Simulation of the effect of introducing micro-generation, energy buffers and accompanied optimization algorithms on the energy efficiency

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Abstract—**The growing awareness of the greenhouse gas effect and rising energy prices lead to more and more initiatives to improve energy efficiency. These initiatives range from micro-generation, local energy storage and more efficient appliances to controllers with optimization objectives. However, the introduction of these initiatives might have a significant impact on the current electricity infrastructure. Furthermore, it is difficult to analyse the succes on the energy efficiency of the introduction of (combinations of) these initiatives.**

Therefore, a simulator is develloped to analyse the impact of different combinations of micro-generators, energy buffers, appliances and control algorithms on the energy efficiency, both within the house and on bigger scale. The simulator is easily adaptable for new types of micro-generators, controllers and other supported devices.

First simulations with the simulator show that the results are correct and promising. However, especially the usage of resources during the simulation has to decrease.

Keywords: Algorithm design, Simulation, Micro-generation, Energy efficiency

I. INTRODUCTION

Nowadays most residential used electricity is generated in central power plants. However, the efficiency of central generation is at most 55% due to inefficient generation [1] (transport losses not taken into account). This low efficiency is mainly caused by dumping heat produced as byproduct and high fluctuations in demand [1], [2]. The growing awareness of the greenhouse gas effect and increasing energy prices require efficiency improvements of electricity production, distribution and consumption. Therefore, a shift towards decentralized electricity production is expected, especially by micro-generators [1]. These devices generate electricity at kilowatt level in or nearby houses resulting in less transport losses and better optimization potential for matching demand and supply. Furthermore micro-generators are more energy efficient than conventional power plants and some are based on renewable energy sources [1], [3].

Controlling micro-generators has also potential to increase generation efficiency of power plants by fluctuation reduction, increase the grid's stability and supply electricity during power cuts. This can be achieved both by local optimizations (e.g. self supportance and supply/demand matching) [2] as well as with global optimizations (e.g. VPP) [4].

Next to increasing the electricity efficieny on the generation side, the efficiency on the consumer side can also be increased. This increase can be achieved by more energy efficient appliances, but also by controlling when appliances are running. Controlling runtimes of appliances might decrease the fluctuations in the usage resulting in a more efficient generation [5]. The runtime is defined as when and for how long the micro-generator is switched on. More efficient appliances are, next to just less consuming appliances, appliances that consume both heat and electricity. Heating water is very energy consuming and can be done very efficient by gas-consuming heaters. So, for example, hot fill washing machines are filled with hot water which is heated by a gas-fired heater which has a higher overall efficiency than heating the water electrical within the washing machine (concerning also the electricity generation).

Furthermore, energy storage is considered as a high potential in addition to the domestic energy infrastructure. Some houses already have a hot water store to optimize the runtime of the heater and therefore increase the efficiency. Distributed electricity storage capacity in the houses is seen as a solution to reduce peaks and store electricity during low demand or high production periods (e.g. at night or during wind periods from windturbine parks).

It may be that the introduction of (a large fleet of) micro-generators, appliances consuming both heat and electricity, energy buffers and control algorithms can have a significant impact on the current generation and transportation infrastructure. To study the effects of these introductions a simulator is develloped, which can simulate a single house to verify the local improvements as well as multiple houses to verify global improvements. Furthermore, the effect on the grid (netto electricity import/export per neighbourhood or city, peak reductions, etc.) resulting from the introduction of (combinations of) micro-generators, efficient appliances and control algorithms can be studied.

We assume that electricity can be exchanged between houses via the grid (concerning import and export limitations) but heat stays within the house.

In the next section the simulation goals and requirements are described. Section II presents the model of the energy streams used to build the simulator. In Section IV a describtion of the simulator itself is given. We conclude in the last two sections with the results and future work.

