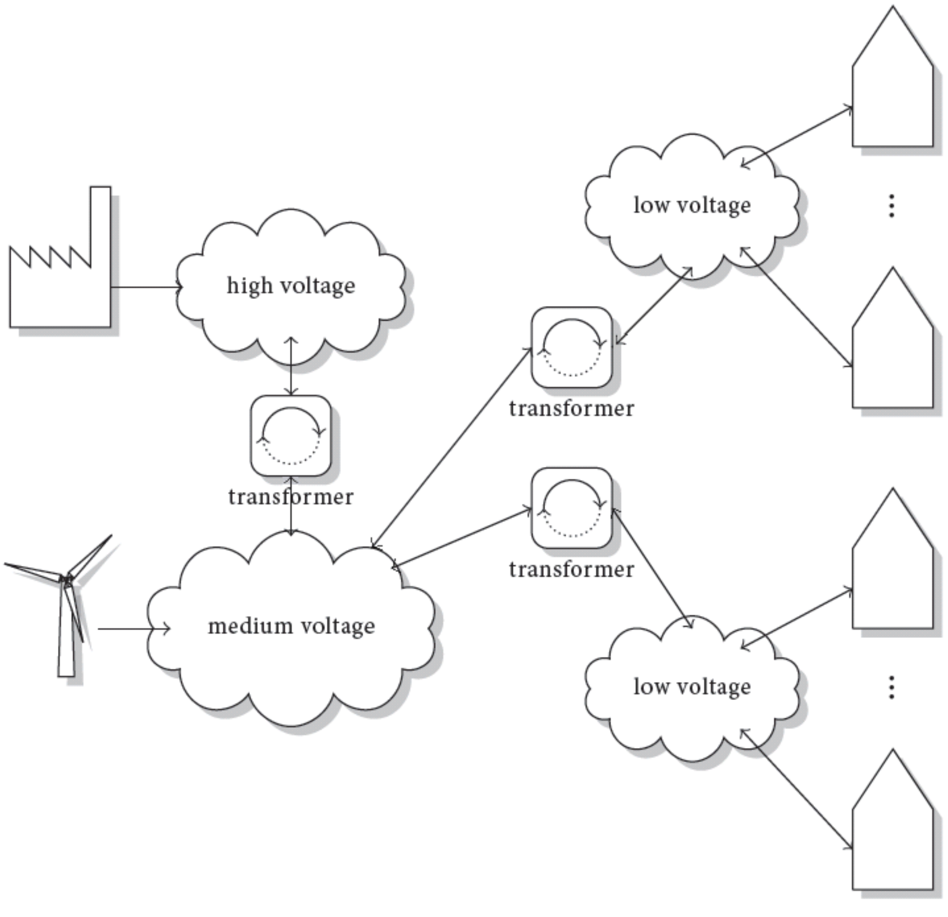


Figure 3: Smart Grid: Combination of multiple buildings and energy suppliers

2.4 Prosumer behaviour and preferences

To accurately analyse the influence of technical design decisions, the prosumer behaviour must be taken into account. The prosumers are responsible for the loads in the network. In the e-balance system, the prosumer does not only influence the system, but also the system can make decisions on behalf of the prosumer. Because this system should work for the prosumer (and certainly not against), the system allows the prosumer to configure its preferences. The prosumer behaviour (Section 2.4.1), preferences (Section 2.4.2) and strategies (Section 2.4.3) are part of our model and should be respected by the algorithms.

2.4.1 Prosumer behaviour

Prosumers influence the electricity grid through their behaviour. Not all prosumers have the same appliances, or use them in the same way. Many things (e.g., composition of households, incomes, nationality) influence the behavioural patterns of the prosumers.

Partners within e-balance have conducted measurements of energy consumption and production in different countries. We extend these measurements with additional smart devices that are expected to be used more often in the future, in order to study various future scenarios. For example, we intend to use this to study future scenarios with a high EV and/or PV penetration.

2.4.2 Prosumer preferences

Our energy balancing algorithms use the freedom of the appliances owned by the prosumer. For example, charging of an electrical vehicle can be slightly delayed such that it is charged when the sun shines and there is a lot of PV production. However, not every delay in charging is acceptable for the user. Such prosumer preferences are important in the e-balance system and place restrictions on how much control the e-balance system has over the appliances.

2.4.2.1 Time-shiftable devices

Time-shiftable devices can be shifted in time within a certain interval that is given by an arrival time, the earliest time at which the device can be started, and a deadline. Examples of time-shiftable devices are: a washing machine, a dryer, and a dishwasher. The prosumer programs the device to start at a given time. The CMU communicates with the device to learn about the program and alter this program when this is desired by the e-balance system. The current model assumes that time-shiftable appliances cannot be interrupted. However, when we use appliances that can be interrupted, we extend the model to reflect the capabilities of appliances.

The prosumer can configure the following preferences for time-shiftable devices.

Setting	**Description**
Max. lead	The number of minutes the start time can be advanced
Max. delay	The number of minutes the start time can be delayed

2.4.2.2 Electrical vehicles

The charging power of an electrical vehicle can be controlled by the CMU. In an extreme case, the charging can be enabled or disabled at certain times in order to shift the load. In a more flexible scenario, the charge power can be set by the CMU. As controlling the EV charging may result in discomfort, the prosumer can configure at what time the car should be charged to a certain level. To make this easier for the prosumer, she can configure the charging level as the distance, i.e., the amount of kilometres the EV can achieve with the charged battery.

The prosumer can add “charge at time” points to the configuration that contain the following settings:

Setting	**Description**
Time	Time at which the car should have a certain charge
Minimal charge	The minimal charge (in kilometres) at the given time
Maximal delay	The delay that is permitted if the reward is high enough
Cents / minute (delay)	The minimal reward that is accepted for a minute delay

2.4.3 Prosumer strategies

The prosumer can configure her overall goal that the system should follow. This is called the “strategy”. The possible strategies are given by the following table:

Strategy name	**Description**
None	The e-balance system is not allowed to use any information of this user. No steering is allowed.
Passive	No steering is allowed, but information is shared with the e-balance system.
Local consumption	The system tries to match household production and consumption.
Low costs	The CMU optimizes for costs of the user. It matches local production and consumption, and it assists the LV-GMU in improving the power quality if the reward is sufficient. This is the default strategy.

