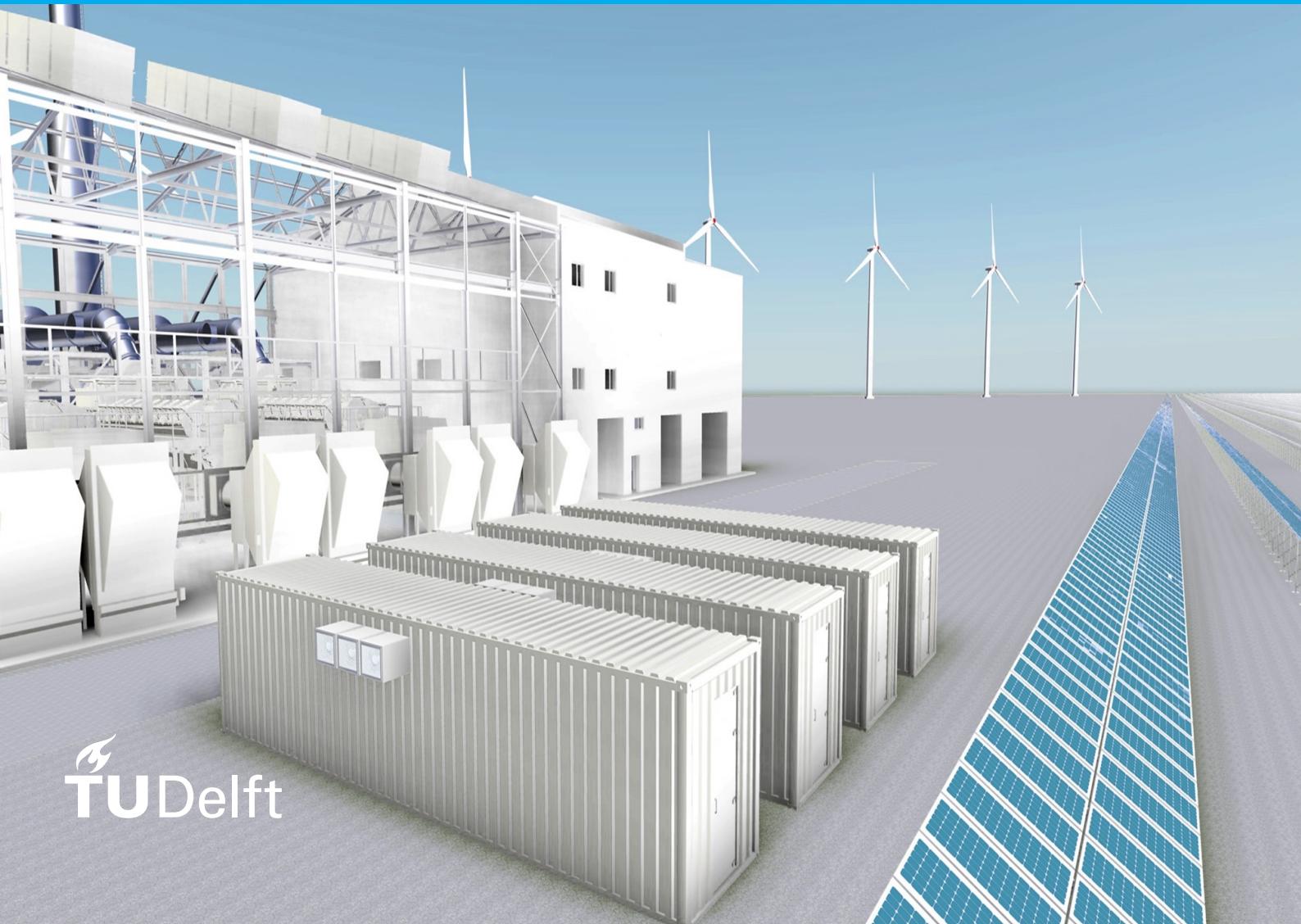


Investigating Hidden Flexibilities Provided by Power-to-X Consid- ering Grid Support Strategies

Master Thesis

B. Caner Yağcı

Intelligent Electrical Power Grids



Investigating Hidden Flexibilities Provided by Power-to-X Considering Grid Support Strategies

Master Thesis

by

B. Caner Yağcı

to obtain the degree of Master of Science
at the Delft University of Technology,
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This thesis is confidential and cannot be made public until August 26, 2020.

An electronic version of this thesis is available at <http://repository.tudelft.nl/>.



Preface

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*B. Caner Yağız
Delft, August 2020*

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1

Introduction

Zero-carbon emission is the ultimate goal for a civilized world. Significant amount of renewable energy sources (RES) are integrated to the electricity network in order to reach this goal. However, stochastic nature of these RES introduces a great challenge of matching the energy demand and supply in the networks. Therefore, flexibility of the existing power grid must be increased from demand side and this requires complex analysis.

1.1. Background

Evolution to sustainable world is an urgent challenge that must be dealt by humankind for a better life. Figure 1.1 shows the amount of greenhouse gases (carbon dioxide (CO_2), nitrous oxide, methane, etc.) emitted to the atmosphere. The effects of climate change is in the full glare of publicity. To mitigate the effects of climate change, Paris Agreement [32] has made by UN members. The objective of the countries, by this agreement, is to keep the global temperature increase below $2^{\circ}C$ and pursue efforts to keep it to $1.5^{\circ}C$ for a progress towards climate- neutral economy with net-zero greenhouse gas emissions by 2050. In order to reach this objective worldwide effort is spending for the decarbonization, especially, of the industry.

This agreement led to increased amount of unpredictable RES to be integrated to the electricity network.

Carbon dioxide emissions, primarily from the combustion of fossil fuels, have risen dramatically since the start of the industrial revolution. Table 1.1 shows ... Use of RES and Hydrogen will increase. District heating will have a transition to electricity. Traditional energy systems, with fossil fuel based generation units, are emitting too much carbondioxide. In order to have affordable, green energy; renewable energy sources combined with P2X are inevitable. On the one hand, the number of low or zero carbon emission renewable energy sources in the electrical network is increasing everyday. ... Countries are preparing to supply %100 of their energy demand by RES in the near future. On the other hand, dependent nature of these renewable energy sources to unpredictable weather puts reliability of the existing electrical systems in great danger. Replacing production based on fossil fuels in chemical, petrochemical, food, steel, and other industries leads to more sustainable and flexible multi-energy systems that offers more flexibility to electrical network for higher share of RES.

Uncertain generation profiles of RES requires more flexible energy systems. Future energy systems must have comprehensive energy management strategies addressing not only electricity but all energy sectors in order to be more efficient and flexible.

Electrification of the industry and Power-to-X (P2X) systems, are one of the most promising ways to combine energy domains with each other.

1.2. Literature Review

This section is divided into three main parts. In the first part, multi-energy systems (MES) and two of the most important P2X technologies are reviewed. In the second part, flexibility in the literature is reviewed and flexibility in this project is defined. Finally, in the third part, hierarchical control and optimal deployment of flexibility is reviewed with respect to multi-energy systems.

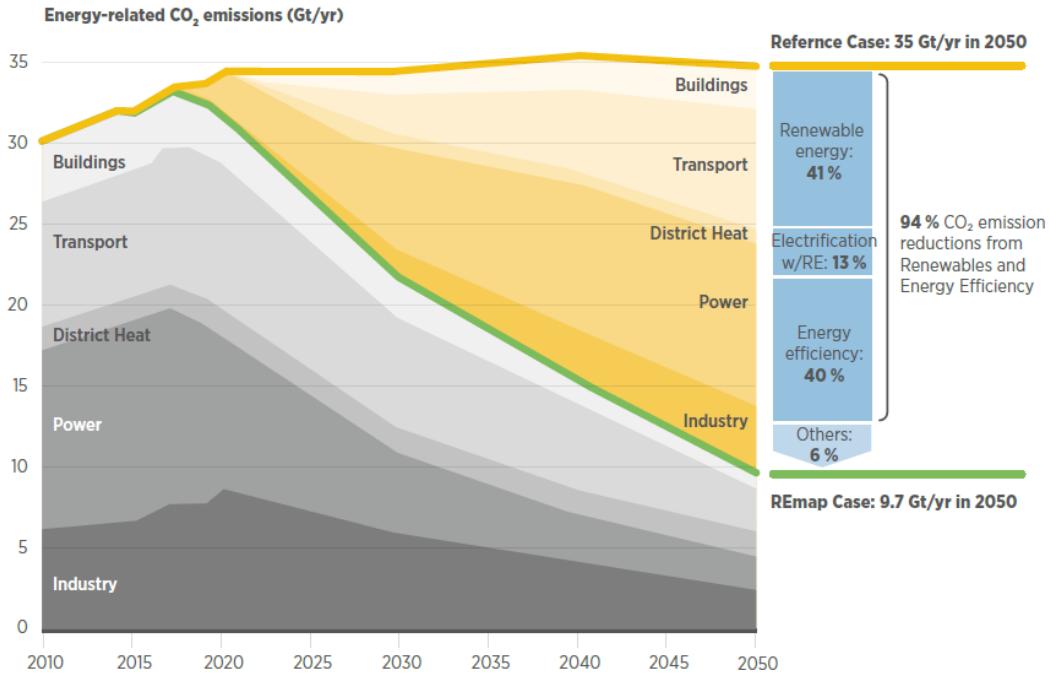


Figure 1.1: Energy-related carbon dioxide emissions with current policies compared to accelerated uptake of renewables (REmap), 2010–2050 [14]

Table 1.1: Final energy consumption by sector, fuel (Mtoe) [1]

			Sustainable Development	
	2000	2018	2030	2040
By sector				
Industry	1 881	2 898	2 949	2 904
Transport	1 958	2 863	2 956	2 615
Buildings	2 446	3 101	2 735	2 709
Other	758	1 092	1 264	1 272
By fuel				
Electricity	1 092	1 915	2 349	2 902
District heat	248	296	264	224
Hydrogen	0	0	6	65
Direct use of renewables	271	482	887	1 142
Natural gas	1 127	1 615	1 816	1 719
Oil	3 124	4 043	3 695	2 838
Coal	542	984	746	533
Solid biomass	638	620	140	75

1.2.1. Multi-Energy Systems

- What is MES?
- Explain all possibilities and why you have selected p2g with electrolyser and p2h with heat pump. However, in a multi energy system, different energy sources such as electricity, gas, heat, cooling, transportation, etc. optimally interact with each other at lower system levels with the help of coupling technologies. What's new in those systems is the integration of RES. Because, multi-energy systems with renewable energy sources (RES) are considered to have better technical, economical, environmental and operational advantages than those conventional energy systems.

Multi-energy systems are Various MES technologies and their combinations exist in the sector.

- Multi-energy systems are inevitable future for more flexibility.
- Traditional energy systems vs. MES
- What are the flexibility and P2X options in a MES?
- About P2X Selection:

Power-to-Gas, Industrial PEM Electrolyser

- Advantages of hydrogen as energy carrier
- Electrolyser Technology performance for grid ancillary services
- Importance of Electrolyser modelling on flexibility analysis (efficiency characterization)
- Chemical and petrochemical industry is considered for Electrolyser integration.

Power-to-Heat, District Heating Electric Heat Pump

- Advantages of using excess RE in District Heating Networks. Food industry is also particularly promising since the required moderate temperature levels promote heat pump integration.
- Advantage of using heat pump combined with boiler :To organize the application of a heat pump as beneficially as possible, and thus achieve a high efficiency, the temperature of the heat source should be as high as possible and the temperature of the heat sink should be at the lowest level. As the power consumption depends upon the temperature difference between heat source and heat sink. (T_{inlet} of HP is regulated by e-boiler.)

The outstanding advantage of the heat pump is that the generation of 100% heat energy requires only 25% power input. The remaining 75% is taken from the environment. This means that increasing energy prices will no longer have such a significant impact on the heat price. Therefore, the heat pump is clearly the power source of the future. Instead of burning sources of energy for the generation of thermal energy, they should be used under high efficiency levels to generate electricity for running heat pumps. Additionally, further use can be made of the waste heat arising from power generation. But there is another remarkable ecological benefit. The carbon dioxide emission is reduced to 0.14 kg CO₂/kWh, and can even reach 0 kg CO₂/kWh if electricity from wind or sun energy is employed. It is useful for comparison to note: oil-based heat generation: 0.31 kg CO₂/kWh and Gas: 0.24 kg CO₂/kWh respectively.

If the heat capacity of the heat pumps is insufficient then electric boilers can be used as complement to increase the temperature of the district heating water.

- Importance of Heat pump modelling on flexibility analysis (COP characterization)

1.2.2. Flexibility

For reliable operation of power system, energy balance between supply and demand must be maintained in any point of time. Electrical systems are able to deal with uncertainties in both supply and demand of energy up to certain point, and this is called energy system flexibility [16]. However, integrating variable renewable energy sources such as wind or solar into electrical network increase the need for energy system flexibility.

Different flexibility metrics and classifications can be found in the literature. [18] divides flexibility into four main parts: grid expansion, energy storage, flexibility on the supply side, and flexibility on the demand side; and defines demand-side flexibility as ability of a load to vary its scheduled profile. [27] investigates industrial flexibility of power consumption using generic data models. [31] classifies flexibility sources as illustrated in figure 1.2. They focus on operational flexibility of power system, shifting the management of power generation and load profiles. [24] proposes a taxonomy for modelling flexibility they simply define flexibility as the ability to deviate from the plan, and mention that flexibility of a given system is a unique, innate, state and time dependent quality. The examples show that different approaches can be taken while defining flexibility metrics, in order to analyse different aspects of electrical system.