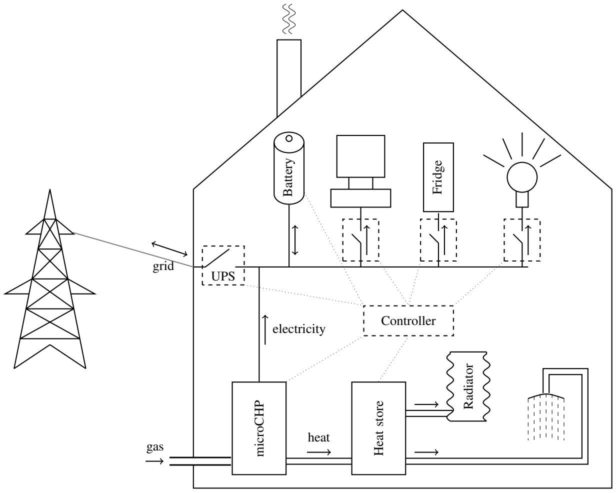

Fig. 1. Proposed house

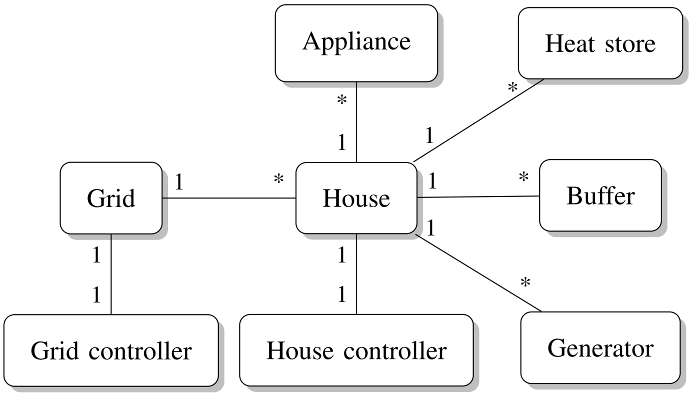

Fig. 2. Schematic layout of the model

II. REQUIREMENTS

The goal of the simulator is to create a tool to analyze different combinations of micro-generators, energy buffers, appliances and both local and global control algorithms. This tool should be easily adaptable for new types of micro-generators, controllers and other supported devices.

Because the purpose of the simulator is to simulate various new scenarios, the simulator has to be flexible. Adding new types of micro-generators, buffers and appliances has to be easy, just as changing control algorithms. Some elements act upon both heat and electricity, for example the earlier mentioned hot-fill washing machine and microCHP appliance. Therefore, for all these elements the behaviour concerning both heat and electricity (production/consumption/storage) has to be defined. The combination of the heat and electricity is mentioned in the rest of this paper with ”energy profile”.

The simulator should be capable of simulating two different scenarios:

- The local effect of local control algorithms within a single house
- The overall effect of the massive introduction of a mix of new micro-generators, buffers, appliances and/or local and global control algorithms

The simulated situation should be similar to the actual situation. The modelled houses should be a representation of a normal house and multiple houses grouped together should form the grid. Figure 1 shows the infrastructure of the foreseen house.

Within the house micro-generator(s), energy buffers and appliances are installed. In addition to the current situation all devices within the house (micro-generators, buffer and appliances) are controlled by a controller, the local controller. The buffers and micro-generators are controlled directly, just like in the current situation regarding central heating and the thermostat. The local controller should be able to query information from the buffer about the fill rate and from the micro-generator about the current production. Furthermore, it should be able to send start/stop requests to the micro-generator. However, not every micro-generator can respond to this signal since not every device is controllable (e.g. micro-wind) nor can every micro-generator immediately respond to the request.

Appliances on the other hand, do not (yet) have an communication interface. Therefor, the appliances are controlled by an overulling switch connected to the controller that can switch off the supply to the appliance. All appliances in the house should be seperately controllable so optimization controllers can observe and switch on/off individual appliances. A basic local controller uses a minimum control to only perform the minimum regulation (e.g. no control of appliances), but this basic control can be extended with optimization objectives.

