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MODELLING AND DYNAMIC SIMULATION OF COUPLED GAS AND ELECTRICITY GRIDS AND THEIR MUTUAL SYNCHRONIZATION USING INTERFACE TECHNOLOGIES LIKE POWER TO GAS AND CHP

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Abstract

In order to achieve the targets for reduction in emissions and an overall shift in focus towards massive integration of renewable energy, various future scenarios including the intelligent production of renewable energy, its transport, storage, and consumption have to be analysed simultaneously. This study is regarding an essential part of such an analysis where the gas grid and the electricity grid are simulated together in real time using a single overall model. It also involves the modelling, dynamic simulation, and analysis of two so-called interface technologies that link both the grids. The first interface technology is decentralized micro CHP where interfacing involves the large-scale implementation of highly efficient micro CHP units that collectively use the gas supplied by the gas grid to produce heat (for households and industries) and power which is in turn fed into the power grid. The second interface technology analysed is Power to Gas where the supply of electricity from the electricity grid results in the production of gas, which in turn affects the gas grid. Additionally, this model can also be used to analyse the impact of interfacing technologies on energy storage. In any future scenario where renewables are integrated, the highly fluctuating nature of renewable technologies like wind and solar-based energy production makes storage an essential component. Therefore, dynamic production profiles of wind and solar-based electricity production are incorporated into the model to analyse whether power to gas or power to heat (using multiple decentralized micro CHPs and local household storage tanks) could be used for energy storage. The model can be scaled down to the city quarter level or scaled up to the regional or national level by varying the size and number of the components used. However, when different geographical locations are analysed, the individual dynamic weather fluctuations in all the simulated locations must also be integrated. In this report, initially the details regarding mathematical modelling of the overall energy system and the integration of important components like Power to Gas plants and micro-CHP units is presented. The modelling language used is Modelica. After the description of modelling, the system parameters and dynamic boundary conditions are discussed to explain how the model is comparable to an energy system in a real geographic location with already available measured parameters and boundary conditions. Further, the simulation setup is described and the energy system model is simulated for a time duration to incorporate all the four seasons. Finally, the experience obtained from other similar projects is briefly added along with a discussion on measures that need to be taken to realize efficient future scenarios where the gas grids and power grids mutually replenish each other thereby enabling renewable energy to play a major role.

1. Introduction

Political and scientific effort to integrate renewable technologies into mainstream energy production and distribution systems is gathering widespread interest in research. For such efforts to be effective, in addition to the integration of renewable energy technologies in the electricity sector, the gas sector must also be given equal importance. The electrical output of plants using renewable technologies like wind and solar are highly sensitive to changes in weather which makes storage systems also very important. Storage mechanisms with different durations for charging and discharging (Chen *et al.*, 2009) are already in various stages of implementation across the world. However, implementing long term storage solutions where the surplus energy produced during one season could be stored for extended periods of time (months in this case) and reused in the next season is still a challenge. Power to gas plants play a vital role here, being an interface technology (Figure 1) that works not only as a storage option for the power grid but also simultaneously supplies the gas network with clean fuel.

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The power to gas plant could be designed to convert surplus electricity from renewable plants into SNG or Substitute Natural Gas which in turn could be transported through the gas grid to finally reach gas consumers in sectors like transportation, housing and industry. However, experimentation and testing at the physical level (on-site) is extremely difficult in such systems as some of the plants are not yet fully operational and in the few plants that are operational, access for experimentation and research is not easy. Further, both construction related as well as operational data for such plants are difficult to find in the public domain. Additionally, the focus is also not to analyse individual technologies as stand-alone systems but to aggregate them into a complete energy system and simulate it. This means that a numerical model capable of simulating the electricity grid coupled to the gas network is needed where PtG and distributed house based energy units like mCHPs act as interfaces helping in synchronising the working of the two networks.