2.5 Simulations

As part of work package WP5, a low level energy simulator is developed. In this simulator, a scenario can be described using the model given in this chapter. By combining the model with measurements we can simulate what happens in the electricity grid. The simulator is not a finished product, but remains under development during the course of the work package. For example, during task T5.2, we add energy balancing algorithms to this simulator and study the effects of these algorithms on the grid.

This section describes our simulator. In Section 2.5.1 we describe and show the input to the simulator. In Section 2.5.2 we discuss and show what kind of information can be obtained from the simulations.

2.5.1 Simulation input

The simulator has a user interface to input the model. For the grid part of the model, it is possible to import grid descriptions from Gaia [3], which is a LV network design software that is used by e.g., Alliander. Figure 4 shows the model of the network of the Dutch demonstrator site Bronsbergen in the simulator GUI. This model contains all the required details for simulation, e.g., cable type, phases, length, GPS coordinates, transformers, etc.

Inside this model, we can assign behavioural patterns / measurements to appliances. We have measurements from the Netherlands and Portugal that can be added to a model. Simulation shows the effect of the production and consumption profiles on a specific network.

The balancing algorithms can be linked to smart appliances. This makes it possible to evaluate the effect of the algorithms on the demonstrator sites before we implement and test them.

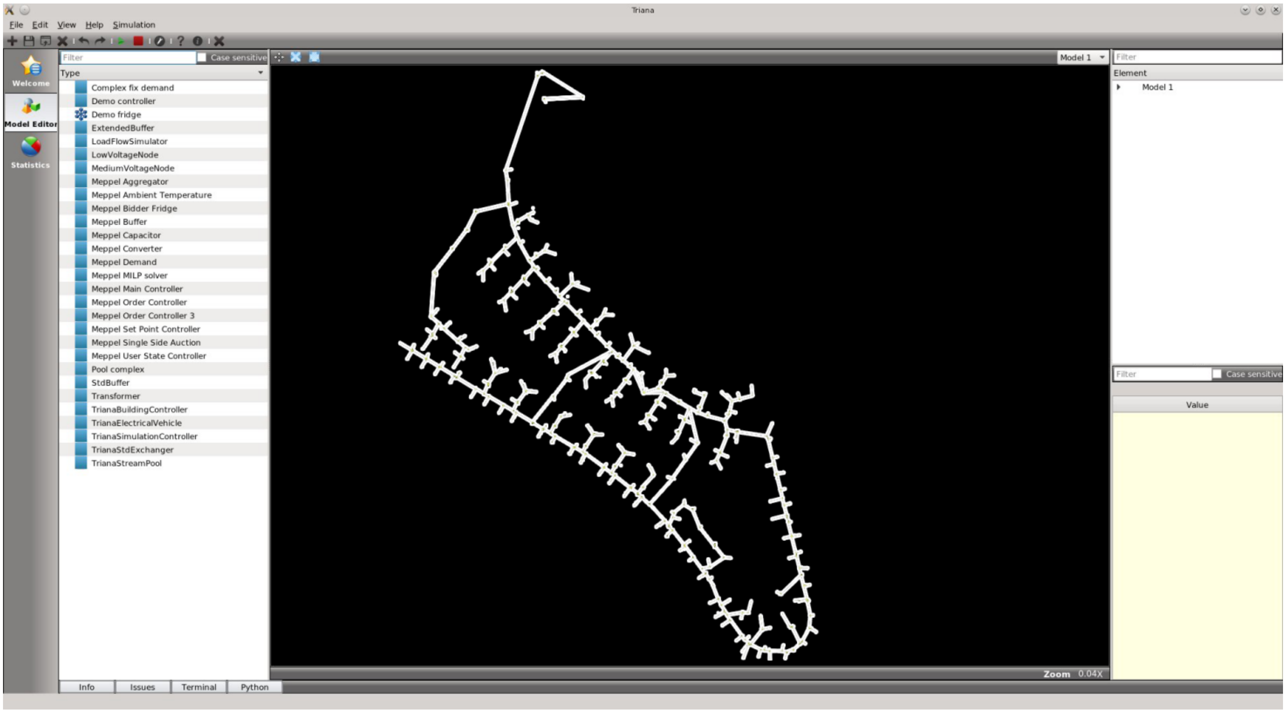
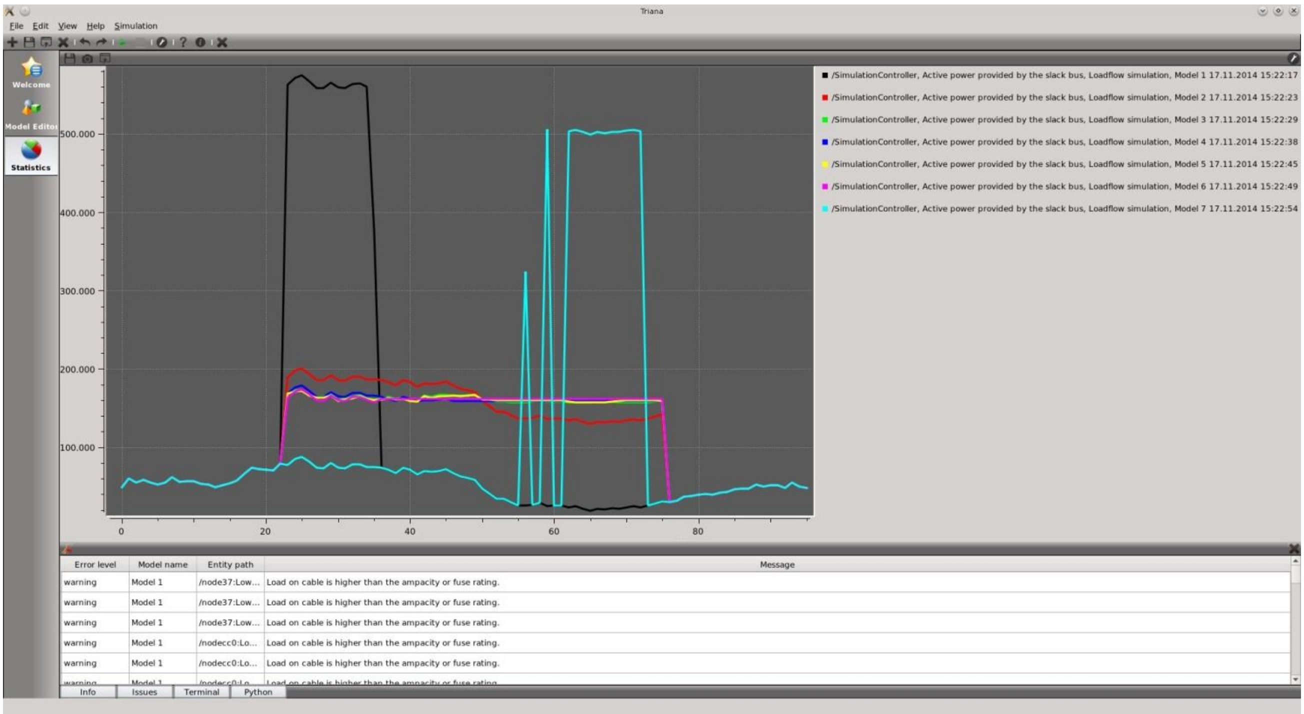