For the simulations of massive introduction of micro-generation, multiple houses are to be combined into a grid. Each house should be individually addressed because every house has its own characteristics and internal state (level in buffers, which micro-generators and appliances are switched on, etc.). The grid should optionally be extended with a global controller communicating with the local controller, like the situation concerning a VPP described in [4]. Due to the different local controllers in the houses, it may be possible that not all houses respond to the global controller because not every type of local controller reacts on the signals (which is a realistic scenario). The grid has to keep track of the total import/export of electricity. This can be used to determine the succes of the controllers. Keep in mind that the global and local controllers are our instruments to reach optimization objectives. Furthermore, the grid should be capable of limiting the maximum amount of electricity that can be imported from or exported to the grid.

III. MODEL

The model of the house is deducted from the realistic situation showed in Figure 1 and requirements described in the previous section. Every house consists of (several) micro-generators, heat and electricity buffers, appliances and a local controller. Multiple of these houses are combined into a grid, exchanging electricity and information with the houses. The generation of power plants (coal, gas, windturbines) is left outside the model in first instance, only the total netto electricity consumption of all houses is registered in the grid.

The setup of this model is schematically shown in Figure 2.

Micro-generators can produce heat and electricity. All available micro-generators are modelled in this way, considering that the generation can be zero or even negative. A microCHP [6] produces electricity and heat, a Photo Voltaic (PV) produces electricity and no heat where a conventional electrical heater generates heat with negative electricity production. Next to the production of heat and electricity, the import of ”fuel” for the micro-generators is considered. This can be natural gas (e.g. for a microCHP device) but also sun or wind. The model keeps only track of the amount of natural gas consumed. Based on the runtime the amount of gas consumed can be calculated. Within the grid the total amount of imported gas is registered.

All appliances in the house are modelled as electricity and heat consumers. Literally all consumers are defined as appliances, from fridge and coffeemaker to central heating and tapwater. For appliances it also holds that consumption (of one of the energy types) can be zero. Appliances have next to their runtimes two more parameters which indicate whether or not the appliance is preemptable and give the priority of the appliance. These parameters can be used by the control algorithms to decide which appliances to supply and which to switch off.

Buffers and heatstores are temporarily electricity and heat storages. When there is more energy production than consumption there is a surplus that flows into (one of) the buffers. When there is less energy production than consumption there is a shortage that flows out of the buffers. The surplus and shortage are separately calculated for heat and electricity.

A more detailed description of the model and first versions of control algorithms can be found in [2], [7].

Within the model the planning horizon is discretisized resulting in a set of consecutive time intervals. The number of intervals depends on the length of the planning horizon and the length of the intervals. In general we use an interval length of six minutes and a planning horizon of one day, resulting in 240 time intervals.

IV. SIMULATOR

The simulator is built from scratch in a object oriented manner in C++. We have chosen for C++ because of the support for object oriented programming, the power of language and the possibility of low level optimizations (especially in memory management).

Furthermore, we have chosen an object oriented language for a modular composition of the classes. A simulation consists of a grid, a grid consists of a controller and houses, etc. In this way we can follow the structure given in Figure 2. The controller, micro-generator, consumer and buffer classes are abstract classes with the minimum functionality implemented. An implementation of an actual micro-generator consists of a class that extends the abstract class overriding that functions that need other behaviour. Because of this construction an element (micro-generator, appliance or buffer) can be added by implementing only the necessary functionality and without changes to the house or the controller. The house and grid class are not abstract classes. This is shown in Figure 3 for the current implementation. Till now, only a Whispergen microCHP [6] is implemented as micro-generator, a Gledhill as heatstore [8], the KiBaM battery model as battery [9] and a standard appliance consuming heat and electricity.

A. Implementation

As mentioned above, there are abstract classes for the controllers, micro-generator, buffers and the consumers. These classes define the basic (and common) functionality.

The implementation of a real element defines the actual behaviour of the corresponding element. It can have an internal state to be able to implement realistic behavior, for example to implement the start- and stop behavior of a micro-generator and losses in the buffers.