In this project, **Flexibility defined as the ability of a component or a collection of components to respond to power fluctuations of renewable energy sources in power systems.** From an operational perspective, P2X flexibility becomes relevant in situations where there is excess RE supply relative to demand in the power system and, therefore, electricity prices are low. During excess RE, this response can be achieved by

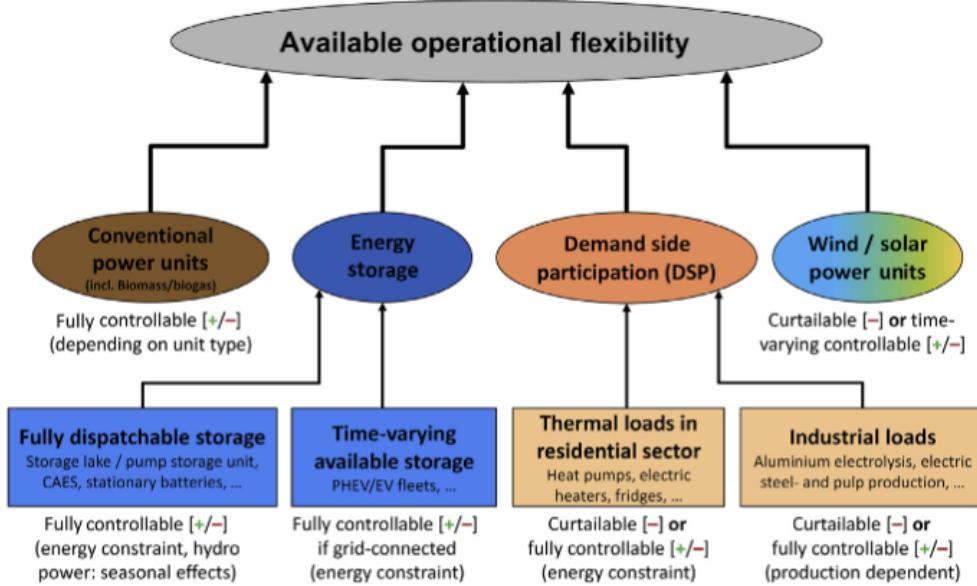


Figure 1.2: Sources of power system flexibility [31]

flexible P2X, as the amount of consumed energy can be increased to higher load state. An increase from their set values for a specific holding duration provides power balance during excess RE and reduces operational costs for P2X owners by shifting load to time of low electricity prices.

[27] mentions that, modelling of flexibility must be standardized in such a way that, models describe flexibility potential as precisely as possible on the basis of various key figures. Figure 1.3 shows the power consumption of exemplary flexible load with flexibility paramters. The key figures, that characterize flexibility, considered in this project are activation duration (t_{act}), holding duration ($t_{flex, on}$), deactivation period ($t_{restore}$) and power capacity [27]. Activation duration is the amount of time to reach flexibility setpoint, and deactivation period is the amount of time to return to base set point and these parameters can be modelled or decided based on the inertia of the flexible system. Holding duration is the time duration in which the chosen power state will be hold. Additionally, storage level indication is inevitable for the flexibility characterization of storage models.

Other flexibility terms in this project are defined as:

- **Hidden flexibility**, is the effect of modelling & simulation considerations on flexibility results of a power system.
- **Optimal deployment of flexibility**, is the energy management strategies of flexible loads in order to make the optimal use of them in a multi-energy system.

1.2.3. Multi-Energy System Energy Management

- What is Hierarchical control?
- Relate with optimal deployment of flexibility.

1. MES's requires more holistic energy management and operation strategy due to traditionally de-coupled energy systems.
2. However, operation of a MES should be investigated with respect to Market DR and Physical DR for the optimal deployment of flexibility service.
3. [21] suggests that, a good combination of Market DR (price signals) and Physical DR is necessary. Existing hierarchical management of MES models not considers energy cost of production(€/MWh). This results with unnecessary trading of electricity and increase in operational cost

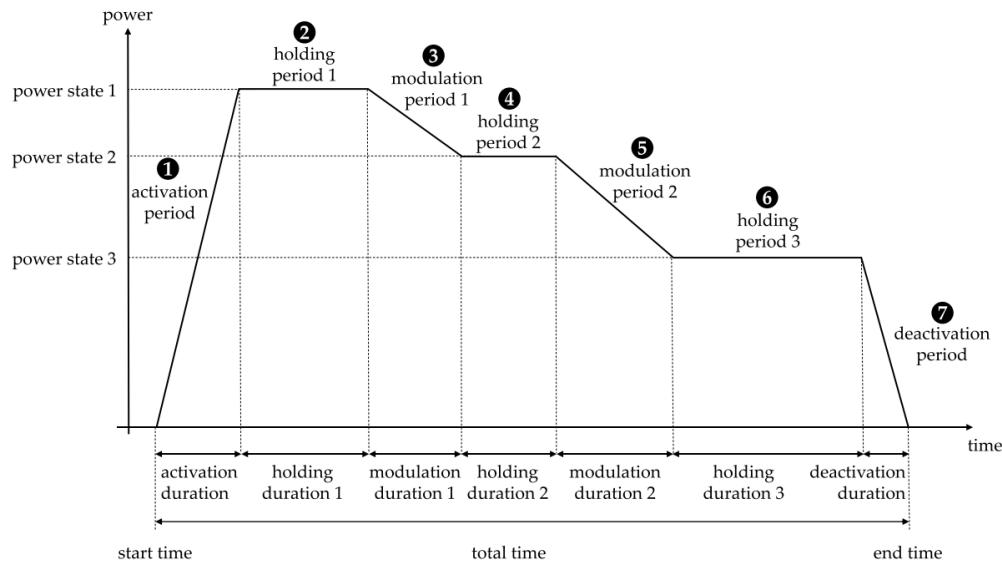


Figure 1.3: An exemplary flexible load measure with the corresponding parameters [27]

Optimal Power Flow

- What is Optimal Power Flow?
- Why it is done?

1.3. Problem Definition

Significant number of RES are integrated to the electricity network and more expected to be connected in the future, as illustrated in figure 1.4. Despite of being carbon free energy sources, highly volatile nature of these generation units introduce a great challenge for grid operator to balance the electricity supply and demand. In order to increase the percentage of RES in the electricity network, the flexibility of the electrical network must be increased. Electrification of the industry is one the most promising ways to increase this flexibility [25]. Industrial systems are able to provide large amounts of energy and energy storage with various efficiencies, ramp up/down rates and storage duration [5]. Industrial processes currently account for 30-35% of the world's total energy demand and related carbon emissions. Replacing production based on fossil fuels in chemical, petrochemical, food, steel and other industries leads to more sustainable and flexible multi-energy networks. However, in order to understand MES phenomena, complex control, flexibility and/or energy management analysis must be carried out and this brings a trade-off between model complexity and simulation time.

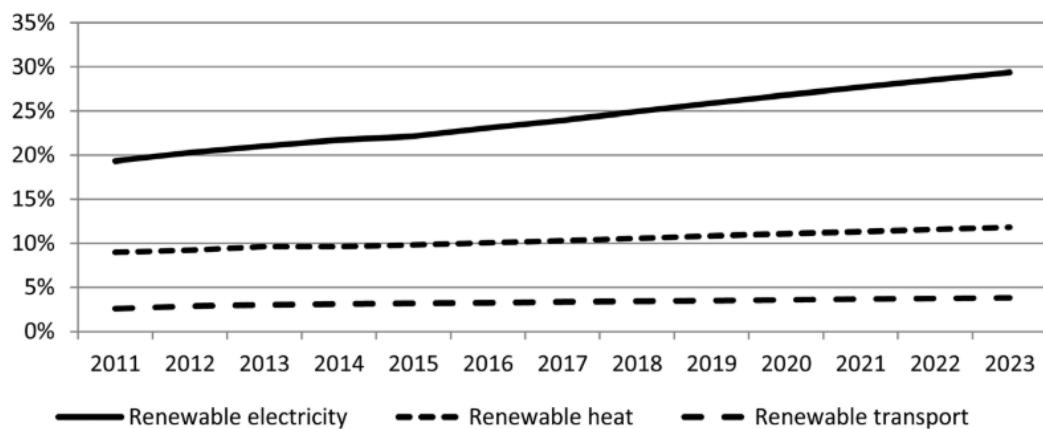


Figure 1.4: Shares of renewables in the energy mix of the power sector, the transport sector, and heat [25]

In order to reduce model complexity constant or linear relation assumption between the power input and energy output is made during modelling of PtX. However, operational performance of PtX such as electrolyser or electric heat pump strongly depends on operational temperature conditions. During flexibility analysis, this critical assumption leads to losing essential dynamics on simulation results. Correct efficiency characterization is crucial to understand the flexibility provided by Power-to-X. Inaccurate flexibility analysis of PtX may lead to increased transmission losses, higher operational costs or miscalculation of the MES capacity. Due to simplifications made in model formulations, flexibilities provided by MES components to network can be concealed in the simulation results (hidden flexibility). Therefore, modelling of PtX should be investigated with respect to be optimally adapted to the requirements of flexibility analysis.

Another problem is, conventional energy management systems only consider generation side with limited amount of information. The planning and operation of multi-energy system needs to be coordinated to make optimal use of the available resources. Due to the interdependencies and connectivity between previously distinct energy vectors, a more holistic energy management and modelling approach must be provided including demand side management. However, this approach requires complex simulations to be set up. Even though [21] suggests that, a good combination of Market DR (price signals) and Physical DR (grid management) is necessary to run a network optimal, many of the existing simulation models for the energy management of MES do not have any information about the energy cost of other components in the network. This approach results in unnecessary trading of electricity with the utility grid and means an increase in operational cost for P2X owners [7].

1.4. Previous Work

Power-to-X technologies, especially electrolyser and electric heat pump, have the potential to be an integral part of an efficient, renewable and interconnected multi energy system. With respect to fuel cell systems, limited number of electrolyser model develop input-output models adapted to the requirements of control and flexibility analysis [19]. The existing generic electrolyser models use an efficiency curve to simulate the transformation of energy from power to gas [30]. While generic models are easy to simulate, they are highly dependent on manufacturer data or experimental measurements that are almost impossible to find for industrial systems. Thus, a lot of effort has to be performed in the modelling of detailed design of such systems. Several projects use partial differential equations for electrolyser modelling [15, 20]. These models are commonly used for mass transport behavior characterization. Some PEM electrolyser models available in the literature use ordinary differential equation (ODE) for efficiency characterization [10, 35]. ODEs are most commonly used for practical applications of electrolyzers. [10] characterize PEM electrolyzer physics and develops a detailed model of an industrial electrolyzer considering pressure, temperature, and current effects. This paper is chosen as the basis for modelling of the PEM electrolyser model.

During modelling of electric heat pump in MES, constant relation between power input and heat output is considered, assuming small variations of coefficient of performance (COP) over time [3, 4, 8, 13]. This assumption is made in order to reduce simulation complexity. However, in practice, COP of an heat pump strongly depends difference between inlet and the outlet temperature. Therefore, flexibility analysis requires more detailed electric heat pump models that considers effects of operational conditions on PtX performance. Diverse empirical approximations of heat pump's physical laws of operation can be made [34]. [2, 6, 22] develop heat pump models with Carnot-COP, dependent on source and sink temperature. These papers are chosen as the basis for modelling of electric heat pump. The dependency of COP on both inlet and outlet temperature is taken into account by a polynomial fit in these two variables during modelling of heat pump. Additionally, several articles suggests using auxiliary electric boilers at the output of the heat pump system in order to increase the efficiency [5, 6]. The effect of auxiliary electric boiler on PtH performance is also considered during analysis.

Most of the research available on hierarchical energy management of MES do not have any information about the production cost of agents in the system. Most commonly, only excess and shortage amounts of PtX is considered, but cost signals of components in a MES are ignored during energy management analysis. Besides grid parameters and physical constraints, cost signals should also be considered in order to find the optimal operation point of MES. [21] analyzes various types of energy management and demand-side

management of intelligent energy systems. They mention that demand response (DR) of flexible load can be divided as Market DR and Physical DR, and consideration of both is required for the optimal operation of intelligent energy system. [7] propose hierarchical energy management strategy based on multi energy system agents. They introduce adjustable power level concept in order to reduce operational cost.

On model level, the influence of temperature simplifications has not yet been investigated in the literature. My contribution is investigating the effect of temperature simplifications of PtX models on flexibility analysis. Effects of auxiliary components on device performance is also considered during modelling. Another contribution is the hierarchical agent based energy management approach considering price signals with co-simulation. Co-simulation provides more detail to manage & observe MES components during analysis and maintains reduced simulation times during analysis by using only necessary input and output.

1.5. Research Questions & Objective

The objective of this project is to investigate the hidden flexibilities provided by different PtX models, with comprehensive energy management approach for the agents of a MES. In order to reach this objective, OpenModelica models for power-to-gas and power-to-heat are connected to designed MES with renewable energy sources. Later, Pandapower power flow solver is combined with OM models in Energysim simulation environment for various co-simulation cases.

Research questions are divided into three main parts. First part considers flexible MES Design and PtX selection. Second part is about modelling of P2X to investigate hidden flexibilities. Finally the third part is about implementing complex simulations to investigate the optimal deployment of flexibility.

The questions addressed in this research are:

- What options exist for minimizing curtailment of renewable energy sources in MES?
 - Which options are available in industrial area?
 - How much flexibility is necessary for the electricity system?
 - Which option has the best performance for the grid and the most profit for the P2X owner?
- What is the effect of modelling considerations on flexibility result?
 - What should be MES model level of detail for flexibility analysis? analysis?
 - Which modelling considerations are more significant for flexibility analysis?
- How energy flow in a MES can be managed for optimal use of sources? (About Hierarchical agent based energy management.)
 - What should be the energy management approach for Multi-Energy Systems?
 - How complex simulation can be created for energy management of MES?
- What is the optimal deployment of flexibility in order to reduce operational cost for P2X owner?
 - How to distribute flexibility between flexible loads? -Flexible operation of P2X causes additional costs. Calculate this for flexibility deployment decision.
 - What is the revenue potential of this flexibility service? -What is the amount of profit made from shifting load to low electricity prices?
 - What is the cost of flexibility service provided?
 - What should be the control architecture of MES?
 - How can different energy domains can be combined and optimized for flexibility
 - What are the dependencies between flexible load pairs?
 - About Simulation and Hierarchical Control
 - About Operational Cost Analysis
 - Which specific technology should cover a given flexibility demand?(economic perspective on the basis of production costs).

1.6. Research Approach

Considering most popular industrial PtX options in the literature and research gap in PtX modelling, PEM electrolyser and electric heat pump with auxiliary electric boiler are selected to be modelled in OpenModelica. Modelling objective is to achieve an effective energy efficiency characterization during system's design and operation.

PEM electrolyser model is created to study the performance behaviour of electrolyser under different operating conditions. An electrochemical steady-state model is created to calculate the stack/cell voltage and the stack/cell temperature evolution from instantaneous operating conditions such as the applied current, pressure and temperature. Temperature dynamics is added for detailed model version in order to compare the efficiency and performance behaviour of electrolyser model under different modelling assumptions. Pressure - Enthalpy table of ideal heat pump cycle working fluid (r134a) is used to characterize fifth order polynomial function of heat pump COP dependent on inlet and outlet temperatures. The aim of this modelling is to evaluate the performance of the heat pump with respect to different operational temperature assumptions and auxiliary electric boiler.