Figure 4: Simulator model designer

2.5.2 Simulation output

The simulator calculates the power flows in the grid. For each interval and each node, the power, voltage and current are calculated and can be plotted. For the entire network, statistics such as minima, maxima and losses can be plotted. The interface of the simulator that is used to create such plots is shown in Figure 5.



Error level	Model name	Entity path	Message
warning	Model 1	/node37:Low...	Load on cable is higher than the ampacity or fuse rating.
warning	Model 1	/node37:Low...	Load on cable is higher than the ampacity or fuse rating.
warning	Model 1	/node37:Low...	Load on cable is higher than the ampacity or fuse rating.
warning	Model 1	/nodecc0:Lo...	Load on cable is higher than the ampacity or fuse rating.
warning	Model 1	/nodecc0:Lo...	Load on cable is higher than the ampacity or fuse rating.
warning	Model 1	/nodecc0:Lo...	Load on cable is higher than the ampacity or fuse rating.

Figure 5: Simulator plots

3 High level model for simulation in Anylogic

This chapter is based on the work presented at the UK-Performance Engineering Workshop (UK-PEW 2014) in Newcastle [4].

3.1 Introduction

In addition to the models and simulator that was described in the previous chapter, we have developed a high level Smart Grid model for the simulation environment created with the Anylogic simulation tool [5]. Using this high level model and simulator it is easy to make a first, fast analysis of newly developed ideas.

The Anylogic software is used for the design of the simulation model. The simulation methods supported are system dynamics, agent-based and discrete event. The programming and setup is done using graphical components along with code based on the JAVA language, which makes it easy to use.

The used software is flexible and allows for the implementation of the multiple simulation methods within the model. For the inner operation of the model, system dynamics is used as it effectively describes the flow of energy through the various components. Each component is then represented as an agent, who then allows them to interact and exchange data with each other; this is done using the agent-based approach within the program. The agent-based approach allows for fast and easy changes and extensions to the model when needed.

3.2 First smart neighbourhood model

In our first model, we focus on a smart neighbourhood that consists of a number of smart houses. Each such house is built up out of several components that will have configurable parameters to make each house have its own characteristic behaviour. In Figure 6, the overall model of an individual residential unit is displayed with all the designed components connected which are able to communicate together through the ports found on each. In the following, the functionality of each component will be presented.

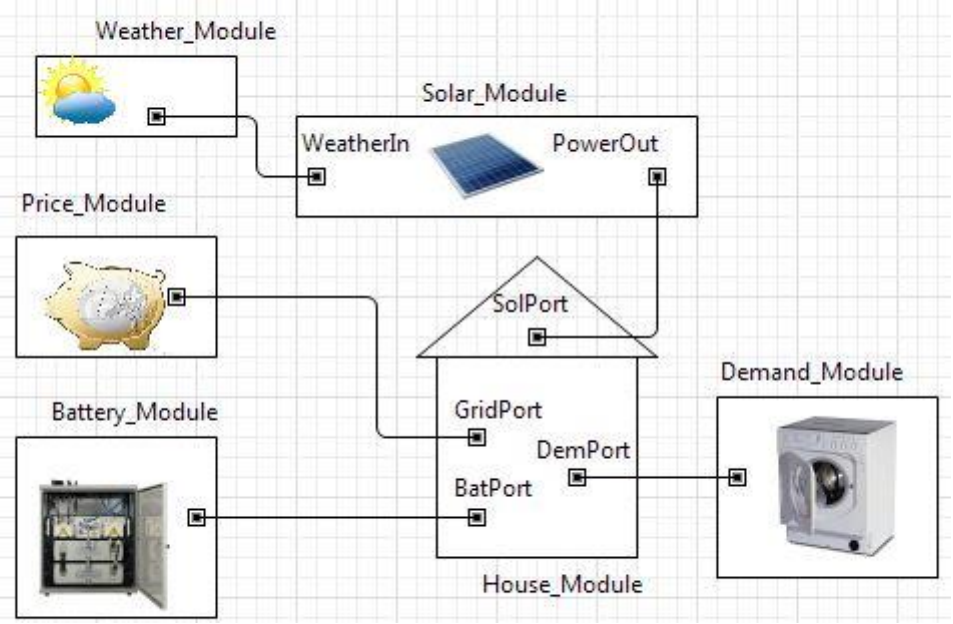


Figure 6: Overview of Anylogic residential unit model.

3.2.1 House

The *House* module is the main element which allows interaction between the other component models. All other components are connected to the house via ports which enable communication between them. The way which the produced and imported power is used and stored is determined by the settings of the house. For example, one can set that the battery is only charged by locally generated energy. Within this module the functionality of the Customer Management Unit (CMU) of the e-balance architecture can be represented.

3.2.2 Demand

In the *Demand* module, the electricity demand profile of the house is defined. The profile gives the average power drawn for every 15 minute interval, which may be dependent on the time of day and the day of year.

One can use standardized demand profiles to describe the demand, for example, EDSN [1] provides standard profiles for the Netherlands. With smart meters one could measure personalized demand profiles, in order to create fully customized simulations.

3.2.3 Weather

The *Weather* module provides the necessary weather data for computing the generated renewable energy. Since the model, for now, is limited to solar panels only irradiation data is used. However, this can easily be extended to include wind speed data for wind generation.