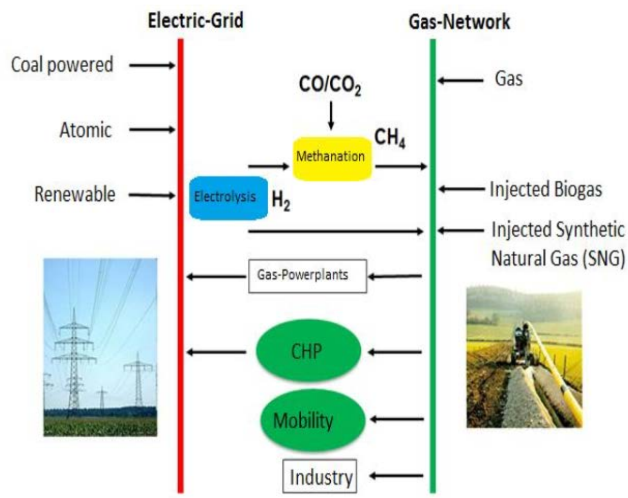

Figure 1: Power to gas as an interface technology between the electric network and the gas network.

To enable a logical structure for this type of modelling, the model is divided into four parts.

1. **Energy production:** Here, dynamic power output of the solar and wind plants is calculated using weather data as input.

2. **Interface technologies**: Power to gas is used as an interface technology for converting power during peak supply hours into SNG and subsequently injecting it into the gas grid. Further, during peak demand hours, the distributed energy systems (like mCHPs) are used to convert the stored SNG back into electricity and feed it to the grid (if the control system so demands).

3. **Energy distribution:** This section includes the simplified modelling of the gas distribution network that accepts in part CNG and in part SNG as inputs and distributes it to various consumers in the industrial, residential and transportation sectors.

4. **Energy consumption:** Here, the various buildings in the residential, industrial and the transportation sectors are modelled. At the present stage, only the residential sector has detailed models of buildings and energy production units inside the buildings. The other two sectors (industrial and transportation) are modelled using load curves.

It is important to consider the dynamic characteristics of all the components and control systems to simulate the system as all the components are interdependent and changes in one often influences the behaviour of the others.

2. State of the art

Preliminary system analysis for the synchronization of the power and gas grids considering the various future consumption sectors (ENEA Consulting, 2016) proves that power to fuel systems could be economically viable in the future if cost reduction occurs in certain key areas (Figure 2) and the quantification of the same requires numerical models. However, numerical models of such systems are still not as much developed as the concept itself. The study conducted in the Netherlands (Weidenaar, Hoekstra and Wolters, 2011) used a decision support tool (DST) based on the three largest Dutch distribution service operators to model future scenarios that would result from changes in the gas grid and its sources. There are also models available that describe various parts of the total energy system in detail. Models describing the dynamic behaviour of the electrical grid (Franke and Wiesmann, 2014) and (Bonvini, Wetter and Nouidui, 2014) are capable of analysing scenarios where solar and wind plants could be connected to the electric grid. The drawback here is that simultaneous coupling of the gas network and gas based consumers is absent. A similar drawback could also be observed in tools for gas network modelling (Kralik *et al.*, 1984) where the integration of complex electrical systems is not the main focus. For power to gas systems, basic modelling using simplified equations presented by Goetz *et al.*(2016) prove that the dynamic numerical models could be developed from basic equations and empirical relations that describe the behaviour to a reasonable degree of accuracy. On the consumption side, the dynamic modelling of distributed energy systems in the residential sector has been carried out by the same authors in one of their previous studies (Prabhakaran, Koeppel and Graf, 2015). Studies show that geographic regions demanding standalone energy supply could increase in the future. In such regions, any solar or wind plant in the vicinity would be required to supply the region and cater to the storage facilities in the local region first before injecting surplus energy into the electricity grid. Projects are already underway analysing this aspect (DVGW-EBI, 2018). However, the main challenge is numerical modelling where the task is to find a tool that supports modelling across different physical domains integrating various energy subsystems. This means that a tool capable of modelling a large number of components is needed capable of covering all the energy sectors and incorporating physical aspects like the transport phenomena, balance equations across various physical domains and the calculation of thermodynamic property relations. Further, simulation models need to be tested regularly by changing initial conditions and parameters. Considering all these requirements, object-oriented approach for modelling the components is deemed best suited for this purpose. This approach would also be favourable when the main focus is the integrated simulation of all the sub components. It has also been proven to offer many advantages (Richter, 2008) like replicability of components and easier calculation of fluid properties. The modelling language chosen for this approach is Modelica (Elmqvist, 1997).