The aim of the agent based hierarchical energy management is to optimize the MES operation with respect to grid parameters, hydrogen/thermal comfort and energy cost. Optimization of the considered MES is carried out by Pandapower power flow solver. Optimal power flow solver calculates the exact operation point considering cost signals within the available power range defined by the physical situation of the Modelica agents. Hierarchical energy management is achieved with co-simulation by combining OM models with Pandapower solver in Energysim as illustrated in figure 1.5.

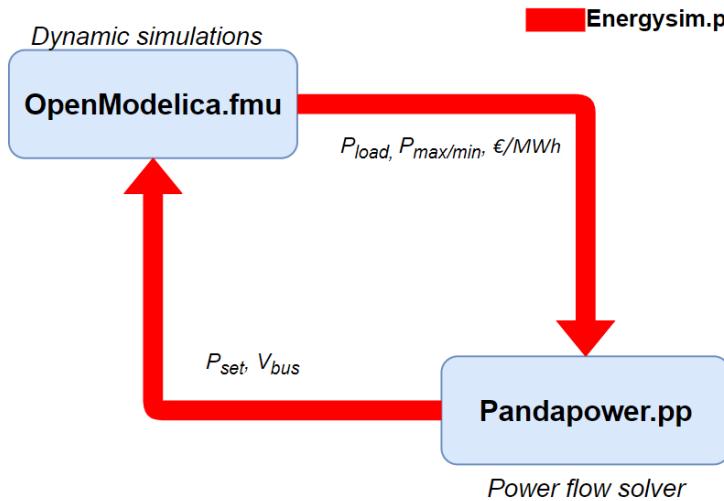


Figure 1.5: Communication between simulation tools

1.7. Outline

- Chapter 2 ...
- Chapter 3 ...
- Chapter 4 ...
- Chapter 5 ...

2

Methodology

2.1. Simulation Tools

Three different softwares are used during project. Open Modelica(OM) is used for modelling of agents. Pan-daPower is used for power flow calculations of the electrical network, and these two software are combined in another, namely EnergySim, for co-simulation and flexibility analysis.

2.1.1. OpenModelica

Modelica is an object-oriented, equation-based programming language which allows for dynamic simulations of multi-domain systems [17]. By reason of Modelica allows a physically based, dynamic simulation of the dynamic reactions; disturbances can be modelled and assessed. It allows the combination of models coming from different technical domains in a unified way. A casual modelling of Modelica provides effortless modelling and fast simulation of complex dynamics. Thus, Modelica language is suitable to simulate coupled energy systems with different levels of detail.

Various OpenModelica (OM) libraries, such as PowerGrids, PowerSystems, PVSystems, WindPowerPlants, AixLib, Buildings etc, have been considered in order to find the optimum balance between the simulation computation time, modelling simplicity and resolution of results. The controller models of PVSystems Library [23] has found useful for grid support analysis, but comes with increasing computation time threshold. As a result, iTesla Power Systems Library (iPSL) [33] has decided to be the best option for the desired amount of simulation time and level of detail.

MES components with first order dynamics and active power, reactive power, voltage control is modelled in OM for each MES agent as illustrated in Fig.8, 9, 10. These models can be further improved for faster or more detailed control and flexibility analysis of MES.

Besides, P2X and RES modelled in object oriented Modelica Language, electrical network is modelled using PandaPower [29] as illustrated in Fig.6 and optimal power flow (OPF) is initiated. In a general manner, results of OPF are the inputs of the Modelica models as can be seen in fig.1.

2.1.2. PandaPower

What is Pandapower?

It allowed me to manage my MES agents from higher control level with comprehensive approach.

It allowed me to solve optimal power flow problem with operational flexibility constraints and market price signals.

Solves global optimal power flow problem for minimizing operational cost of MES. Sends active power orders to PtX models via EnergySim.

2.1.3. EnergySim

To evaluate the flexibility available from P2X and the impact they can have on the electrical grid, complex simulations need to be set up [11]. Co-simulation is used for such complex system in order to implement hier-

archical control, reduce computational burden and couple different energy domains. It allows complex control and flexibility analysis with multiple agents and a higher control level. There exist many co-simulation tools for MES that allow coupling of models from various energy domains, each with their pros and cons. Energysim (previously, FMUWorld) [11] is used for co-simulation. It is a python-based tool that was developed specifically to simplify energy system based co-simulations and focus on analysis by conceptualising the setup. It allows users to combine:

- Dynamic models packaged as Functional Mockup Units (FMUs)
- Pandapower Networks packaged as pickle files
- PyPSA models (BETA) packaged as Excel workbook
- csv data files

The models are tested on OpenModelica (OM) and exported as FMUs using inbuilt FMU Export function. Models, their inputs/outputs and simulation start time for simulation case 1 &2 is illustrated in fig.2 (Detailed version for case 3 is fig.3). There are no results from this part yet. Therefore, exact step, exchange and total time is not known. However, considering the flexibilities that will be provided and the simulation time results from OpenModelica models, total duration have to be more than 5-7 hours (target: 24 hours) with 5-15 minutes exchange time.

2.2. Considered System

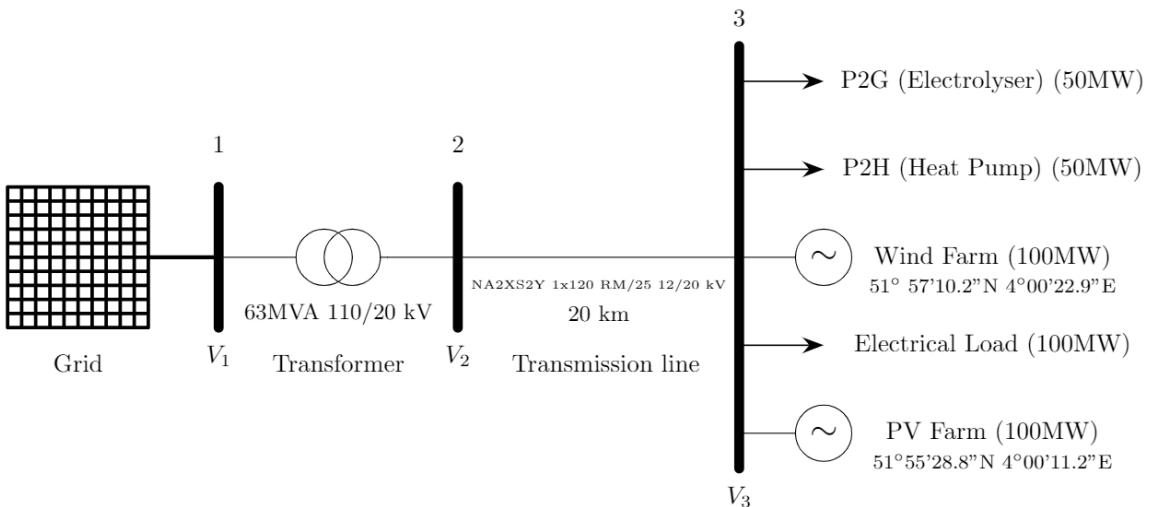


Figure 2.1: Pandapower electrical network

2.2.1. Energy Production

See appendix B.

Figure 2.2 shows the location of the installed windfarm.

Figure 2.3 shows the location of the installed solar park.

2.2.2. Energy Demand

Power-to-Gas: 50MW PEM Electrolyser with auxiliaries. Temperature ... Pressure...

Power-to-Heat: District heating plant consists of electric heat pumps and auxiliary electric boilers. Waste water at temperature that is proportional to $T_{ambient}$ is pumped to the evaporator of the heat pump (or used in e-boiler first to regulate the inlet temperature of the heat pump). The efficiency of a heat pump depends on the choice of refrigerant. Refrigerant R134a is used inside the heat pump cycle. Temperature of the district heating water delivered is 70-80 °C. Pressure ...



Figure 2.2: Location of the 100 MW wind park in Maasvlakte



Figure 2.3: Location of the 100 MW solar park in Maasvlakte

In general, two different strategies can be applied to a heat pump in order to load a storage tank. The circulation pump (CP) that circulates water between the generator and the tank can have a constant mass flow. The compressor power of the heat pump is then controlled according to the needs of the tank. This is typically done using a PIcontrol for a modulating heat pump. Alternatively, the compressor power of the heat pump can be kept at full load while the mass flow of the CP is controlled according to the needs of the tank. In our case study, the compressor power is controlled...

To smooth out the daily variations and thus provide a more flexible operation of the system a hot water accumulator (storage tank) is connected to P2H(district heating network). The accumulator holds ... m₃ water.

Figure 2.5 shows the considered heating network.

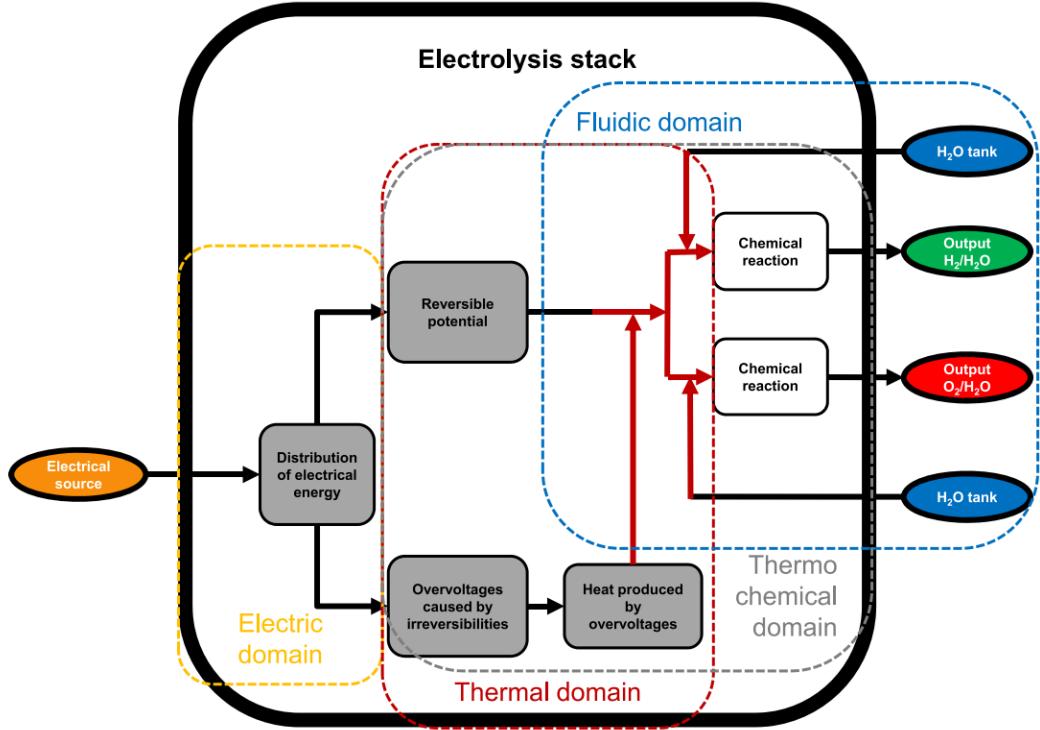


Figure 2.4: Coupled multiphysic phenomena involved in an electrolysis stack [19]

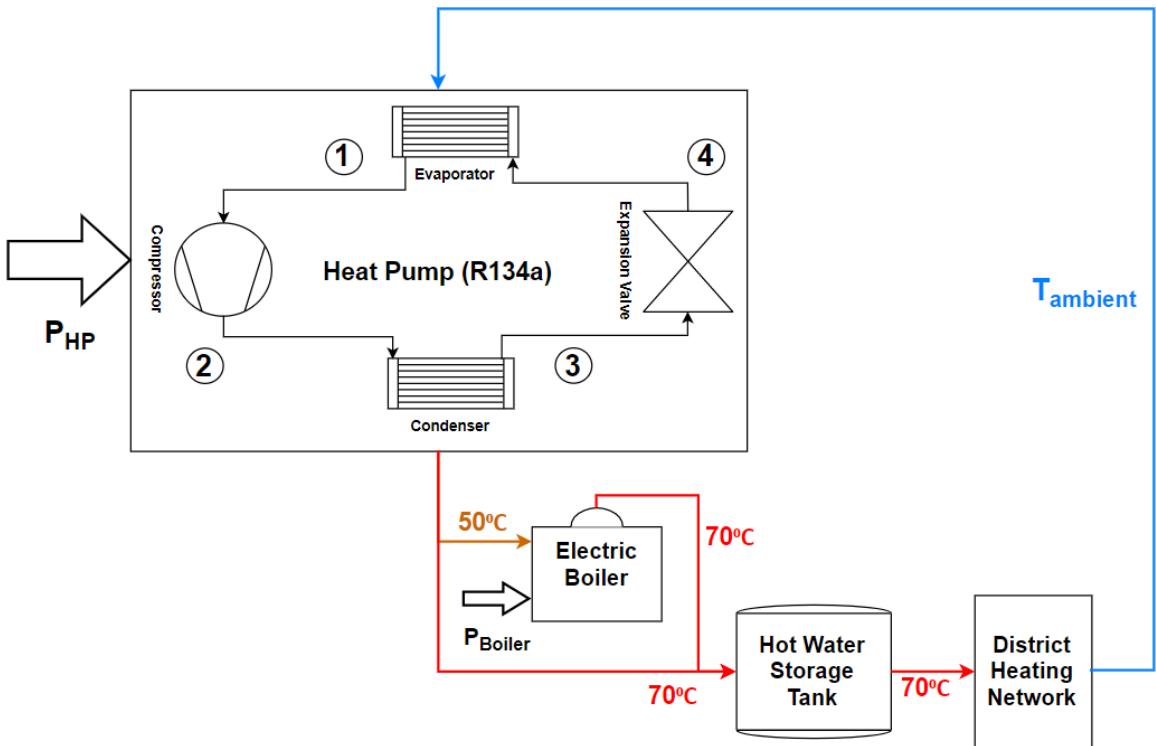


Figure 2.5: Heating Cycle of Water

2.3. Agent Base Hierarchical control

At lower control level objective of the OM agents is to supply demand at all times. At higher control level, objective of the optimal power flow is to reduce operational cost considering the adjustable power level in-

formation coming from OM agents.

Flexibility service is provided for short-term balancing of renewable energy sources.