For locations in the Netherlands, the weather data is readily available via the Royal Netherlands Meteorological Institute (KNMI) [6]. It provides Global Horizontal Irradiance (GHI) data, which can be used for the computation of the generated solar energy. The GHI consists of the Direct Normal Irradiance and Diffuse Normal Irradiance [7], and is measured over a horizontal plane, 0 degree tilting.

3.2.4 Solar Panel

The *Solar Panel* module converts part of the solar irradiance into electrical power [8]. The output power is highly dependent on the position of the panel with respect to the sun. However, to incorporate this fully it would require many input parameters from the user. So, in order to keep the model easily configurable and limit the involvement of the user, the relation between the GHI and the output power P is given by the following approximate relation:

$$P = \varepsilon \times A \times GHI$$

Where: ε is the efficiency of the solar panels and A is the area of the panels.

3.2.5 Battery

The *Battery* is used as a storage element within the smart grid system. The battery model should be user-friendly, which means the battery specification can be adjusted by the users. Many different types of battery models have been developed for various applications over the years [9]. There are two crucial requirements for the battery model. The first is a small number of parameters which makes the model simple and easy to configure. The second is a high accuracy. In most cases, a trade-off between the number of parameters and accuracy are exist [10]. The battery is chosen to be modelled using the Kinetic Battery Model (KiBaM) [11].

The way the battery is used depends on the decisions made by the CMU, modelled in the *House* module. For example, the battery can be used as a buffer for solar energy, storing energy at times of high production and delivering energy when the panels are not able to deliver sufficient power.

3.2.5.1 Pricing Module

The *Pricing* module allows the user to keep track of the amount of money paid for the energy used as well as the amount credited when selling energy back to the grid. Different suppliers can be compared to show which packages are most convenient for the user's set up. Also, this module can be adapted to analyse alternative market models.

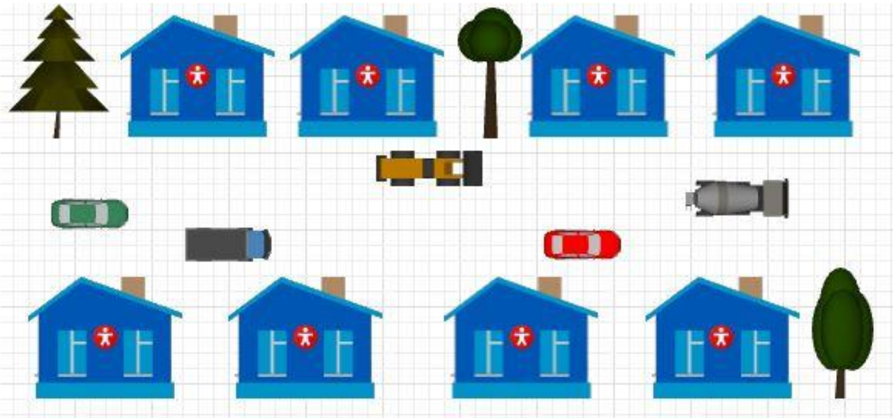


Figure 7: Neighbourhood model

3.2.6 Neighbourhood

By configuring multiple houses, a neighbourhood can be created within the model, as visualized in Figure 7. For each house the different modules can be uniquely defined, to fit to the individual demand profiles and available battery capacity and solar panels. It is also possible to create multiple instances of identical houses to create a larger population of houses. In this way, for example, one can easily study the effect of an increase of the penetration of solar panels on the interaction of a neighbourhood with the grid.

3.3 Simulation studies

In order to give an impression of what is possible with the simulator, we show some results of an example study.

3.3.1 Set-up

The simulation is run on two levels, the neighbourhood level and the residential level, to observe the operation of the designed model. These simulation results will show how the requirements listed are met in the designed smart grid environment. At the neighbourhood level 14 residential units are simulated with the setup as shown in Table 1. The 14 residential units are build-up from 8 differently configured units, with different solar panel size and battery capacity. For five of these configurations multiple instances are used in the neighbourhood. The size of the household determines the demand profile of each house. The weather profile is the same for all houses. All of the following results are obtained by simulating one month in summer.

In all houses the locally generated energy is used locally as much as possible. The batteries are only charged with solar energy generated by the PV-system in the same house. The energy in the battery is used when the locally generated energy is not enough to support the local demand. The energy from the battery is never fed in to the grid.

Table 1: Smart grid set-up scenario

Household	House A			House B		
	Units	Panel (m^2)	Battery (Ah)	Units	Panel (m^2)	Battery (Ah)
Single	2	7	60	3	5	50
Couple	1	9	70	1	13	65
Family, 1 Child	2	16	80	1	18	80
Family, 3 Children	2	25	90	2	21	94

3.3.2 Neighbourhood level

At the neighbourhood level, cumulative data of all the residential units can be gathered what allows for the study of the interaction between the neighbourhood and the portion of the grid it is connected to. In Figure 8, we display the energy trade figures for the given scenario. It shows how much energy is imported from the grid by the whole neighbourhood, and how much of the generated energy is exported to the grid. In the simulated period, approximately 4000 kWh has been generated by the solar panels. Nearly 2500 kWh has been used in the neighbourhood, either directly or by storing it in the batteries. The rest, approximately 1600 kWh, was delivered to the grid.

In Figure 9, the ratio of the energy supplied by the sources and storage to the demand can be seen. With the implementation of the above configuration nearly 50% of the energy required for the neighbourhood can be supported directly by the solar panels. Another 18% of the demand is supplied indirectly by solar energy, through the batteries. The user can study relations such as the effect of an increase of the number of PV-panels on the amount of energy imported from and exported to the grid by the neighbourhood. Thus, one can investigate to what extend the neighbourhood could operate autonomously from the central grid.