Every time interval every element receives a signal so it can update its internal state concerning the previous state and the input signals. These input signals are on/off switch requests, the energy flowing into or from the buffers, etc. For all elements within the house the input signals are generated by the local controller. However, the element might not respond always (immediately) to a signal: a microCHP device only switches on when the minimum cooldown period is past and when there is free capacity in the heatstore, where a PV does not respond at all.

Within an implementation of an element, parameters can be defined. For the current microCHP implementation for example, the electricity generation level and the ratio between electricity and heat are parameters. In this way multiple versions of an element can be defined with one single implementation. This can be used to pick out the best parameters for an element or a quick exploration of the possibilities. Such a version of an implementation with values defined for the parameters is called a configuration.

We defined a standard methodology to define which parameters are used for the implementation of an element and what their type is. This standard methodology simplifies building a GUI and the storage of configurations. The non-abstract classes for the house and the grid also contain parameters (which micro-generators are available, etc.), these parameters are defined in the same way. Equivalent to abstract classes, multiple configurations of non-abstract classes can be defined.

Every type of element has its own functionality. The micro-generators can be switched on and off, however it decides itself whether it responds to the request (concering its internal state). The controller can query it how much energy is generated.

The energy buffers, both for heat and electricity, can absorb and supply energy. The controller calculates the energy flow from and to the buffers every time interval. However there is a maximum flow and a maximum level. When more energy flows to a buffer than the buffer can absorb in one time interval or when the buffer is full, the energy is lost. When more energy is demanded of a buffer than it can deliver, there is an energy shortage. These problems should be avoided by correct functioning controllers.

The current standard appliance implementation defines a profile and whether the appliance is preemptable during runtime. The runtime itself and the priority are defined in the house. A coffeemaker configuration can be used in multiple houses with different runtimes. The controller can query every appliance how much energy it requires the next time interval and then decides whether the appliance is supplied.

The local controller decides based on the current state of all elements in the house and optionally the signals of the global controller which micro-generators and appliances are to be switched on. Next, the energy streams between these elements are calculated by a controller. Furthermore, it decides

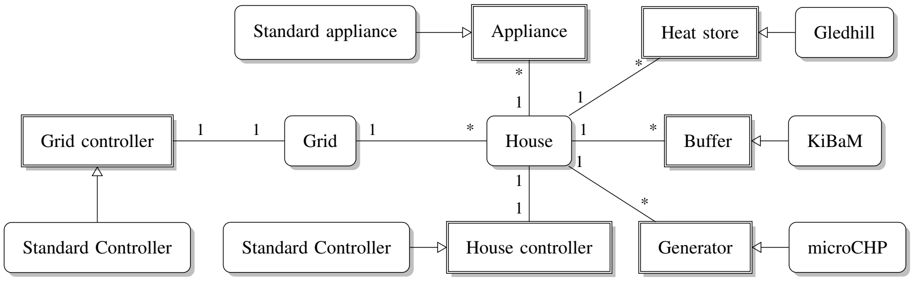

Fig. 3. Simulator C++ classes

how much electricity is imported and exported, within the boundaries of the current state.

The basic version of the controller only regulates the energy streams between the elements and starts a micro-generator when necessary (only heat-led), without optimizations in runtimes or battery usage. So it only switches on a heat micro-generator when heat is required (and the level in the tank is too low), just like the thermostat in normal houses. However, this algorithm can be extended with an optimization objective for controlling the runtime of the micro-generators and appliances, a decision how much and when energy is stored in the buffers and how much and when electricity is imported from and exported to the grid.

A house configuration combines the above described elements to one house. It defines which micro-generator configurations are installed, just like which buffer, appliance and local controller configurations are available. For the appliances are also the runtimes and the priorities are defined.

Finally, the grid configuration combines house configurations and the global controller configuration. For every house configuration can be defined how many times that particular configuration are present within the grid. The global controller can query the status of the houses for an according local controller and give a request for the next state. However, the local controller decides whether it follows the request.