2.4. Input Data

Scheduled (Static) Energy Demand Profiles

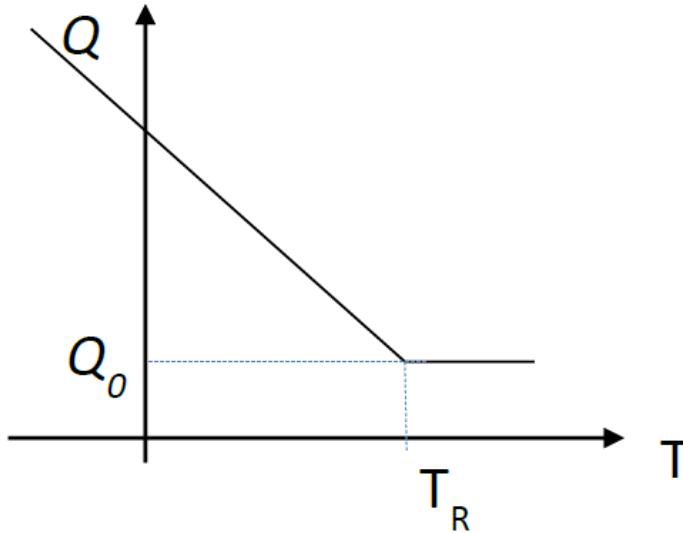


Figure 2.6: The relation between ambient temperature and hydrogen & heat demand [36]

$$Q(t) = Q_0 + \frac{Q_{max} - Q_0}{T_R - T_{min}} \max(0, T_R - T(t)) \quad (2.1)$$

Table 2.1: Ambient temperature - demand relation parameters

	$T_{Reference}$ [°C]	T_{min} [°C]	Q_0 [m ₃ /s]	Q_{max} [m ₃ /s]
Industrial PtG	25	5	3.1372e-03	3.8502e-03
District Heating PtH	25	5	3	4

Levelized Cost of Energy Production

$$\text{Levelized cost of hydrogen} = \frac{\left(\frac{CAP+O\&M}{LT[a]}\right)_{Electrolyser} + \text{Carbon penalty}}{\text{efficiency}(t)} \quad (2.2)$$

$$\text{Levelized cost of heat} = \frac{\left(\frac{CAP+O\&M}{LT[a]}\right)_{HP} + \left(\frac{CAP+O\&M}{LT[a]}\right)_{Boiler} + \text{Carbon penalty}}{COP(t)} \quad (2.3)$$

$$\text{Carbon penalty [EUR/kW]} = CO_2 \text{ emission factor [g CO}_2 \text{ kW}^{-1}] \times \text{Carbon price [EUR g CO}_2^{-1}] \quad (2.4)$$

ENTSO-E Day-ahead Market Price Historical Data

See appendix F

Table 2.2: Cost considerations for PtG & PtH

	Electrolyser	Electric Heat Pump	Electric Boiler
CAPEX [EUR/kW]	200	1000	70
O & M [EUR/kW]	8	33.5	1.4
Lifetime [a]	20	20	15
Carbon emission factor [gCO2/kWh]	16.6	62.3	-
Carbon penalty [EUR/kW]	16.6	62.3	-

2.5. Simulation Scenarios

The year of 2019 is divided into 8 sections of 45 days. As a result 8 days from 2019 is selected for the analysis. Table 2.3 shows considered days for historical data.

Table 2.3: Selected days for historical data

Selected Days for Historical Data
07.02.2019
23.03.2019
07.05.2019
23.06.2019
07.08.2019
23.09.2019
07.11.2019
23.12.2019

- MES Analysis (Base case): is carried out in order to understand the flexible demand of RES in the area. In this case there is no available flexibility provider. This case is for comparison and holding duration decision. Area, weather analysis. Without any flexibility service, measuring the amount of excess RE with scheduled gas heat demand profiles. None of the P2X available for flexibility service (static P2X).
- Hidden Flexibility Analysis (First case): only one P2X available for flexibility service. Explain same flexibility request for both models. For a given flexibility request, comparing the detailed model with simple model, and quantify hidden flexibility. Single P2X available for flexibility service.
- Optimal Deployment of Flexibility Analysis: (Second case): both P2X's are available for flexibility service. Explain decision making for flexibility sharing. With Market DR (price signals) and adjustable power level control, measuring the amount of shared flexibility between P2G P2H and quantify the reduction in total operational cost. Both P2X available for flexibility service.

3

Modelling

3.1. Industrial Loads

3.1.1. Power-to-Gas

Figure 3.1 shows the power-to-gas model.

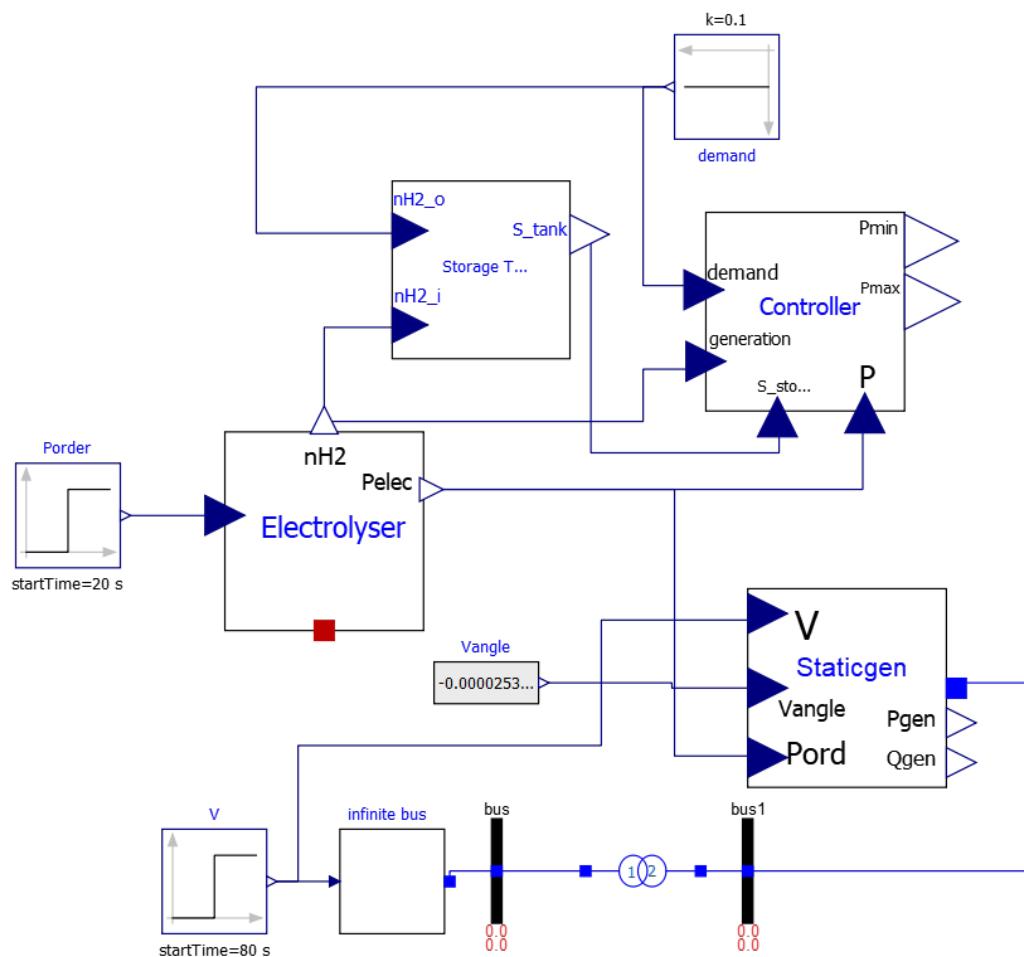


Figure 3.1: Power-to-gas model in OM

Electrolyser

Energy losses within the PEM stack increase the required voltage and are modelled as overpotentials:

- Activation Overpotential: Non-linear
- Ohmic Overpotential: Linear
- Concentration Overpotential: Highly non-linear, only significant when current limit exceeded. Can be ignored for industrial operation.

Electrochemical:

$$V_{cell} = V_{ocv}(T, p) + V_{act}(T) + V_{ohm}(T) \quad [V] \quad (3.1)$$

$$V_{ocv} = V_{rev} + \frac{R \cdot T_{op}}{2 \cdot F} \cdot \ln \left(\frac{pp_{H_2} \cdot pp_{O_2}^{0.5}}{pp_{H_2O}} \right) \quad [V] \quad (3.2)$$

$$V_{rev}(T_{op}) = V_{std} - 0.0009(T_{op} - T_{std}) \quad [V] \quad (3.3)$$

$$V_{act} = \frac{R \cdot T_{op}}{2 \cdot \alpha_{an} \cdot F} \cdot \operatorname{asinh} \left(\frac{i_{dens}}{2 \cdot i_{0,an}} \right) \quad [V] \quad (3.4)$$

$$V_{ohm} = R_{mem} \cdot i_{dens} \quad [V] \quad (3.5)$$

$$R_{mem} = \frac{1}{\sigma_{mem}} \delta_{mem} \quad (3.6)$$

$$\sigma_{mem} = \sigma_{mem,std} \cdot \exp \left(\frac{E_{pro}}{R} \cdot \left(\frac{1}{T_{op}} - \frac{1}{T_{std}} \right) \right) \quad (3.7)$$

Thermal:

$$C_{th} \frac{dT}{dt} = \dot{Q}_{electrolysis,heat}(V, I) + \dot{W}_{pump,loss}(P) - \dot{Q}_{cooling}(P) - \dot{Q}_{loss}(T) - \sum_j \dot{n}_j \cdot \Delta h_j \quad (3.8)$$

$$\dot{Q}_{electrolysis,heat} = (V_{cell} - V_{tn}) \cdot I \cdot n_{cells} \quad (3.9)$$

$$\dot{W}_{pump,loss} = \dot{W}_{pump,elec} \cdot \eta_{motor,elec} \quad (3.10)$$

$$\dot{Q}_{loss}(T) = \frac{1}{R_{th}} (T_{op} - T_{amb}) \quad (3.11)$$

Pressure:

$$pp_{H2O} = 6.1078 \cdot 10^{-3} \cdot \exp\left(17.2694 \cdot \frac{T - 273.15}{T - 34.85}\right) \quad [bar] \quad (3.12)$$

$$pp_{H_2} = p_{cat} - pp_{H2O} \quad [bar] \quad (3.13)$$

$$pp_{O_2} = p_{an} - pp_{H2O} \quad [bar] \quad (3.14)$$

Massflow:

$$\dot{n}_{H_2} = \frac{n_{cells} \cdot I}{2 \cdot F} \cdot \eta_f \quad [mol/s] \quad (3.15)$$

$$\dot{n}_{O_2} = \frac{n_{cells} \cdot I}{4 \cdot F} \cdot \eta_f \quad [mol/s] \quad (3.16)$$

$$\dot{n}_{H_2O} = \frac{n_{cells} \cdot I}{2 \cdot F} \cdot \eta_f \quad [mol/s] \quad (3.17)$$

Table 3.1 summarizes the features of electrolyser models. Model "A", operates at constant temperature while Model "B" calculates the temperature of the electrolyser system with dynamic thermal submodel. Both models are semi-empirical and have static equations but the thermal submodel is dynamic which makes the general behaviour of the electrolyser system dynamic for Model "B". Finally, thermal submodel equation also includes balance of plant (BOP) elements such as circulation pump or cooling work that affect the temperature evolution and efficiency.

Table 3.1: Modelling considerations of electrolyser

Model	Physical Domains	Modelling Approach	Dynamic Behaviour	Modelling Scale
A	Electrochemical Electrical	Analytic + Empirical	Static	Cell/Stack
B	Electrochemical Electrical Thermal	Analytic + Empirical	Static + Dynamic (ODE)	Cell/Stack + BOP

Figure 3.2 shows considered electrolyser models.

Compressed Gas Storage Tank

$$H_{2,prod} = n_{cells} \frac{M_{H_2}}{\rho_{H_2}} \cdot \frac{I_{cell}}{2 \cdot F} \cdot \eta_f \quad [m^3] \quad (3.18)$$

$$O_{2,prod} = n_{cells} \frac{M_{H_2}}{\rho_{H_2}} \cdot \frac{I_{cell}}{4 \cdot F} \cdot \eta_f \quad [m^3] \quad (3.19)$$

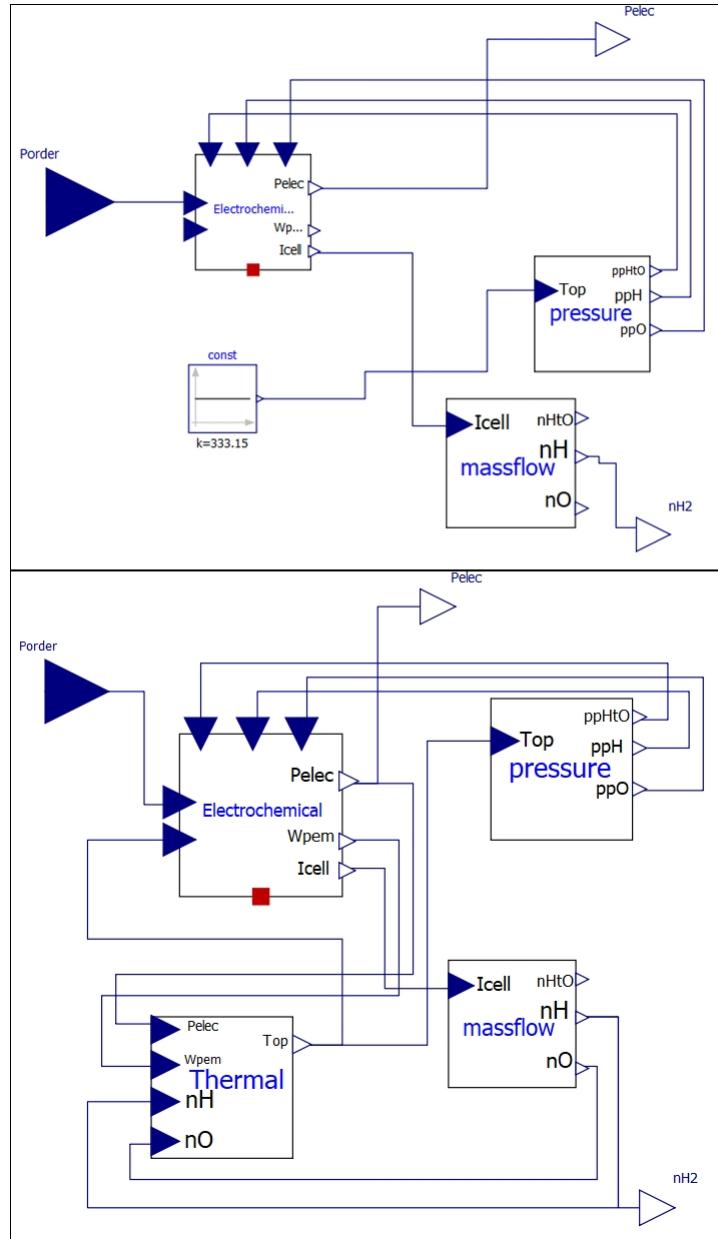


Figure 3.2: Electrolyser model "A" (upper) and model "B" (lower) model in OM

Table 3.2: Hydrogen & Oxygen characteristics at 80 °C

Parameter	Hydrogen	Oxygen
M (molar mass) [kg/mol]	2.016e-3	31.999e-3
ρ (density) [kg/m³]	0.06953	1.104
F (faraday constant)	96485	96485

Adjustable Power Level Controller

$$P_{min} = \begin{cases} 0.1 \text{ p.u.} & \text{if } S_{storage}(t) > S_{max} \\ P(t) - (\dot{n}_{H_2,prod} - \dot{n}_{H_2,demand}) \times K_{gain} & \text{if } S_{emergency} \leq S_{storage}(t) \leq S_{max} \\ 1.0 \text{ p.u.} & \text{if } S_{storage}(t) < S_{emergency} \end{cases}$$

$$P_{max} = \begin{cases} 1.0 \text{ p.u.} & \text{if } S_{emergency} \leq S_{storage}(t) \leq S_{max} \\ P_{min} & \text{else} \end{cases}$$

Figure 3.3 illustrates the implemented controller model in OM.