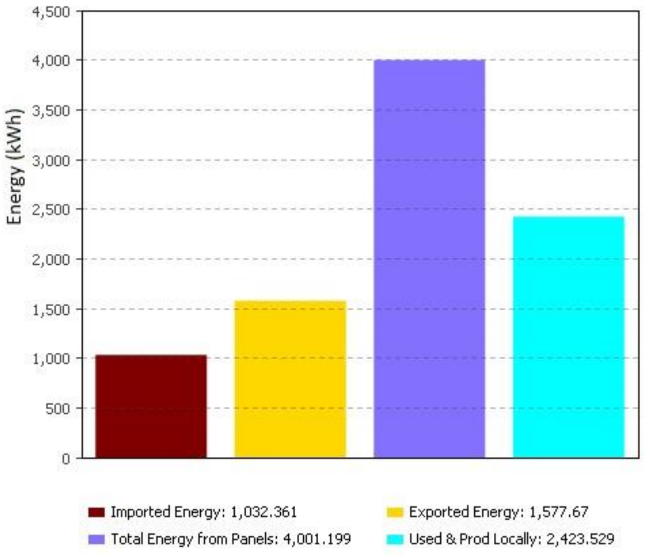


Figure 8: Distribution of neighbourhood energy

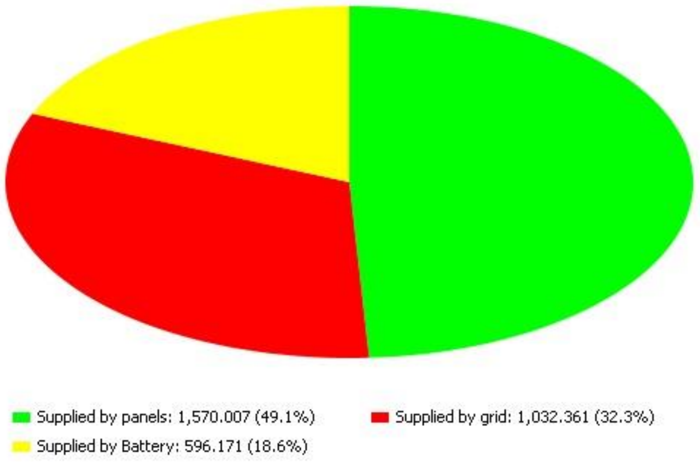


Figure 9: Energy Source Distribution

3.3.3 Residential level

Within the same simulation run the effects for the individual houses can be studied as well. The presented results are for a household of a family with 3 children, with house type A. Similar results can easily be obtained for the other household types as well.

At the residential level data similar to that on the top level can be viewed, such as the distribution of the sources that are used to meet the demand. In addition to that, data can be gathered and displayed for the power usage profile as can be seen in Figure 10. The usage profiles shown are for a period of 24 hours (hours 695 to 720 in our simulation) from the different sources. From such graphs the switching between energy sources can be carefully studied, especially when implementing complex control algorithms. Furthermore, in Figure 11 one can see the distribution on the total generated power from the solar panels to the various elements in the system.

Within the Pricing Module the user can keep track of the debit and credit, due to reselling excess back to the utility companies. Figure 12 shows the hourly sales for the chosen configuration, while in Figure 13 the total exchange over a period is shown, in this case one month. With these results users can get estimates about the net cost effects when using particular energy companies, and see the effects of different pricing schemes. Other algorithms could be implemented which could regulate energy use based on pricing models from the utility companies.

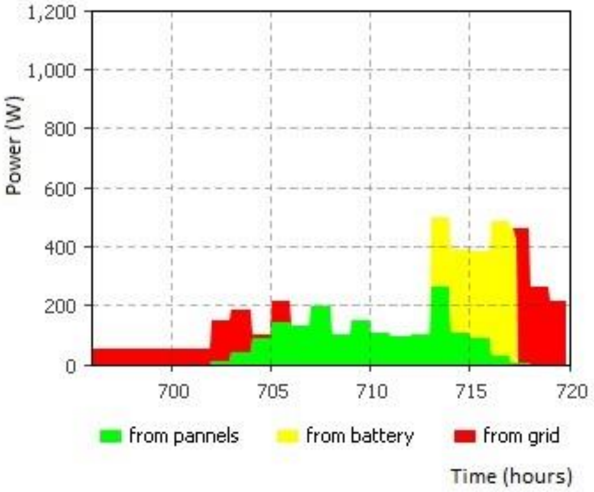


Figure 10: Power Supplied by Sources and Power Usage

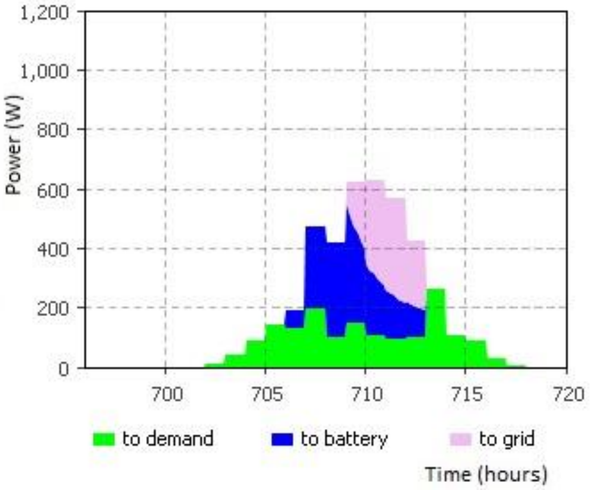


Figure 11: Power distribution from panel production

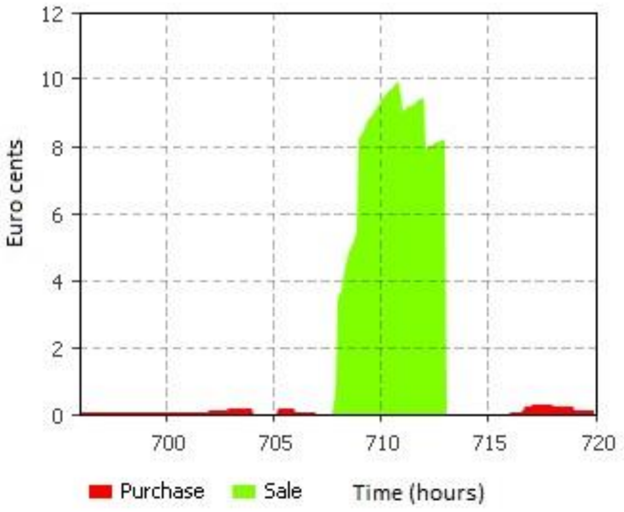


Figure 12: The amount of money spend or earned by one household in each hour.