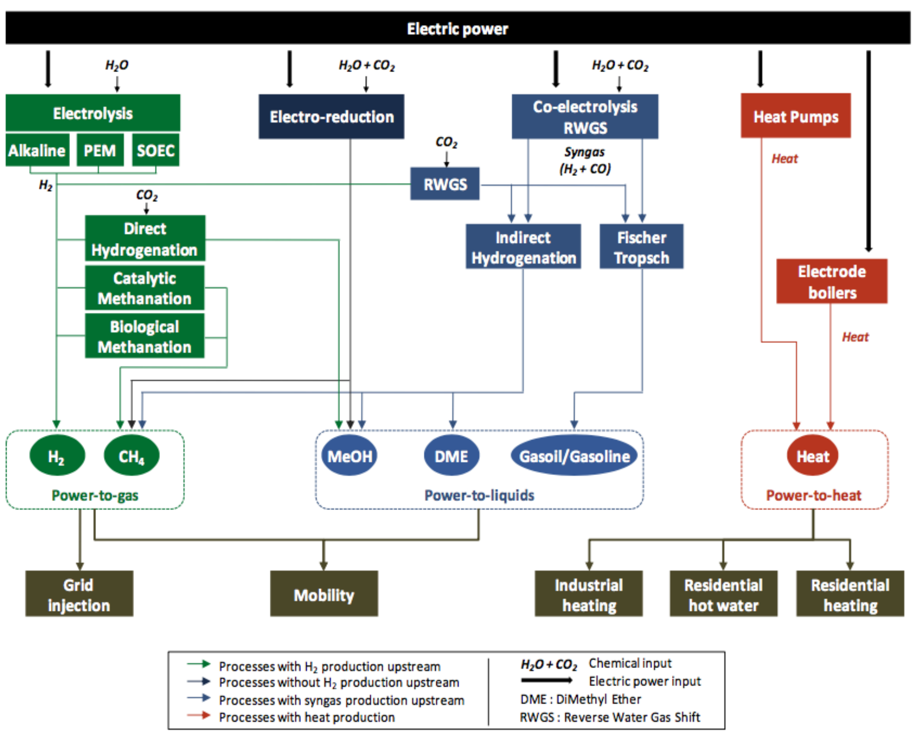

Figure 2: PtX concept describing the future scenarios. Image source: (ENEA Consulting, 2016)

3. Structure of the modelling

The logical structure followed in modelling the system involves the so-called bottom up approach where the individual parts of the system are described first followed by their integration into a complete system. The same logical order is also followed in this report. The parts involved in modelling are:

1. Renewable energy (electric) production systems like wind and solar plants and the electricity transmission network
2. Power to gas system
3. The gas transport network
4. Distributed energy consumption units like mCHPs and boilers and the respective buildings in which they are housed

Following the description of the individual parts, they are aggregated to form the complete system. Subsequently, the focus moves from modelling to simulation where the integrated system is simulated for various boundary conditions. The important assumptions with respect to the dynamic behaviour of certain components are then explained and justified along with the depiction of some sample results. The report is concluded by discussing future scenarios that might be relevant and how the system simulations themselves could be further improved.

3.1. Electrical network

The electrical network is modelled based on the study by Bonvini, Wetter and Nouidui, (2014). The capability to analyse different phase systems (Franke and Wiesmann, 2014) and to simulate AC and DC based systems separately is also present. The dynamic power generation profiles of wind and solar plants in the region and the additional energy drawn from the higher voltage grid are the inputs to the electrical system. Here, it is not recommended to model all the transmission lines across all the node points as it will make the simulations extremely slow without any added benefit. The transmission lines are therefore modelled by taking the sum of lengths all lines having the same characteristics like resistance and material. The selection of transmission lines and their modelling is highly region specific and needs to be updated on a case to case basis.

3.2. Power to gas

Within the scope of this study, the modelling of the power to gas subsystem consists of simplified modelling of its constituent parts (Figure 3).