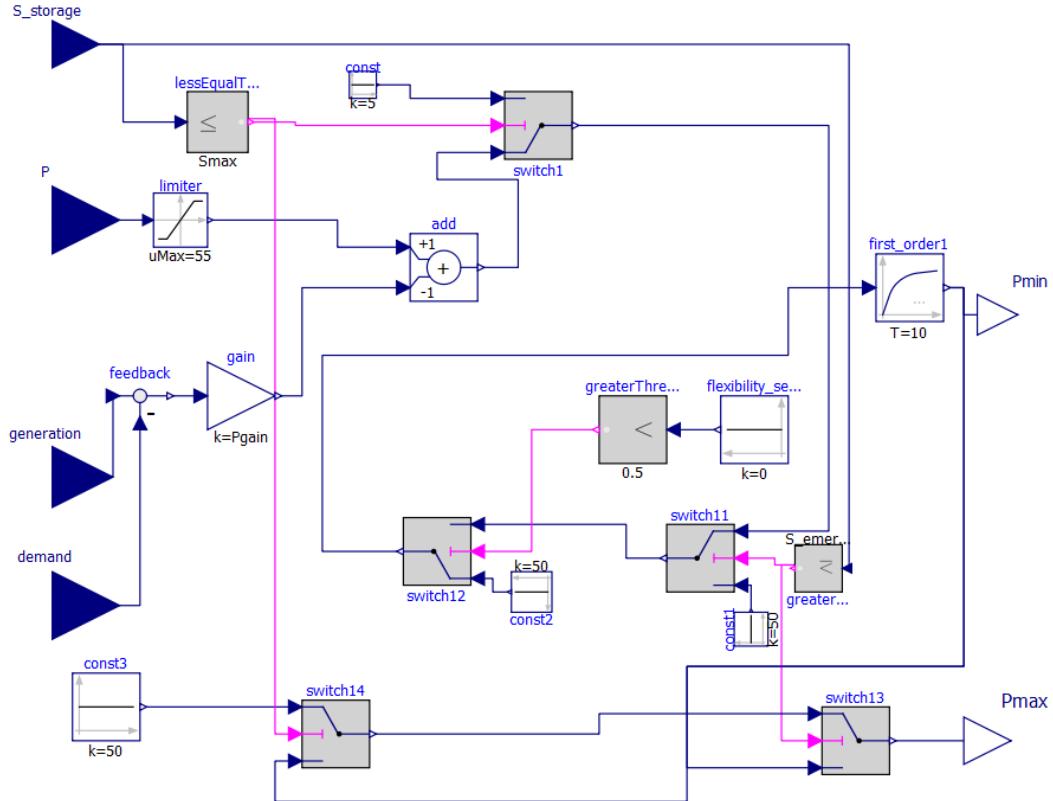


Figure 3.3: Adjustable power level controller in OM

Static Generator

Static generator models in figure 3.1, 3.4 are directly from iPSL library [33]. Their behaviour is similar to current-controlled voltage source converter, and they provide interface with the electrical network.

3.1.2. Power-to-Heat

Figure 3.4 shows the power-to-heat model.

Heat Pump

Using pressure - enthalpy table of refrigerant R134a and Matlab curve fitting tool, fifth order polynomial functions of COP depending on ambient and condenser temperature are created. h_2 is linearly approximated assuming isentropic compression during compressor work. Rest of the assumptions can be observed in figure 3.5. COP results for various $T_{ambient}$ and $T_{condenser} = 50, 70^\circ\text{C}$ is shown in 3.3.

$$COP = \frac{Q_{produced}}{P_{consumed}} = \frac{Q_{condenser}}{W_{compressor}} = \frac{h_2 - h_3}{h_2 - h_1} \quad (3.20)$$

Three different models are considered for power-to-heat. In model A, daily average ambient temperature is considered to be the evaporator temperature. In model B, hourly measured ambient temperature is the evaporator temperature. for model C, auxiliary electric boiler is connected to the output of electric heat pump in order to increase the efficiency of heat pump. Table 3.4 shows modelling considerations for heat pump.

$$COP(T_{amb}) = a_1 T_{amb}^5 + a_2 T_{amb}^4 + a_3 T_{amb}^3 + a_4 T_{amb}^2 + a_5 T_{amb} + a_6 \quad (3.21)$$

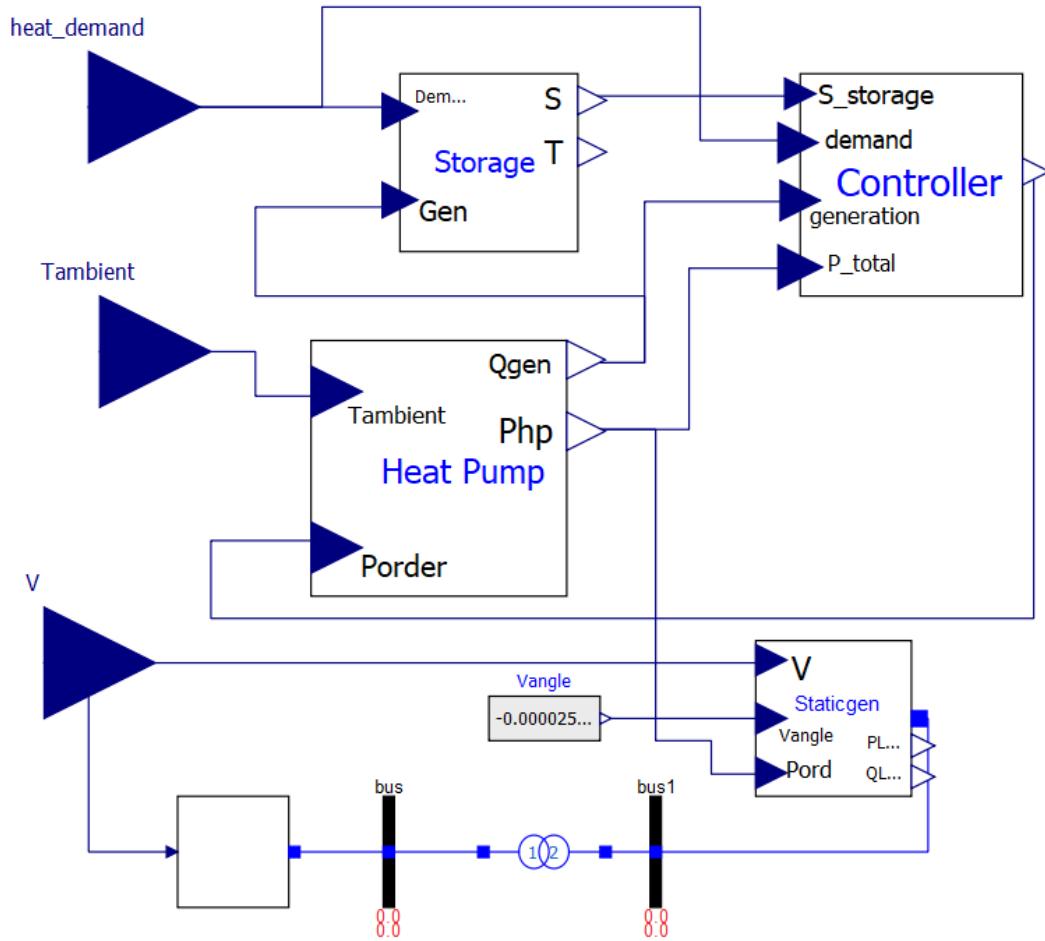


Figure 3.4: Power-to-heat model in OM

Table 3.3: COP results for various ambient and condenser temperatures

$T_{ambient}$	-20	-16	-12	-8	-4	0	4
COP @ $T_{cond} = 50^{\circ}C$	3.3931	3.6429	3.9268	4.2500	4.6251	5.0604	5.5750
COP @ $T_{cond} = 70^{\circ}C$	2.4174	2.5586	2.7150	2.8887	3.0837	3.3013	3.5476
$T_{ambient}$	8	12	16	20	24	28	32
COP @ $T_{cond} = 50^{\circ}C$	6.1957	6.9452	7.8660	9.0564	10.5899	12.7115	15.7889
COP @ $T_{cond} = 70^{\circ}C$	3.8298	4.1514	4.5195	4.9559	5.4618	6.0736	6.8178

Table 3.4: Modelling considerations of heat pump

Model	Modelling Approach	Ambient Temperature	Modelling Scale
A	Regression	Daily average	Heat pump
B	Regression	Hourly measured	Heat pump
C	Regression	Hourly measured	Heat pump with auxiliary electric boiler

Hot Water Storage Tank

$$\dot{m} Q = c_p \rho (70 - T_{amb}) V \quad (3.22)$$

Adjustable power level controller and static generator models are similar to power-to-gas.

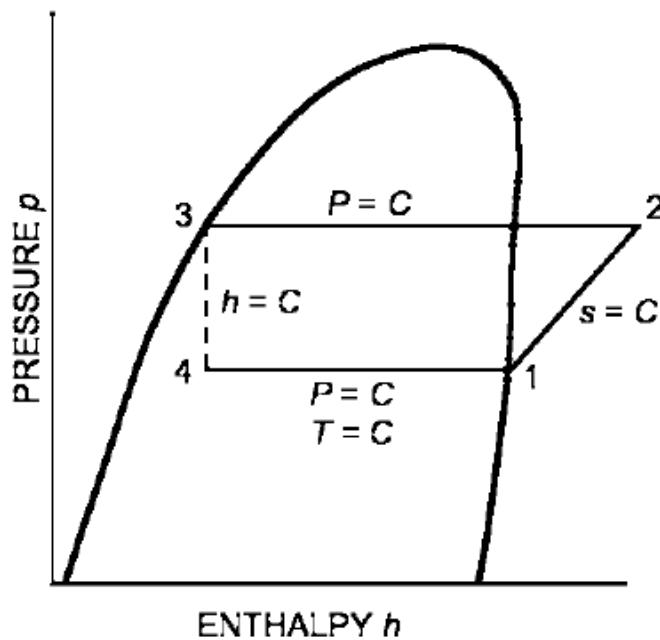


Figure 3.5: Theoretical Single-Stage Vapor Compression Refrigeration Cycle ($C = \text{Constant}$) [9]

Table 3.5: 5th order polynomial function parameters for $T_{\text{condenser}} = 50, 70^\circ\text{C}$

$T_{\text{condenser}} (\text{ }^\circ\text{C})$	a_1	a_2	a_3	a_4	a_5	a_6
50	3.46e-8	1.29e-6	4.35e-5	2.387e-3	1.186e-1	5.063
70	1.46e-8	-9.66e-8	6.61e-6	1.01e-3	5.864e-2	3.295

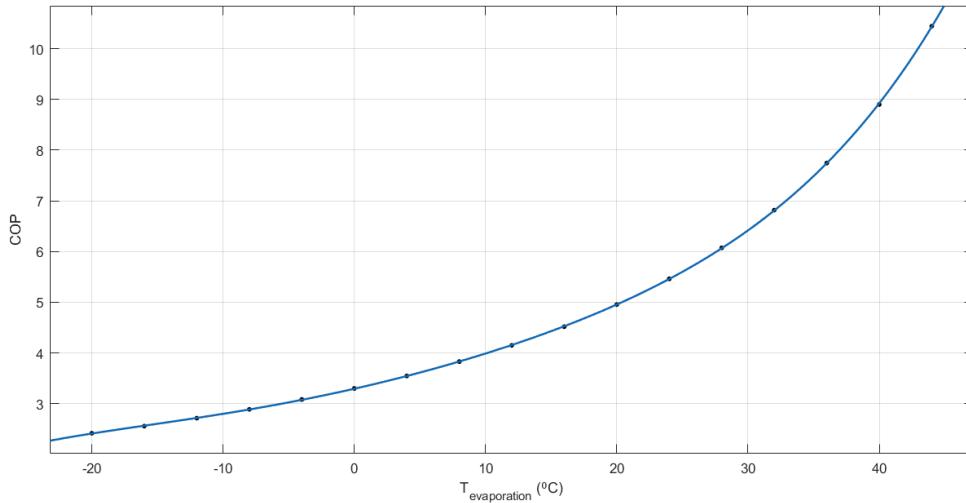


Figure 3.6: COP vs. T_{ambient} , $T_{\text{condenser}} = 70^\circ\text{C}$

3.1.3. Electrical Base Load

Connected in PandaPower, as illustrated in Figure 2.1, to represent the constant base load in the industrial area.