B. Simulation

The configurations are saved in configuration files. These files can be created and edited within the GUI. Next, the simulation is initiated based on these files. The grid configuration defines which house configurations are present. The corresponding house configuration files define which micro-generator configurations are installed, etc. For every instance of an element an object is created. Multiple houses can use the same microCHP configuration, but this result in multiple microCHP objects with the same configuration. After all, all these microCHP objects have their own internal state, are switched on at different times, etcetera.

After the initialisation, the simulation starts. All objects receive a signal to update their internal state every time interval. Though, the sequence of signals, and with that the sequence of state transitions, is very important. First, the global controller queries all houses about their status (netto import/export of electricity, via the local controller) and calculates an optimal next status for every house based on his objectives. The preferred status for every house is passed to the local controllers as a request. Next, the status of each house is calculated. Based on the status of all elements within the house, optionally on the received request from the global controller and on its own objectives the local controller decides which appliances are supplied, which micro-generators are switched on and off, how many electricity is imported/exported, etc. Then, each element of the house calculates its own next state, based on the decisions of the controller. For example, if the controller wants to switch off a micro-generator, if the micro-generator is controllable and if it is allowed concerning its current state (minimum runtime, heat store level), the next state of the micro-generator will be the beginning of the stopping state (stopping can take multiple time intervals). When all houses are evaluated the next state of the grid can be calculated based on the status of each individual house. This finishes the calculations for the current time interval and the next interval starts. During the simulation every element stores information about its status. This information can be visualized after the simulation.

C. GUI

On top of the simulator a GUI is built. This GUI is a graphical interface to the functionality of the simulator. Configurations can be added, edited or removed. For every part of the simulator as shown in Figure 2 a tab is available. For abstract parts, an actual implementation can be selected and the parameters set (see Figure 4(a)), For non-abstract parts only the parameters can be set (see Figure 4(b)). Within the simulation tab the simulation can be initiated and started. The result tab (Figure 4(c)) visualizes the result of the simulation.

V. RESULTS

The first simulations with the current version of the simulator described in this paper are promising. Both the scenario for one house with a local controller and the scenario with multiple houses and a global controller are simulated. The details of these simulations are described in respectively [2] and [7].

The results of the simulations are carefully examined to verify whether the simulator produces correct and accurate results. Next to the correctness, flexibility and functionality, the speed and the memory usage are important for simulations with a massive amount of houses. A first quick exploration of the possibilities showed that 10.000 houses can be simulated on a Core2Duo$^{\text{TM}}$ with 2 GB memory running Linux within 5 minutes. Though, almost 2 GB of memory and more than 50% of the processor is used; so this is, with the current version, the maximum amount of houses.

VI. FUTURE WORK

The current version of the simulator uses too much resources. Therefore, speed and mainly amount of memory used are to be optimized. Especially the memory usage limits the amount of houses that can be simulated. This could be optimized by less extensive logging of the data for every house and optimizations in data sharing of equal elements (e.g. the energy profiles). The speed might be optimized by parallellizing the calculations for different elements, especially with the current multicore systems.

Furthermore, in advance defined randomization of the parameters should be added, especially for the runtimes of appliances. To simulate 10.000 houses, 10 different house configurations are defined and each configuration is used 1000 times. But then, all 1000 houses with equal configurations are exactly the same, so all appliances have equal runtimes and the local controller takes the same decisions. When the runtimes could be randomized by a previously defined amount all houses become unique houses. This is a realistic situation, since similar houses with similar families (family house, free standing houses, 2-person households, etc.) have similar behaviour, but they are not exactly the same.

Finally, the model of the hot water streams must be changed into a separate stream for space heating and tap water. The current model assumes that the space heating and tap water are provided by the same heat store. For the heat store used so far, a Gledhill, this is a correct assumption. However, in most houses the space heating and tap water are separate energy streams, though often produced by the same micro-generator.