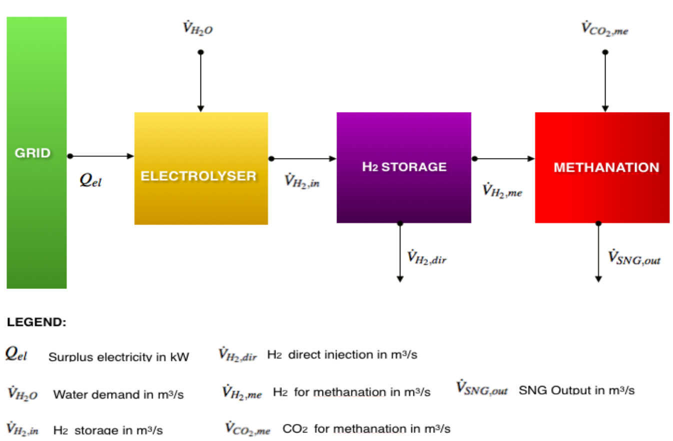

Figure 3: Concept of PtG modelling used in the study

The electrolyser is modelled using a simple volume specific power consumption factor (in kWh/m3). Commercial electrolysers with efficiencies ranging from 4 – 5 kWh/m3 are presently available (Zoulias and Varkaraki, 2004). For the simulations, a consumption factor of 4.5 kWh/m3 is assumed. In the power to gas system, following production of Hydrogen, the subsequent step is its storage[1]. The storage capacity of the hydrogen tank depends on the capacity of electrolyser, the capacity of the methaniser and the dynamic control systems used in both. The quantitative determination of an optimum storage capacity would require optimizing the system as a dynamic optimal control problem. Based on ongoing work in this area and experience obtained from various power to gas operators, the storage capacity of the hydrogen tank is given as an input to each simulation on a case to case basis. Richter, (2008) contains the balance equations describing the fluid dynamic balance equations used to model the storage tank. To model the methanation unit, several methods have been proposed (Rönsch *et al.*, 2016). Although various reactor concepts like micro reactors, three phase reactors etc. could be used in this case, the model itself is made reactor technology agnostic and the technology is represented using a dynamic production rate (Methane produced in m^3/h). This input value is also varied on a case to case basis. The Hydrogen produced can also be blended into the existing gas network. Hydrogen injected into the gas network is fixed at 2% by volume as studies conducted (Altfeld and Pinchbeck, 2013) indicate that a higher percentage by volume level of Hydrogen in the gas distribution network may not be ideal for use in devices at the industrial and transportation sectors.

3.3. Gas distribution network

The model of the gas distribution network in reality contains many node points with varying geodetic height differences, pipe diameters, lengths and pressure loss coefficients. However, for the purpose of system analysis where the distribution of gas across a geographic region is lesser in focus when compared to the storage potential of the network as a whole, the gas network is abstracted to its simplified form. This simplified network is created by performing the following steps:

1. **Abstraction based on pressure:** As a first step parts of the network are classified based on the pressure levels at which they operate. All the node points operating at the same pressure level are grouped.

2. **Abstraction of the node points and lengths in the simplified network:** Here, for each pressure level, all the pipelines between node points with the same diameters are grouped and their lengths are added to conceive a single long pipe (with a uniform diameter) and all the mass flow rates at node points are aggregated to form a single consumption mass flow rate for the entire pipe.

3. **Correction of pressure drop across the simplified network:** Pressure drop measurements for the original pipeline is averaged for the entire length of the simplified network

The simplification in geometry is validated using details of existing pipeline topologies available from network operators. The model is checked to make sure that the total length (and thereby volume) of the pipeline in the simplified model is equal to sum of all lengths of individual pipelines (node to node) from the actual pipeline topology for which data is already available. The balance equations for gas flow inside the pipelines and fluid property calculations are done using TIL Media (Schulze, 2014). The ratio of trace substances as well as the composition of final components in the gas mixture alters its chemical properties. This is important in simulations where different sources of gas like biogas, SNG and CNG are expected to mix. Therefore, it is assumed that the gas used in the simulation is a mixture of Methane, Hydrogen and trace substances. The ratio of trace substances need to be varied on a case to case basis depending on the quality of the gas. The pressure loss calculations of the pipeline as well as the properties of the pipeline materials used in the simulations are also validated against data available from various network operators.

[1] Arguments have been made for and against using storage systems in power to gas plants. It depends on the technology used in the methanation reactor and the electrolyser. It also depends on whether the methanation reactor and the electrolysers are controlled separately. In the model used here, storage is deemed necessary.