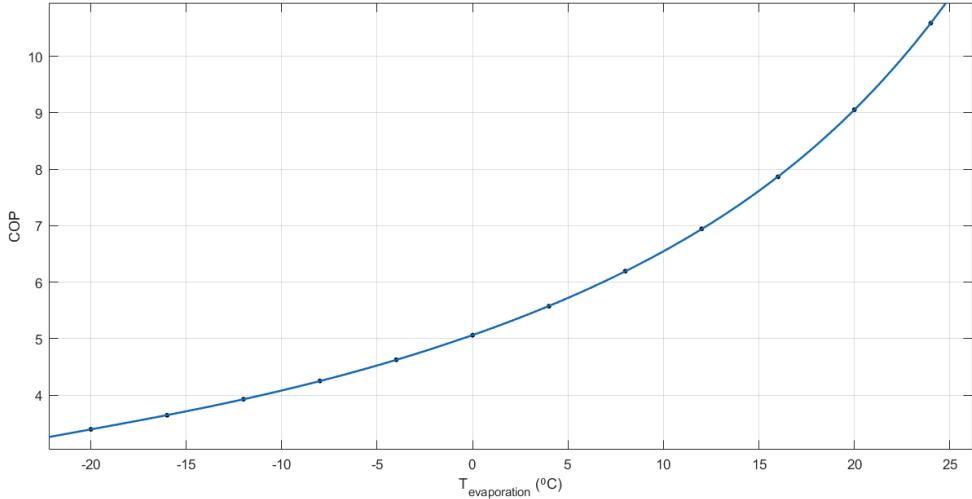
Figure 3.7: COP vs. $T_{ambient}$, $T_{condenser} = 50^\circ C$

Table 3.6: Power-to-Heat storage parameters

Parameter	Value
\dot{m} (massflow) [kg/s]	5
Q	[kj/kg] (t)
c_p (specific heat) [kj/(K Kg)]	4.190
ρ (density) [kg/m ³]	977.74
Storage Volume [m ³]	2400

3.2. Renewable Energy Sources

Renewables.ninja models are used. Renewables.ninja allows user to run simulations of the hourly power output from wind and solar power plants located anywhere in the world [25]. Wind farm model [28]. PV farm model [26].

3.3. Electrical Network & Optimal Power Flow

Figure 3.8 illustrates the co-simulation flowchart for case 3. At $t = 0, \dots$

3.3.1. Formulation of the Optimization Problem

Objective function:

$$\min \sum_{i \in load} f_i(P_i) \quad (3.23)$$

Cost function:

$$f_{pol}(p) = c_n p^n + \dots + c_1 p + c_0 \quad (3.24)$$

3.4. Co-simulation Setup

- Simulation duration: 3600*24 (s)
- Exchange time: 900 (s)
- Step time P2G: 3 (s)

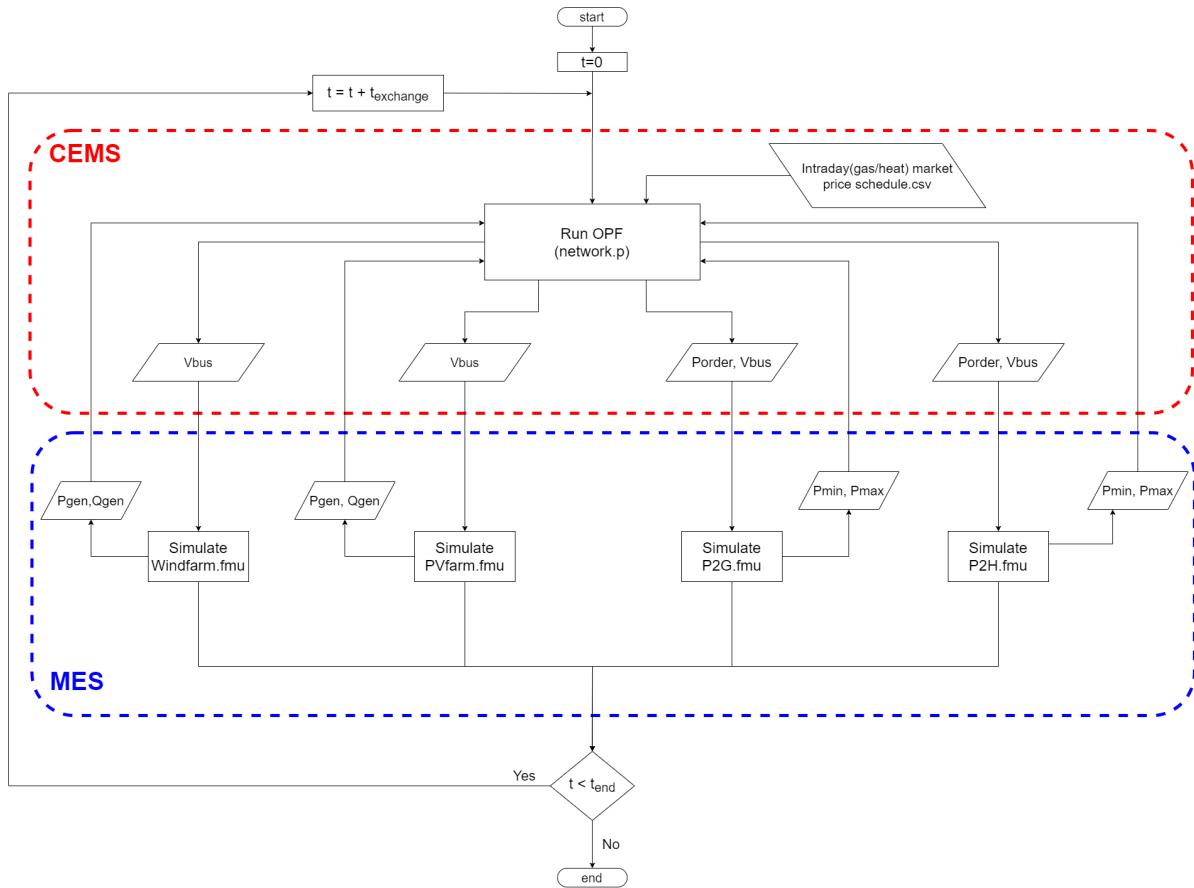


Figure 3.8: Co-simulation flow chart

Table 3.7: Constraints

Element	Constraint	Remarks
Load Static Generator External Grid	$P_{min,i} \leq P_i \leq P_{max,i}$ $Q_{min,i} \leq Q_i \leq Q_{max,i}$	Operational power constraints (Device flexibility)
Transformer	$L_i \leq L_{max,i}$	Branch constraint (maximum loading percentage)
Line	$L_i \leq L_{max,i}$	Branch constraint (maximum loading percentage)
Bus	$V_{min,i} \leq V_i \leq V_{max,i}$	Network constraint

- Step time P2H: 3 (s)
- Step time pandapower network: 300 (s)

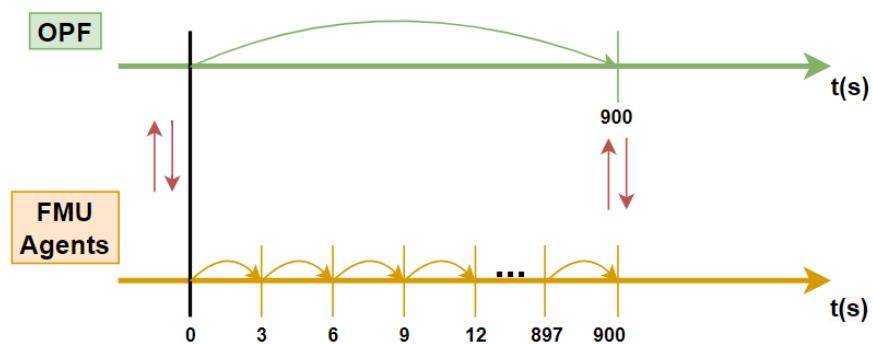


Figure 3.9: Co-simulation synchronization

4

Results & Discussions

4.1. Technical Evaluation

4.2. Simulation Cases

Implementation of the case studies are explained in section 2.5 and the results are shown below.