VII. ACKNOWLEDGMENTS

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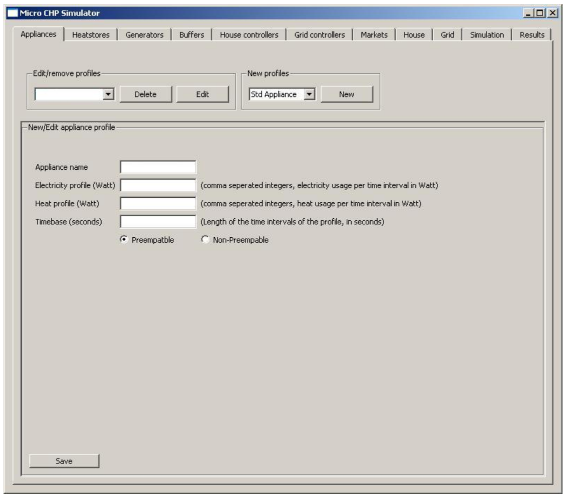


New profiles: Std Appliance

Appliance name

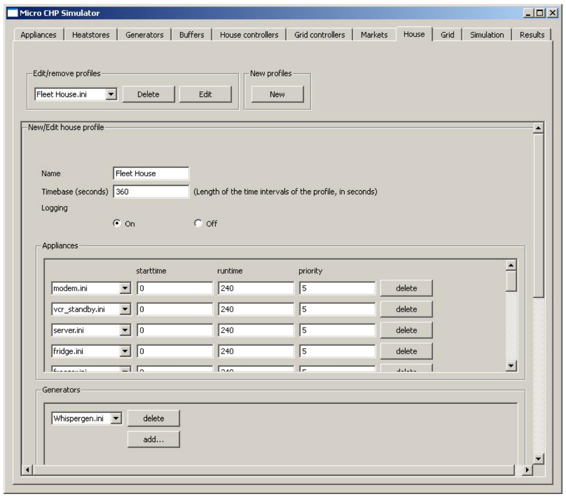
Electricity profile (Watt) (comma seperated integers, electricity usage per time interval in Watt)

Heat profile (Watt) (comma seperated integers, heat usage per time interval in Watt)

Timebase (seconds) (Length of the time intervals of the profile, in seconds)

● Preempatble ○ Non-Preempable

(a) Appliance tab



Edit/remove profiles: Fleet House.ini

Name: Fleet House

Timebase (seconds): 360 (Length of the time intervals of the profile, in seconds)

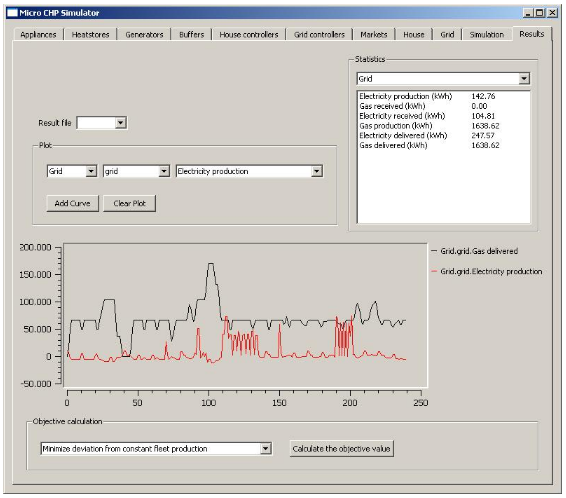
Logging

● On ○ Off

	starttime	runtime	priority
modem.ini	0	240	5
vcr_standby.ini	0	240	5
server.ini	0	240	5
fridge.ini	0	240	5

Generators: Whispergen.ini

(b) House tab



Statistics: Grid

Electricity production (kWh)	142.76
Gas received (kWh)	0.00
Electricity received (kWh)	104.81
Gas production (kWh)	1638.62
Electricity delivered (kWh)	247.57
Gas delivered (kWh)	1638.62

Plot: Grid, grid, Electricity production

Objective calculation: Minimize deviation from constant fleet production

(c) Result tab

Fig. 4. Simulator screenshots