1.1. Consumption side

The analysis of the consumption side involves modelling and simulating the buildings together with their respective energy production units like mCHPs, boilers, gas heat pumps and electric heat pumps (Figure 4). The houses (with their integrated energy production systems) are connected to both the gas as well as the electric grids. Similar to the gas distribution network, a level of abstraction is also used in the modelling of the consumption side. The buildings are grouped based on the energy production devices used in them. A geographic region for example could be divided into a set of houses with gas boilers, another set with electric heat pumps and another with mCHPs and so on. Here, inside each group, the buildings housing the energy production devices may themselves show a variation in size as well as materials used for insulation. To incorporate this, a weighted mean of the heat transfer coefficients of all the buildings in a group is used and the total volume of each individual living space (for which data is available) is cumulated. The simulation is then validated using data available for clusters of buildings in real geographic regions. The use of energy production devices is estimated to change in the future. Gas boilers are estimated to be replaced by mCHPs and highly efficient electric heat pumps in the future (Cogeneration Observatory and Dissemination Europe, 2014). The method of modelling used here is also capable of analysing such future scenarios as the percentage of devices in each geographic area can be changed in the simulation thereby allowing their collective effect on the electricity and the gas grids also to change. The buildings using mCHP systems are given special focus during analysis as they can also be a source of electricity. Similar to the gas distribution network, modelling the consumption side essentially involves three parts:

1. **Modelling and validation of individual building types:** Individual building types are modelled along with the energy production units used inside them. The detailed modelling (Prabhakaran, Koeppel and Graf, 2015) of the building and energy systems is followed by validation at the GasPlusLab which is an in-house test facility for devices like mCHP units, fuel cells and boilers.

2. **Scaling up to the system level:** Following the modelling and validation of the individual building types, the individual buildings are grouped according to the housing scenario data available for the city. This has to be performed for every simulation separately.

3. **Validation with energy measurements:** Similar to the gas network, the energy consumption measurements from network operators are used to validate the house models in a region.

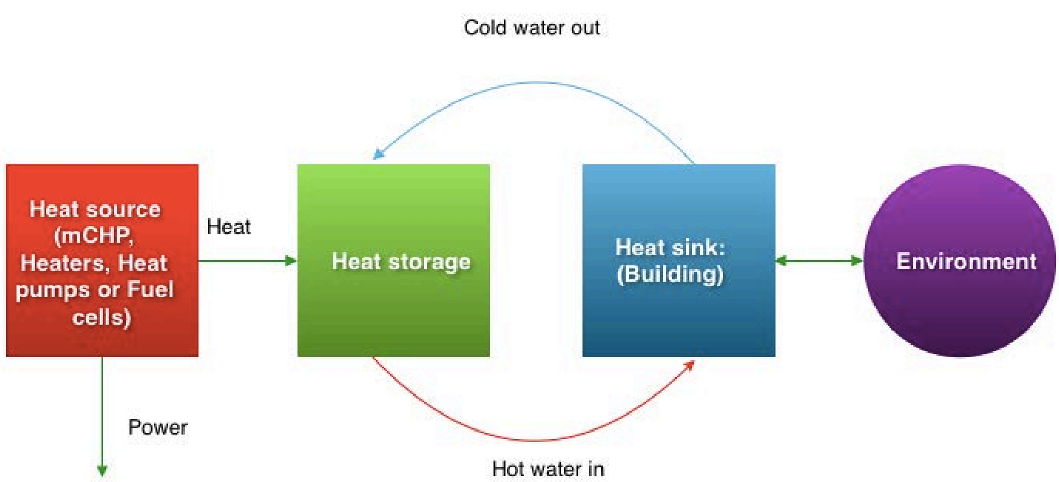

Figure 4: Concept of modelling buildings.

4. System simulation

The system simulation was carried out for the year 2016. The first task was to select a region for analyzing the energy scenario there. The models require the dynamic generation profiles of the solar and wind plants around the chosen geographic region as input. The duration of analysis is the first week of January and the time scales are so chosen to clearly portray the dynamic nature of the components involved. It is very important to note here that although the simulation is described for each constituent part, the entire model is simulated as a single entity where all the parts are interconnected.