4.2.1. MES Analysis

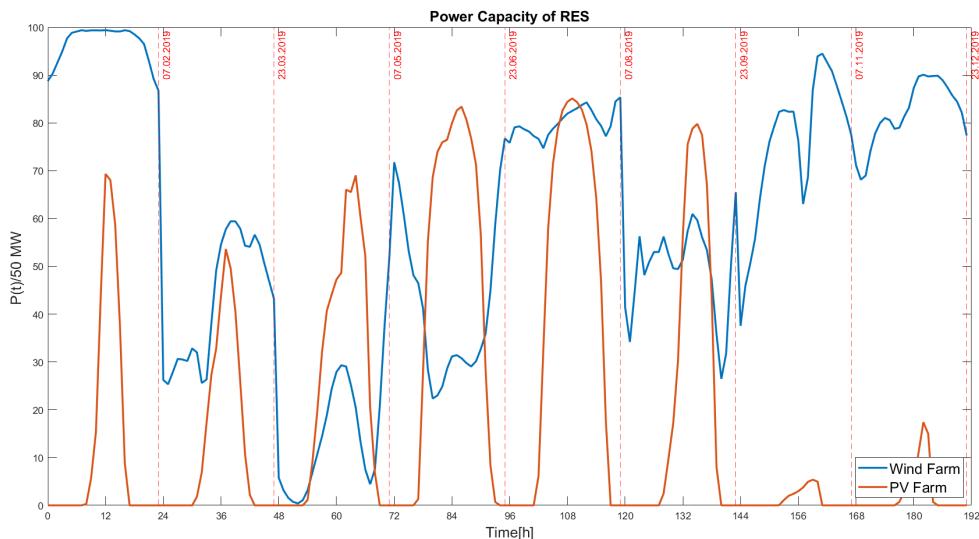


Figure 4.1: Power capacity of renewable energy sources

4.2.2. Hidden Flexibility - Modelling

4.2.3. Optimal Deployment of Flexibility - Energy Management

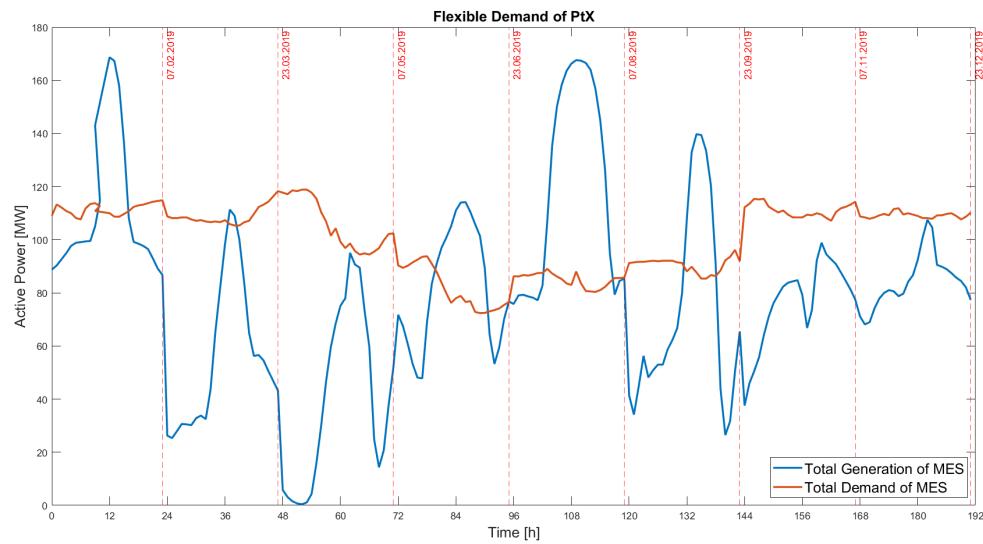


Figure 4.2: Flexible demand of multi-energy system

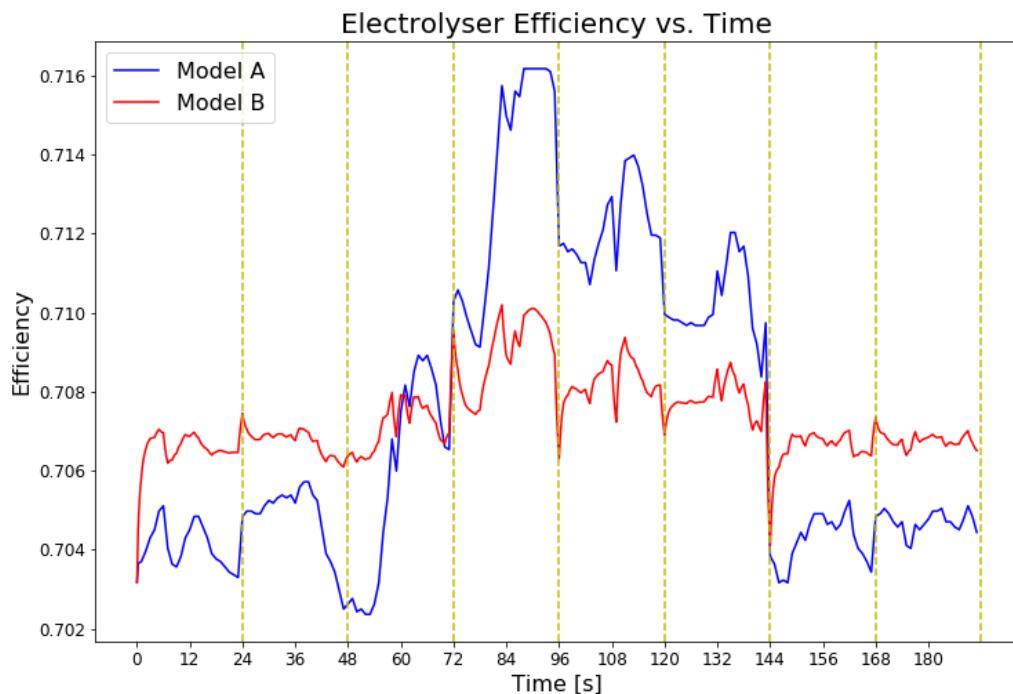


Figure 4.3: Efficiency comparison of electrolyser models

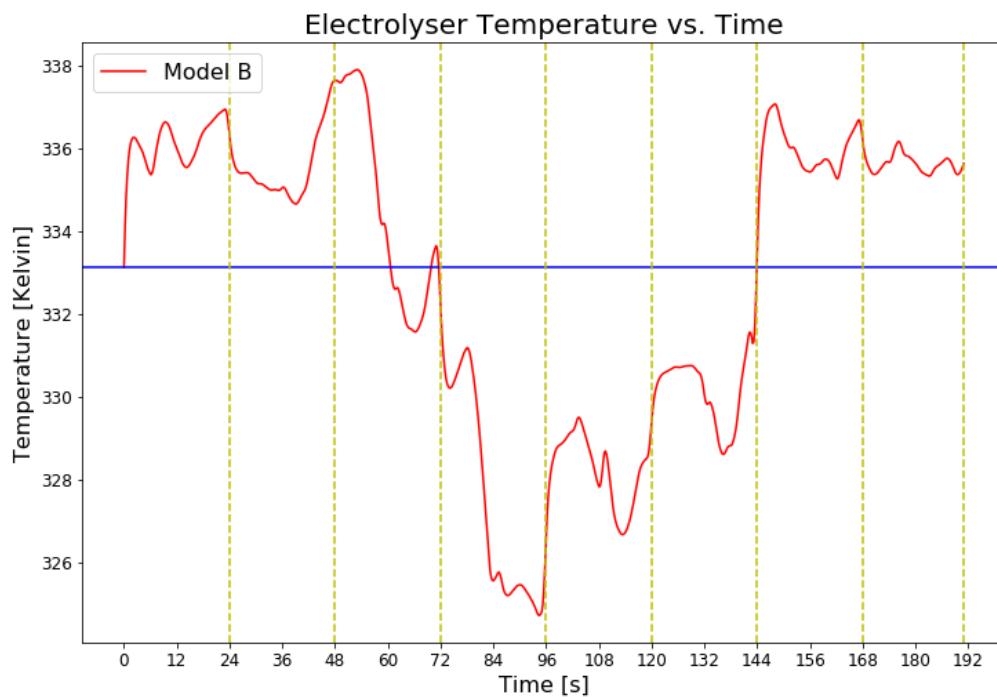
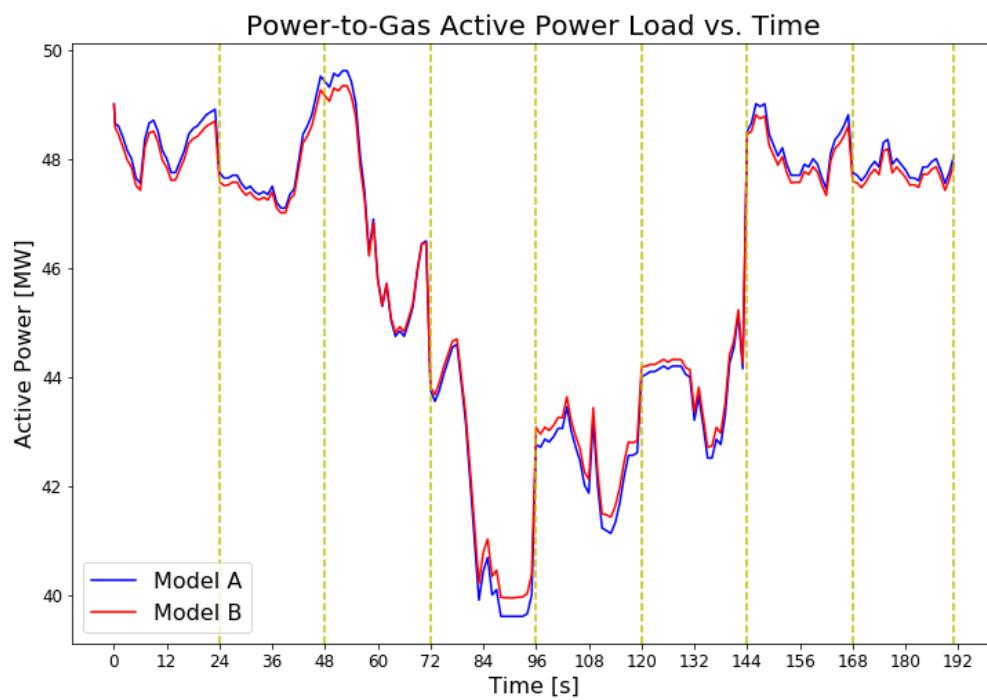


Figure 4.4: Operational temperature comparison of electrolyser models

Figure 4.5: $P_{Load,PtH}$ of electrolyser models

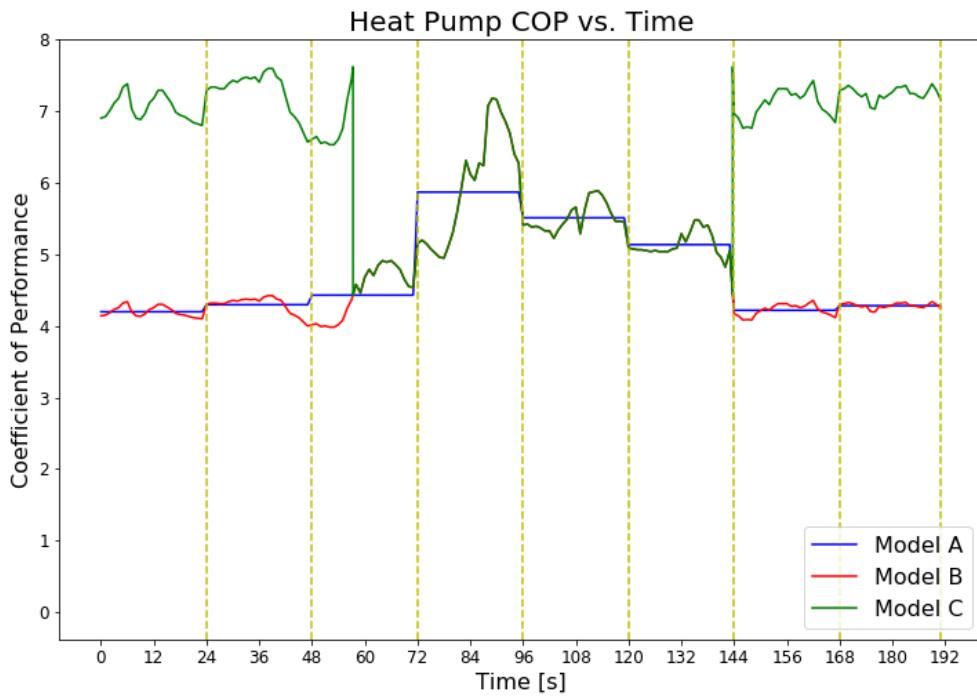
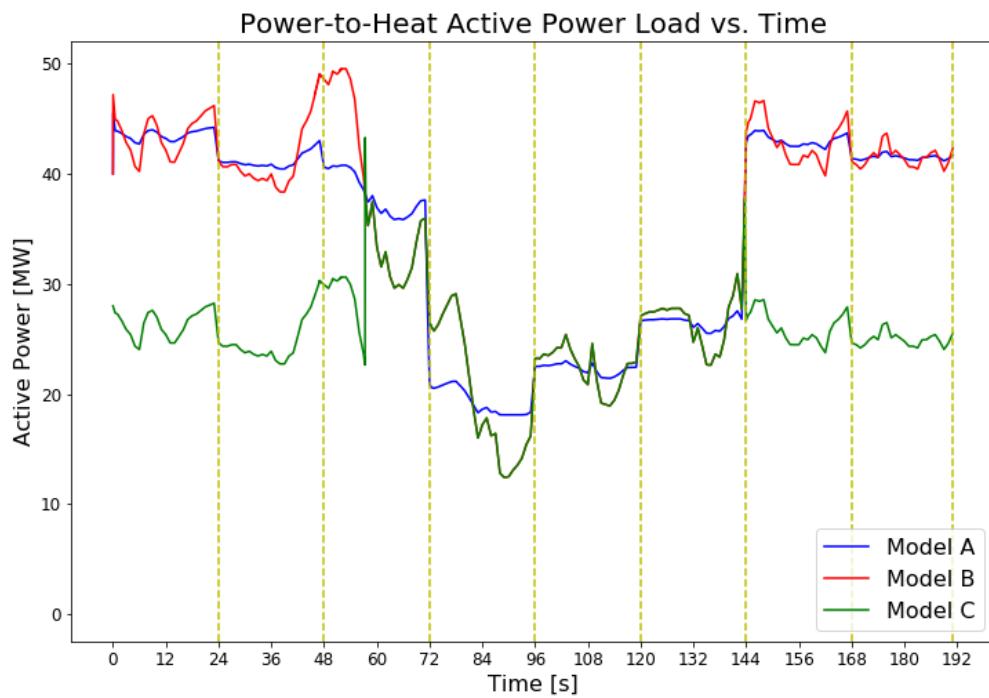


Figure 4.6: COP results of heat pump models

Figure 4.7: $P_{Load,PtH}$ of heat pump models

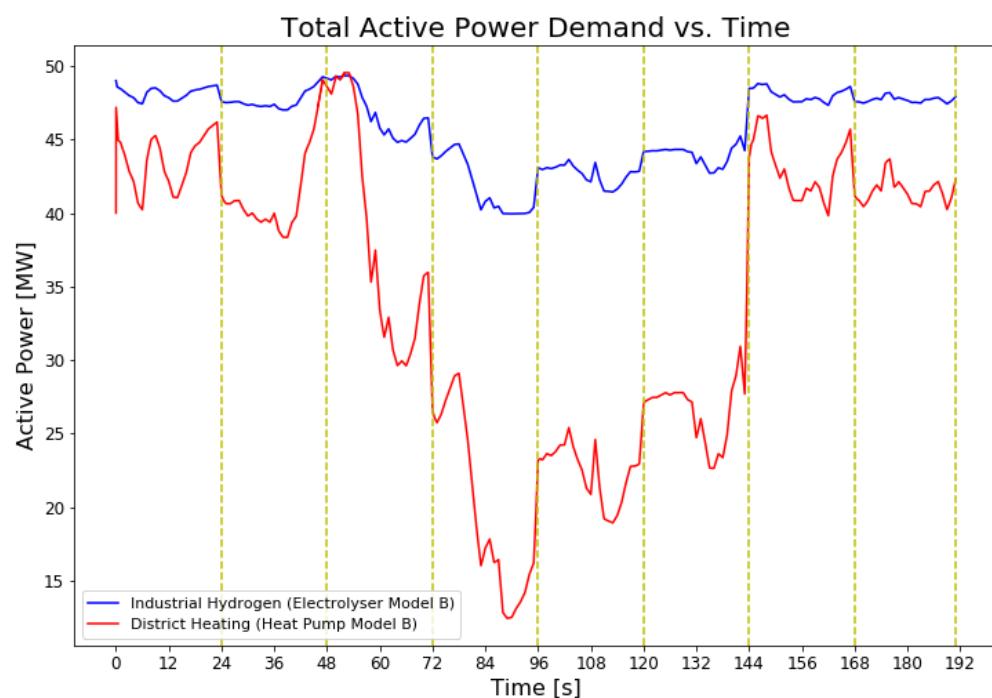


Figure 4.8: P_{Load} results for Model "B" of PtG & PtH for comparison with figure ??

5

Conclusion & Future Work

5.1. Conclusion

5.2. Recommendation for Future Work

A

Historical Data Processing & Probabilistic Weather

Historical data process is summarized in the figure A.1. 2019 historical wind speed and solar irradiation data of Port of Rotterdam will be divided into 8 regions that consist of 45 days. For every hour of each 45 day group a histogram will be created to calculate Weibull or Beta PDF parameters [12]. Later, this parameters will be the input via CombiTimeTables.

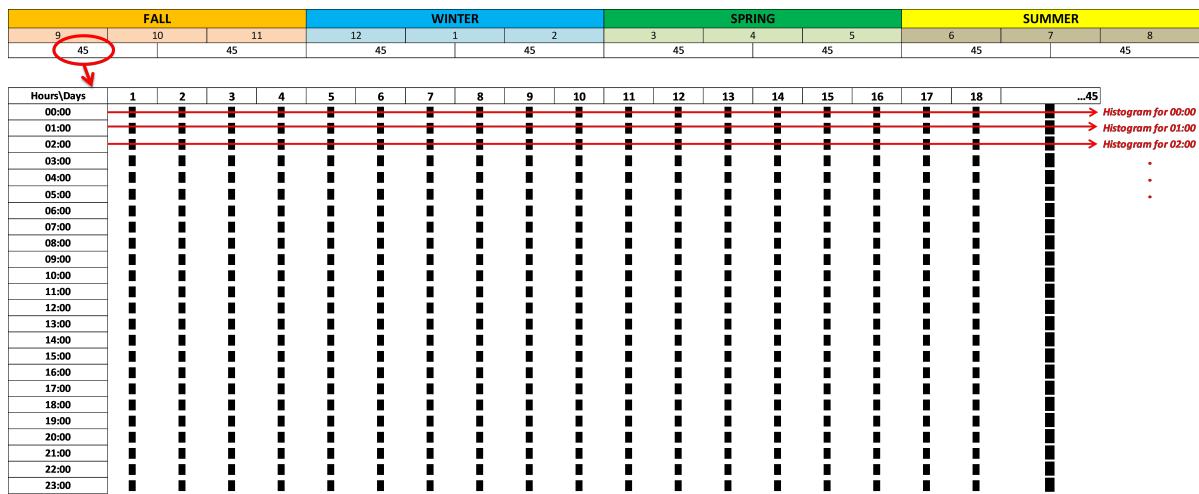


Figure A.1: Historical data processing

It is considered that Probabilistic Density Function (PDF) of Weibull and Beta for windspeed and solar irradiation generation respectively will be modelled based on historical data processing and the effect on renewable energy generations will be observed. (Probabilistic vs. Historical data) However, this type of simulation requires simulation duration for months and, during the modelling phase, it is observed that these models increases the simulation time significantly with the increased number of equations. Therefore, due to high computation time these models currently not in use. This part is not one of the main focuses of the project anymore, but same task can be implemented as pre-work in MATLAB and the resulting (minute or hourly) windspeed and solar irradiation data can be input as .txt to FMU's.

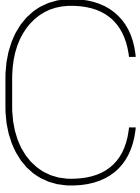
- Weibull probabilistic distribution function is used for wind speed estimation. First, histogram tables will be created via historical data. Then parameters of the Weibull PDF (shape, scale) are calculated by curve fitting in MATLAB. Finally, Text files are created for hourly shape, scale parameters in "CombiTimeTable".
- Beta probabilistic distribution function is used for solar irradiance estimation. First histogram tables will be created via historical data. Then parameters of the Beta PDF (shape, scale) are calculated by

curve fitting in MATLAB. Finally, Text files are created for hourly shape, scale parameters in “CombiTimeTable”.