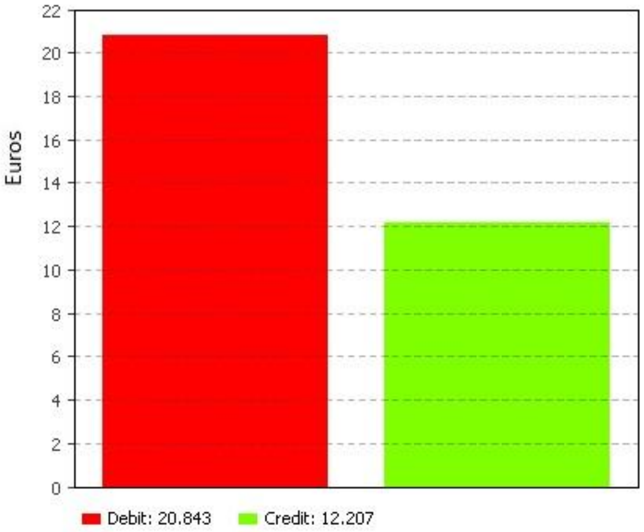


Figure 13: Total money exchanged in a one month period for one household.

4 Model for resilience of energy supply

This chapter is based on the work described in our paper submitted to IEEE Dependable Systems and Networks 2015 [12].

4.1 Introduction

Resilience is often defined as *the ability of a system to cope with an external factor that undermines it, with the system bouncing back* [13]. Within the grid, externally or internally induced faults may occur in many different forms and locations, e.g., broken power lines, short circuits, or too high voltages. In the classical concept of grid resilience, resilience is mainly obtained by automatic fault detection and acting by reconfiguring the network such that the fault is bypassed.

The introduction of DER may introduce additional stress and faults in the network, by the created un-balance between production and consumption. It, however, may also provide additional opportunities in making the grid resilient. For this, the scope of resilience needs to be extended from the classical *being grid connected* to *having appropriate electricity supply to end-users*. The availability of DER in combination with local balancing by the e-balance system could help in the continuation of the supply of electricity in a neighbourhood that is disconnected from the grid, e.g., by falling back on locally generated or stored electricity. In this way the electricity supply to end-users is resilient, while the grid connection is not. However, the connectivity to the grid can typically only be compensated for by locally generated and/or stored for a finite amount of time, otherwise the neighbourhood would be fully self-supporting, which is considered too costly (or too optimistic) at this point in time. The time the neighbourhood can be self-supporting depends on how the balancing algorithms use the available stored and generated energy.

In any case, grid operators and smart neighbourhood operators should be in the position to trade between the costs of resilience measures to be taken, and the probabilities that events occur that need such facilities. This sort of *risk analysis* has to take as input information for the grid structure, the neighbourhood facilities (its local grid, storage and generation facilities) and the workload. Also local conditions do play a role here, e.g., the type of organizations being supplied with electricity or the local weather conditions (mild climate or the harsh US east-coast climate with lots of thunderstorms).

4.2 Model set-up

In our approach, the system we consider is a house with PV-panels for energy generation and a battery for energy storage. Figure 14 shows a block diagram of the scenario. The demand within the house is presented by a time dependent function $Dem(t)$. The locally generated energy is given by the function $Prod(t)$. The function $Batt(t)$ describes how the battery is charged and discharged.

At any point in time, the demand has to be served either from the local production, the battery, or the grid. The *energy management system* within the house makes the decision on when to use which energy source. This functionality will reside in the CMU of the e-balance system.

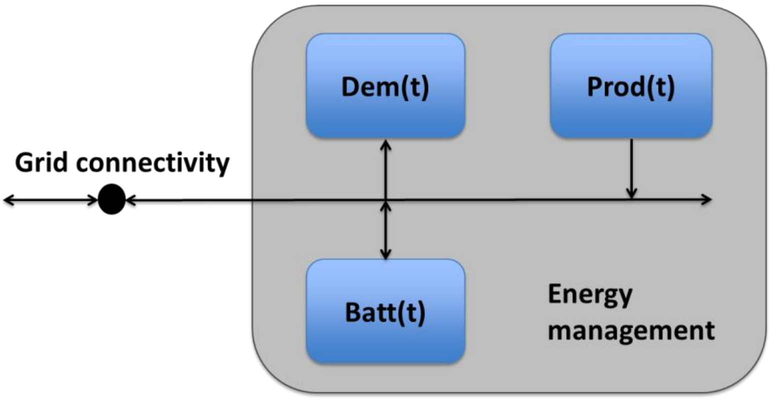


Figure 14: Block diagram of the system

Given such a model, we can address a variety of interesting questions. For instance, what happens when, at some point in time *t**, the connection to the grid is disrupted? In particular, we can pose the question how long the locally stored energy, together with the locally generated energy, is enough to satisfy the actual workload. Clearly, the answer to this question depends on the moment *t**, that is, the time of the day when the disconnection takes place, the future locally generated energy, the future local workload, and the content of the local storage at the moment the disconnection takes place. Another interesting question is what the maximum time period for non-connectivity is, before the disruption leads to outages at end users. The answer to that question poses constraints on the failure, detection and recovery procedures that need to be installed in the smart grid, for the restoration of the connectivity. As a final example, consider trade-off studies in which the impact of the size (in kWh or m^3) or costs (in €) of local storage on the resilience is studied.

In order to answer these questions we cast the system in a hybrid Petri net model. In the following we sketch the developed model in an informal way. For more background on hybrid Petri nets we refer to [14, 15].