5. Boundary conditions

The dynamic generation profiles for wind and solar plants are available from the energy company Tennet (*Open power data,* 2017) in Germany and the same were used in this study. The region chosen for the simulation is assumed to fall inside this network and the region is so chosen that it would directly benefit from both the solar PV as well as the onshore wind plants. However, the wind and solar generation profiles are calculated for the entire network. In comparison, the geographic region chosen for the simulation is much smaller. This implies that the dynamic generation profile of all the wind farms in the smaller area chosen for simulation must be estimated from the profiles available for the entire network. For this, the yearly consumption (in kWh) of the chosen geographic region is first calculated (for wind and solar plants separately). The same calculation is then performed for the entire network to get its yearly consumption. Then the two values are compared to get the ratio of energy consumed by the smaller region to that of the entire network. It is then assumed that the dynamic generation also follows the same ratio. Finally, the dynamic generation of the smaller region is estimated from the total network using this ratio.

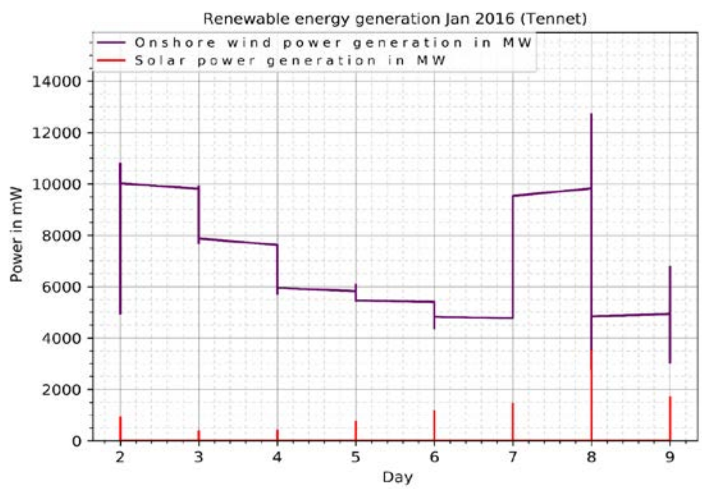

Figure 5: Wind and solar generation profiles for the Tennet network in Germany.

1.2. Power to gas plant

In the power to gas plant simulation, it is assumed that:

1. The production of methane is delayed by a small-time period after the introduction of Hydrogen into the methanation reactor. The exact quantification of the delay and the reactor kinetics and thermodynamic changes that causes it is currently being investigated. At this preliminary stage of modelling, the delay itself is estimated from experiments conducted for similar plant capacities and provided as an input to the simulation.

2. The production of SNG is not found to follow the stoichiometric ratio of 1:4. Experience obtained from experiments show that the value is be slightly below the stoichiometric ratio as a small percentage of Hydrogen remains unreacted inside the reactor. In the modelling, this is incorporated using a correction factor.

3. The ramp up and ramp down times are different for the electrolyser and methanation units where the methanation unit is typically slower. Therefore, a correction factor is also introduced here to make sure that the methane production rate in the simulation matches to the measurements made in reality.

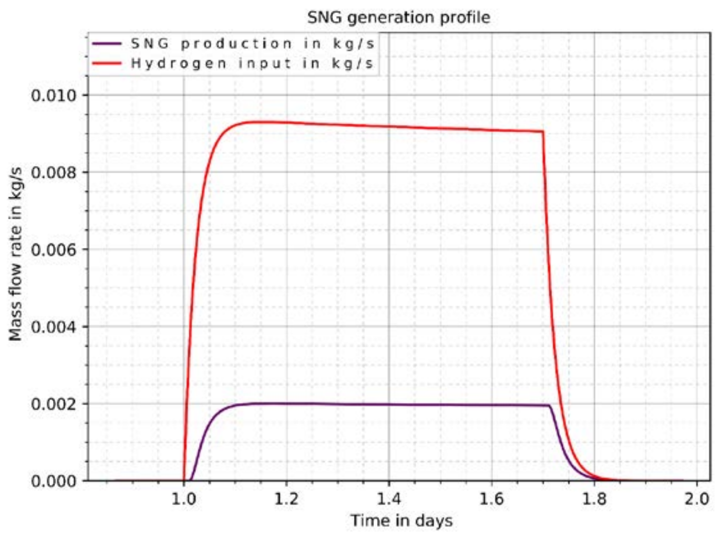

Figure 6: Power to gas output profiles

1.3. Energy consumption sector

In the energy consumption sector, the geometries of the individual buildings are initially set using information available from other projects. The individual buildings are then grouped based on the energy production systems used inside them and connected to both the gas grid and the electricity grid.