4.2.1 Petri net Model

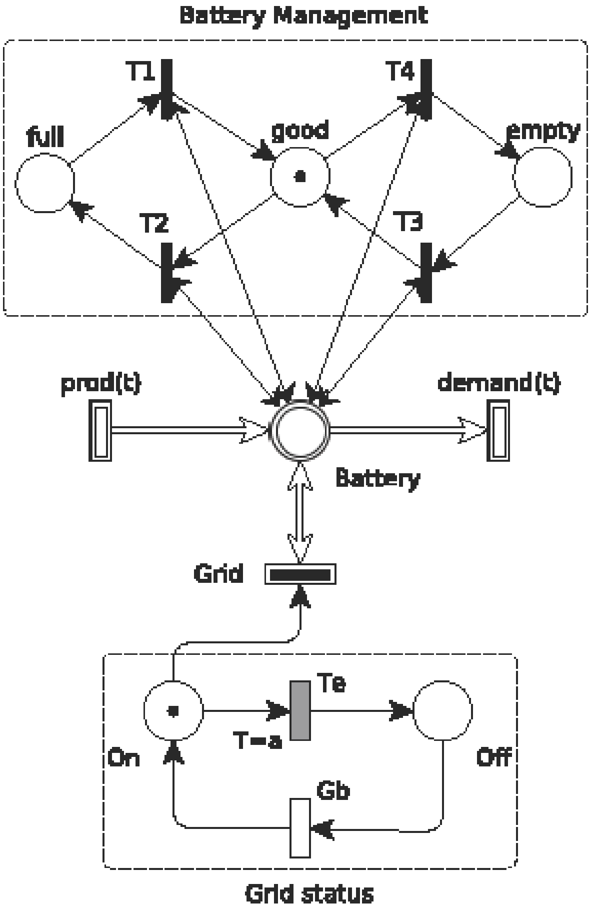


Figure 15: Hybrid Petri net model for resilience analysis

In this section we present a Hybrid Petri net model for a smart house, corresponding to the block diagram presented in Figure 14. Figure 15 shows the Hybrid Petri net model of a smart house; it consists of three parts (from top to bottom) (i) the battery management system, (ii) the model of the battery together with production and demand, and (iii) the model for the status of the grid.

The battery is modelled as a continuous place with overall capacity B, its current state of charge changes with the *time-dependent* production $prod(t)$ and demand $demand(t)$. We assume an ideal battery, where the change of charge is always linear. For simplicity of representation in the figure, we have collapsed the deterministic rates representing the different production and demand rates during the day into the time-dependent rates $prod(t)$ and $demand(t)$. Note, that they represent in total up to 18 different rates that have been used in the model to closely model the production and demand at different times of a single day. In case the local generation produces more energy than is used and can be stored in the battery, this energy can be forwarded to the grid, similarly in case there is not enough local energy available to power the house, energy is taken from the grid into the house. However, this is only possible when the grid is operational, i.e., a token is currently in place *On*. In case of a grid failure (which can be assumed at different times of the day through the variable a) the token moves to place *Off* and the house is then practically isolated from the grid. The grid returns from its failure according to a stochastic repair distribution that can be chosen freely.

The *Battery Management unit* controls the flow of power between the local generation, the battery, the house and the grid. In case more energy is needed than is produced from the local generation, it decides whether to take the additional power from the grid or from the battery, depending on the battery management strategy used. The model distinguishes between three states of the battery, it can either be *full*, *good* or *empty*, where the state empty can be interpreted relative to the overall capacity of the battery B. The transitions T_i for $i \in \{1, 2, 3, 4\}$ coordinate the change of state via test arcs that enable the firing of transition T_i according to some threshold that is compared to the available capacity of the battery. Different strategies for the use of the battery can be created by appropriately choosing the levels of the thresholds T_i.

The simultaneous inflow and outflow of energy from the battery in the model is, of course, in reality not possible. One cannot charge and discharge the battery at the same time. In practice the simultaneous production and demand will bypass the battery. However, the presented model will yield the same results with respect to our chosen measures of interest.

4.2.2 Model evaluation and measures of interest

Recently, efficient analysis algorithms have been developed for the restricted sub-class of Hybrid Petri nets with General Transitions (HPnG) that contain only one general transition that is allowed to fire just once, i.e., there is exactly one random variable present in the model. It is then possible to compute the transient probability to be in a state with a certain property [14], but it is also possible to specify more complex properties, using the logic STL [16]. For example, the following timed until formula:

$$survivability = battery_{up} U^{[a,a+t]} grid_{on}$$

It can be used to specify the survivability for so-called *Given the Occurrence Of Disaster* (GOOD) models, where a failure (the power outage) is assumed to occur at a certain time a. The above formula then specifies that power is available from the battery continuously until the grid is back on after time t. For finite values of t algorithms for model checking such formulae have also been presented in [16] and have been implemented in the FluidSurvivalTool [17], that allows to import the model as textual input and then provides a graphical user interface to specify and analyse the properties of interest.

Due to the efficiency of the model checking algorithms, it is possible to compute the probability to be in a survivable state at the moment of the grid failure for a wide range of failure times a, so that parametric studies can be done.

4.3 Results

In this Section we show a small selection of results obtained with the model. Further results will be presented in D5.3, where the energy resilience algorithms will be further developed and evaluated.

4.3.1 Scenario

The scenario we consider is a sunny summer day. The demand profile is based on the EDSN profile for a total yearly demand of 3000 kWh. The ESDN profiles give the average power used for a given connection type with a resolution of 15 minutes. However, to reduce the computational complexity for the hybrid Petri net model, we use a more coarse grained approximation. The approximation is given in Figure 16.

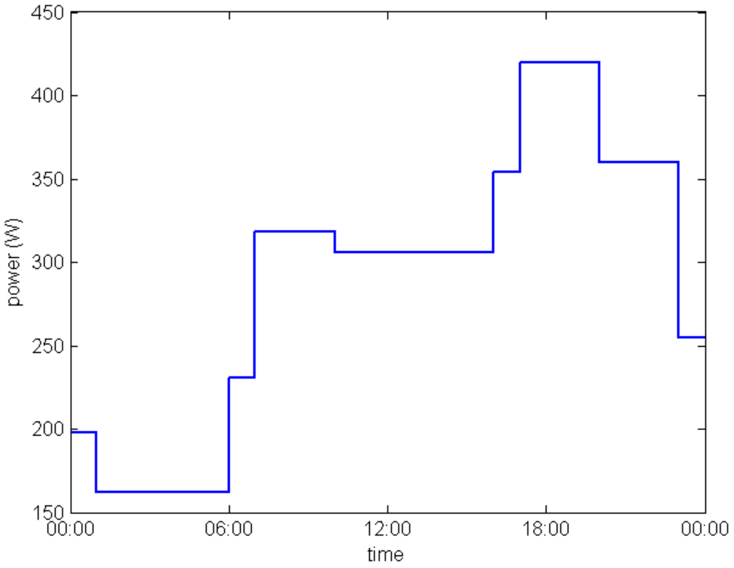


Figure 16: Approximation of the summer day demand profile.

The production profile is based on data obtained from the web tool PVWatt [18]. This tool allows to compute hourly production power for a given PV-system. The PVWatts profile is computed for a system located in Amsterdam with twelve 250 Wp (Watt peak) solar panels (3 kWp total), facing south with a 45 degree tilt. The system losses, and all advanced parameters have been kept to the default values. These input values result in a yearly production of approximately 2750kWh. Again, for complexity reasons the profile has been approximated, similarly as the demand profile. This approximation is shown in Figure 17.

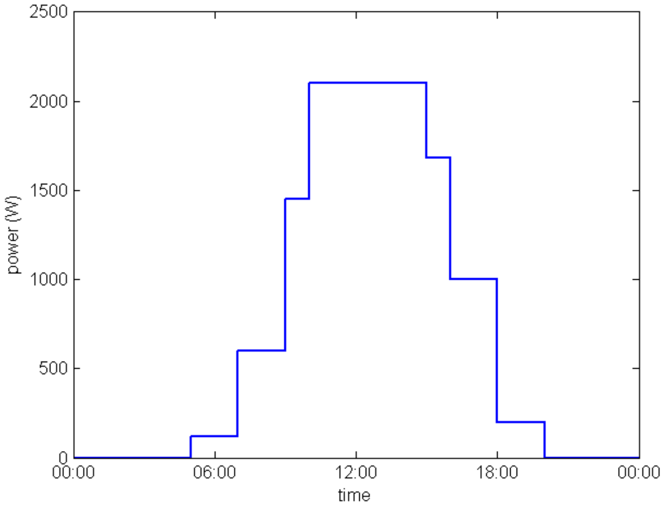


Figure 17: Approximation of the production profile of a sunny summer day.

We consider a simple battery management strategy. When the local production is smaller than the local demand, the battery is used to provide the shortage. This is done until the battery is fully drained. The battery is charged by the PV-power that exceeds the local demand. Only when the battery is full the locally generated energy will be fed into the grid. This is a simple strategy to reduce the interaction of the house with the grid.

4.3.2 Survivability results

In the following, we consider the impact of a grid failure. The grid may fail at different times of the day and is repaired after a random repair time, that is distributed according to a folded Normal distribution, with age 2 and standard deviation of 1 (hour).

We show the survivability of the system, that is, the probability that the house can be powered continuously for battery sizes between 500 and 3000 Wh, starting with a full battery at midnight (which corresponds to time 0 in the figure).

The results are shown in Figure 18. The time of failure is depicted on the x-axis and the probability that the system is survivable on the y-axis. The time of failure (on the x-axis) corresponds to the firing time of the failure transition T_e in the HPnG model and does not represent the transient evolution of time. Clearly, the state of charge of the battery changes over time, hence, the time of failure has a direct impact on the survivability of the system.

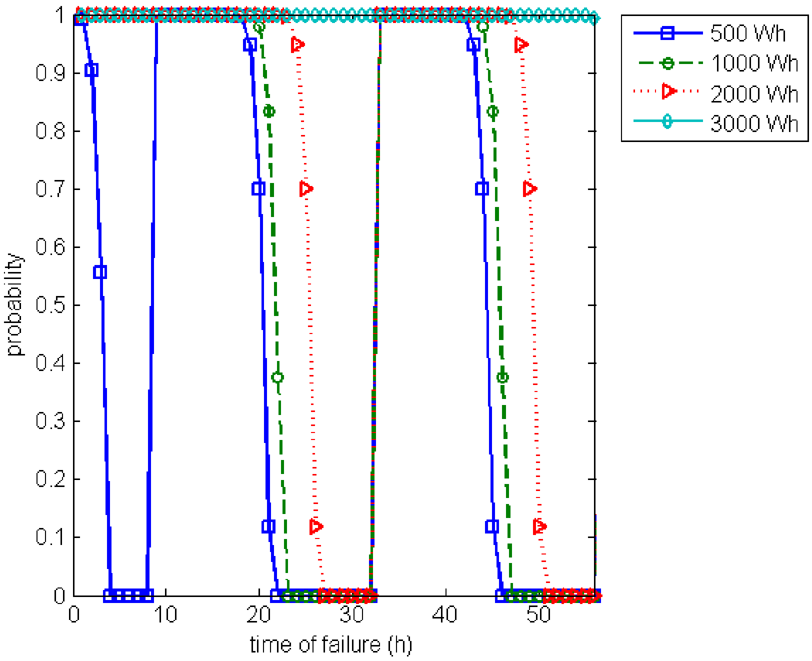


Figure 18: Probability of surviving a grid failure as a function of the time that the failure occurs.

The system starts with a high survivability, since we start with a fully charged battery. Only for the smallest battery, 500 Wh, the survivability drops to 0 during the first night, only rising again when the sun rises and the demand can be supplied from the local generation. During the day the battery is fully charged again, and the energy supply in the house is 100% resilient against grid failures. During the second night, we see the probability to survive a grid failure again drops rapidly. The time this drop occurs depends on the battery capacity. Only the largest battery contains enough energy to ensure 100% survivability for the full day.

The survivability of the system can be increased by reserving back-up capacity in the battery. Further results will be presented in D5.3, where we will compare different battery management strategies and other production and demand scenarios.

Conclusions

In this deliverable we have presented three different models that can be used during the development of the e-balance system for the analysis and verification of the developed mechanisms.

The three models have a varying level of detail and focus on different aspects of the e-balance system. With the low-level model it is possible to fully simulate various scenarios, and analyse the system behaviour in detail. One of the main aspects that can be analysed with this model is the energy flows within the system and how they change when energy balancing is applied.

The detailed analysis of the low-level model may, however, take too much time and in some cases a high-level analysis can be sufficient. Such a high-level analysis can be done with the other two models. The high-level models are easier to configure and are fast in their computations.

The first high-level model focusses on the energy flows within the e-balance system. Thus, this model can quickly supply preliminary results, before doing an in-depth analysis with the low-level model.

The second high-level model has the same level of detail as the first, but has a focus on resilience of the energy supply. With this model, we can different strategies for the usage of DER in case of grid failure, and make a quick comparison. Further, the modelled household can be used to represent also higher levels in the energy grid, as it is aligned with the e-balance concept of energy grid being fractal-like.

The models and the simulator tool are used in task T5.2, task T5.3 and in task T6.4, where further results will be presented.

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