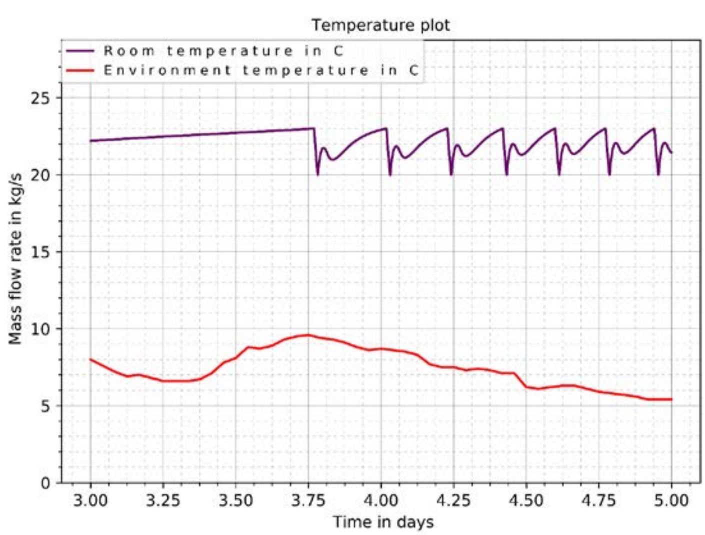

Figure 7: Temperature profile in individual buildings (Controlled to always stay inside the comfort temperature level)

The control systems used inside individual buildings are designed in such a way that all the buildings (irrespective of the devices used inside them for heating) maintain a comfort temperature level between 20 C and 22 C. All buildings use the same control system which specifies that the heating is turned off in each individual building automatically whenever the temperature goes above the comfort level (Figure 7) and the heating is turned back on automatically when it falls below the lower level. The mCHP or other energy production systems that power the heating is controlled using the storage tank temperature (Figure 8). The results of simulation are validated both at the component level for each component as well as at the building level. It is to be noted here that energy simulations inside a building also depend on the requirements of the inhabitants residing in the building and such user specific preferences can vary based on various factors. This makes grouping them very difficult. Many assumptions and correction factors based on measurement data are therefore used in this part of modelling. However, an elaboration of the same is a separate study in itself and therefore beyond the scope of this report.

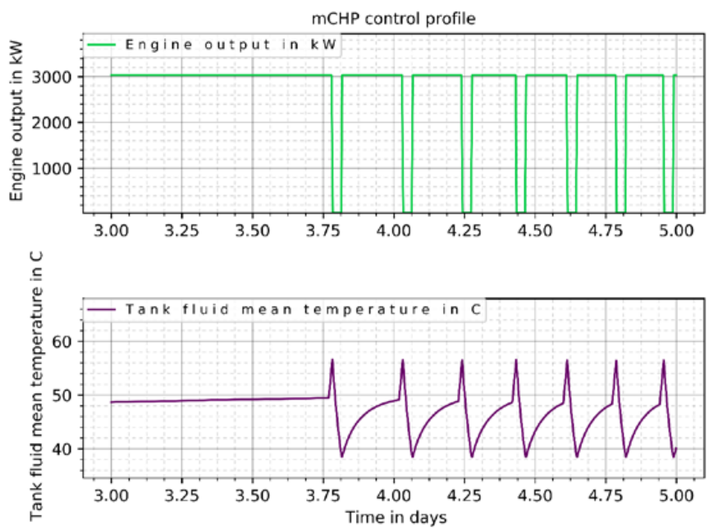

Figure 8: mCHP control profile based on storage tank temperature

6. Conclusion and future work planned

To summarise, the complete energy network is modelled using a single physical model. The modelling language used is Modelica and the simulations were carried out using measured temperature boundary conditions and geometries of the components estimated from other studies. It has to be noted that this is a preliminary step and the models themselves need to be iteratively improved in each case to incorporate all the aspects of modelling energy systems. Efforts to incorporate dynamic optimization and control, model predictive control and incorporation of GIS based location points to generate network topologies are planned for the future. However, such improvements need to be critically evaluated as addition of each new feature increases the number and complexities of equations in the system thereby increasing the possibilities of non-linearity, local chattering and non-convergence during simulation. None the less, it is also to be noted that future scenarios like integration of more bio-gas plants into the gas network or an increase in the installed capacity of wind and solar plants or the potential blending of Hydrogen into the natural gas system can be analysed using this tool in its present condition.

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