B

Wind Farm & PV Farm Data

Hour\Day	7.02.2019			23.03.2019			7.05.2019			23.06.2019			7.08.2019			23.09.2019			7.11.2019			23.12.2019		
	Power (kW)	Speed (m/s)																						
0:00	88750.949	11.357	26222.646	6.026	5778.91	3.742	71760.561	9.325	75839.049	9.693	41444.907	7.124	37547.003	6.861	71138.664	9.271								
01:00	90293.251	11.659	25343.918	5.952	3129.872	3.145	67431.457	8.964	79043.579	10.029	34188.088	6.619	45931.625	7.431	68130.061	9.02								
02:00	92691.445	12.187	27907.221	6.161	1549.057	2.609	60889.148	8.451	79285.795	10.055	44850.676	7.359	50252.668	7.736	68972.071	9.089								
03:00	94943.193	12.897	30633.557	6.365	716.795	2.153	53278.167	7.929	78669.285	9.989	56283.77	8.138	55714.664	8.094	74136.082	9.539								
04:00	97679.965	14.228	30509.491	6.354	413.059	1.879	48115.306	7.575	78198.107	9.934	48165.889	7.577	64016.641	8.689	77557.683	9.896								
05:00	98850.022	15.322	30188.681	6.328	1095.603	2.39	46490.986	7.47	77243.433	9.838	50929.367	7.763	70894.933	9.245	79975.279	10.131								
06:00	99100.837	15.721	32822.538	6.529	3165.853	3.155	41149.653	7.102	76661.851	9.782	52996.879	7.91	76095.485	9.726	81036.2	10.253								
07:00	99382.052	16.694	31590.499	6.46	6867.586	3.937	28384.259	6.192	74697.25	9.591	52895.806	7.904	79305.323	10.057	80584.682	10.196								
08:00	99238.043	17.523	25590.066	5.971	10553.679	4.499	22338.246	5.702	77480.106	9.864	56227.548	8.134	82310.382	10.397	78760.55	9.998								
09:00	99349.675	17.157	26332.091	6.037	14436.677	4.951	23008.658	5.768	78786.739	10.001	52567.046	7.881	82674.717	10.451	78973.695	10.021								
10:00	99356.365	16.46	38080.872	6.89	18870.301	5.4	24853.248	5.921	79793.231	10.111	49573.244	7.668	82333.159	10.399	81306.589	10.284								
11:00	99333.389	16.334	49167.86	7.641	24356.035	5.88	28608.043	6.209	80934.875	10.241	49429.618	7.659	82348.441	10.406	83172.51	10.515								
12:00	99383.457	16.864	54587.354	8.017	27905.152	6.161	31151.452	6.407	81937.291	10.36	51394.572	7.802	76273.889	9.736	87300.527	11.106								
13:00	99278.348	17.416	57749.304	8.235	29307.875	6.265	31415.206	6.418	82505.947	10.429	57369.278	8.214	63028.409	8.624	89706.955	11.532								
14:00	99128.934	17.749	59427.451	8.357	29040.348	6.241	30777.014	6.371	83062.074	10.497	60948.575	8.47	68626.596	9.051	90078.552	11.616								
15:00	99122.275	17.76	59391.34	8.349	25193.696	5.945	29767.001	6.304	83750.64	10.59	59644.62	8.376	86850.573	11.038	89703.55	11.541								
16:00	99375.851	16.978	57832.151	8.249	20474.632	5.538	29044.578	6.247	84292.071	10.663	56074.862	8.117	93921.445	12.568	89807.618	11.561								
17:00	99195.918	15.915	54297.25	7.995	13290.124	4.832	30128.316	6.326	82669.919	10.445	53408.634	7.939	94476.638	12.737	89856.165	11.571								
18:00	98507.267	14.914	54086.295	7.983	7482.077	4.035	32681.769	6.519	80757.825	10.217	47225.525	7.512	92628.803	12.201	88915.665	11.39								
19:00	97685.474	14.232	56603.001	8.155	4246.706	3.456	35892.824	6.738	79381.122	10.066	35734.21	6.728	90811.928	11.767	87427.67	11.121								
20:00	96489.627	13.546	54587.368	8.017	7583.19	4.056	44830.193	7.349	77206.858	9.828	26468.626	6.045	87753.325	11.186	85747.873	10.864								
21:00	92980.903	12.297	50634.278	7.743	20709.728	5.559	58727.891	8.307	79324.886	10.059	31732.329	6.446	84581.58	10.703	84459.467	10.686								
22:00	89190.383	11.442	46900.932	7.489	37600.406	6.863	70017.108	9.168	84478.143	10.688	50210.49	7.721	81326.929	10.287	82105.607	10.375								
23:00	86740.936	11.014	43229.483	7.25	51959.945	7.835	76733.954	9.789	85345.637	10.811	65482.238	8.802	77500.611	9.866	77335.324	9.85								



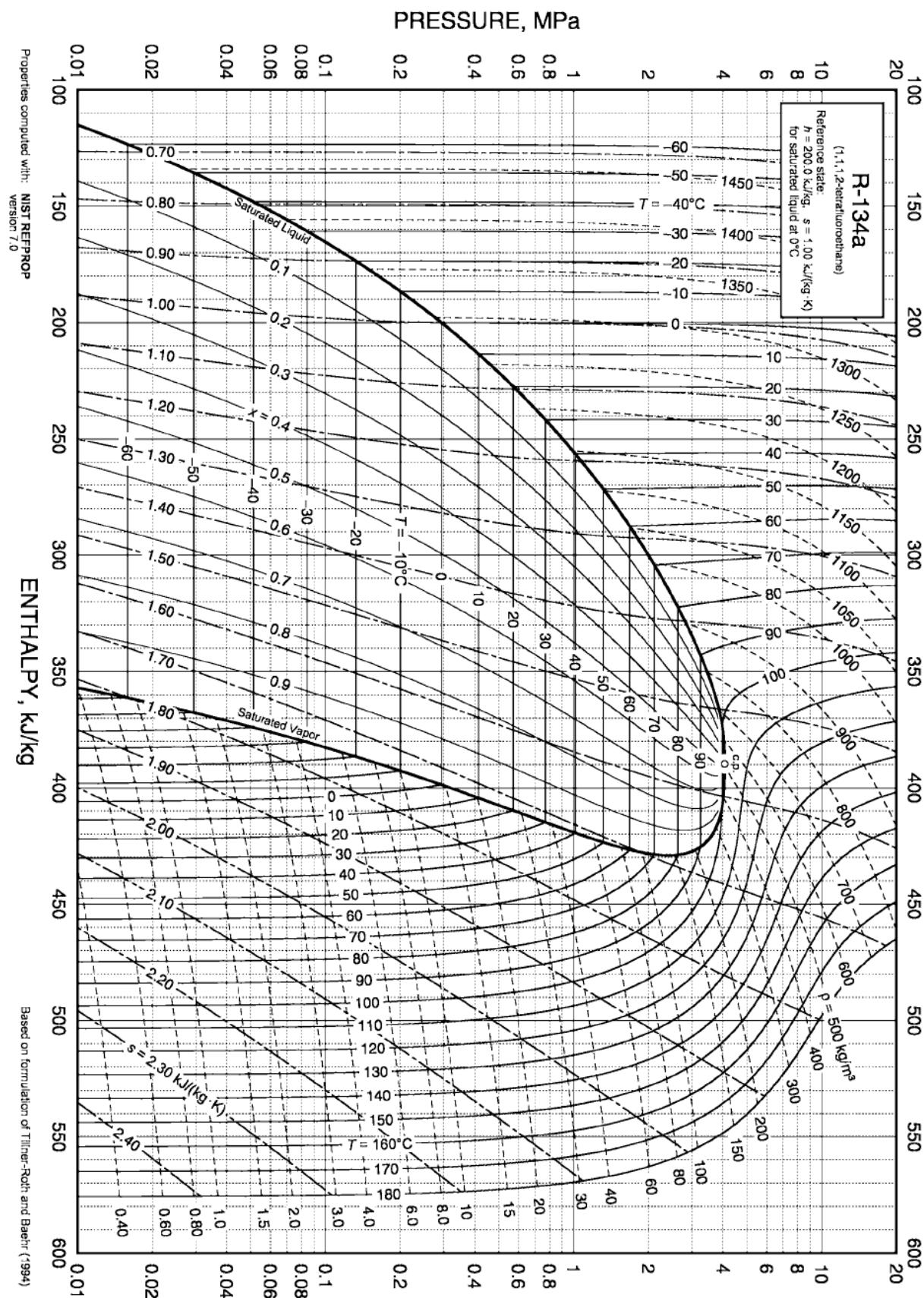
Ambient Temperature & Energy Demand Data

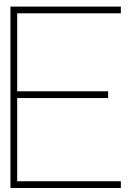
Hour\Day	7.02.2019			23.03.2019			7.05.2019			23.06.2019		
	Tamb (°C)	Industrial Hydrogen Demand (m³/s)	DHN Demand (m³/s)	Tamb (°C)	Industrial Hydrogen Demand (m³/s)	DHN Demand (m³/s)	Tamb (°C)	Industrial Hydrogen Demand (m³/s)	DHN Demand (m³/s)	Tamb (°C)	Industrial Hydrogen Demand (m³/s)	DHN Demand (m³/s)
00:00	6.8	0.00378603	4.82	8.6	0.003721860	4.64	5.3	0.0038395050	4.97	16.6	0.003436660	3.84
01:00	6.9	0.00378247	4.81	8.8	0.003714730	4.62	5.5	0.0038323750	4.95	17	0.003422400	3.8
02:00	7.3	0.00376821	4.77	8.8	0.003714730	4.62	5	0.0038502000	5	16.6	0.003436660	3.84
03:00	7.8	0.00375038	4.72	8.7	0.003718295	4.63	5.1	0.0038466350	4.99	16	0.003458050	3.9
04:00	8.1	0.00373969	4.69	8.7	0.003718295	4.63	4.9	0.0038537650	5.01	15.5	0.003475875	3.95
05:00	8.8	0.00371473	4.62	9	0.003707600	4.6	4.9	0.0038537650	5.01	15	0.003493700	4
06:00	9	0.00370760	4.6	9.2	0.003700470	4.58	5.3	0.0038395050	4.97	14.9	0.003497265	4.01
07:00	7.4	0.00376464	4.76	9.1	0.003704035	4.59	6.1	0.0038109850	4.89	16.3	0.003447355	3.87
08:00	6.8	0.00378603	4.82	9.3	0.003696905	4.57	8	0.0037432500	4.7	17.8	0.003393880	3.72
09:00	6.7	0.00378960	4.83	9.4	0.003693340	4.56	9.3	0.0036969050	4.57	19.9	0.003319015	3.51
10:00	7.1	0.00377534	4.79	9.3	0.003696905	4.57	11.5	0.0036184750	4.35	22.2	0.003237020	3.28
11:00	7.8	0.00375038	4.72	9.4	0.003693340	4.56	10.3	0.0036612550	4.47	24.4	0.003158590	3.06
12:00	8.1	0.00373969	4.69	9.1	0.003704035	4.59	12.5	0.0035828250	4.25	23.3	0.003197805	3.17
13:00	8.6	0.00372186	4.64	9.7	0.003682645	4.53	13.5	0.0035471750	4.15	22.8	0.003215630	3.22
14:00	8.6	0.00372186	4.64	9.9	0.003675515	4.51	12.7	0.0035756950	4.23	24.2	0.003165720	3.08
15:00	8.2	0.00373612	4.68	9.9	0.003675515	4.51	14	0.0035293500	4.1	24	0.003172850	3.1
16:00	7.8	0.00375038	4.72	9.4	0.003693340	4.56	14.6	0.0035079600	4.04	28.2	0.003137200	3
17:00	7.2	0.00377177	4.78	9.2	0.003700470	4.58	14.4	0.0035150900	4.06	28.7	0.003137200	3
18:00	7	0.00377890	4.8	8.2	0.003736120	4.68	14.6	0.0035079600	4.04	28.6	0.003137200	3
19:00	6.9	0.00378247	4.81	7.2	0.003771770	4.78	14.1	0.0035257850	4.09	27.8	0.003137200	3
20:00	6.7	0.00378960	4.83	6.9	0.003782465	4.81	13.5	0.0035471750	4.15	27.2	0.003137200	3
21:00	6.5	0.00379673	4.85	6.5	0.003796725	4.85	12.2	0.0035935200	4.28	26.4	0.003137200	3
22:00	6.4	0.00380029	4.86	5.8	0.003821680	4.92	11.2	0.0036291700	4.38	24.9	0.003140765	3.01
23:00	6.3	0.00380386	4.87	5.1	0.003846635	4.99	11.1	0.0036327350	4.39	24.2	0.003165720	3.08
Average	7.45	0.003762858	4.76	8.55	0.003723643	4.65	9.98	0.0036725	4.50	21.77	0.003277423	3.39

Hour\Day	7.08.2019			23.09.2019			7.11.2019			23.12.2019		
	Tamb (°C)	Industrial Hydrogen Demand (m³/s)	DHN Demand (m³/s)	Tamb (°C)	Industrial Hydrogen Demand (m³/s)	DHN Demand (m³/s)	Tamb (°C)	Industrial Hydrogen Demand (m³/s)	DHN Demand (m³/s)	Tamb (°C)	Industrial Hydrogen Demand (m³/s)	DHN Demand (m³/s)
00:00	18.6	0.003365360	3.64	16.1	0.003454485	3.89	7.1	0.003775335	4.79	8.6	0.00372186	4.64
01:00	18.7	0.003361795	3.63	16	0.00345805	3.9	6.8	0.00378603	4.82	8.7	0.003718295	4.63
02:00	18.4	0.003372490	3.66	15.9	0.003461615	3.91	6.1	0.003810985	4.89	8.9	0.003711165	4.61
03:00	18.5	0.003368925	3.65	15.9	0.003461615	3.91	6.2	0.00380742	4.88	8.7	0.003718295	4.63
04:00	18.3	0.003376055	3.67	15.8	0.00346518	3.92	6.1	0.003810985	4.89	8.4	0.00372899	4.66
05:00	18	0.003386750	3.7	15.7	0.003468745	3.93	7.2	0.00377177	4.78	8.2	0.00373612	4.68
06:00	18	0.003386750	3.7	15.8	0.00346518	3.92	7.6	0.00375751	4.74	8.4	0.00372899	4.66
07:00	17.2	0.003415270	3.78	15.7	0.003468745	3.93	8	0.00374325	4.7	7.5	0.003761075	4.75
08:00	18.1	0.003383185	3.69	15.7	0.003468745	3.93	7.7	0.003753945	4.73	7.4	0.00376464	4.76
09:00	18.7	0.003361795	3.63	15.7	0.003468745	3.93	8.3	0.003732555	4.67	8.3	0.003732555	4.67
10:00	19.2	0.003343970	3.58	16	0.00345805	3.9	8.7	0.003718295	4.63	8.1	0.003739685	4.69
11:00	20.1	0.003311885	3.49	16.1	0.003454485	3.89	8.7	0.003718295	4.63	8.3	0.003732555	4.67
12:00	20.4	0.003301190	3.46	17.7	0.003397445	3.73	8.7	0.003718295	4.63	8.5	0.003725425	4.65
13:00	17.7	0.003397445	3.73	16.8	0.00342953	3.82	8.3	0.003732555	4.67	8.8	0.00371473	4.62
14:00	20.1	0.003311885	3.49	17.9	0.003390315	3.71	8.4	0.00372899	4.66	8.8	0.00371473	4.62
15:00	21.7	0.003254845	3.33	19.1	0.003347535	3.59	8.1	0.003739685	4.69	8.9	0.003711165	4.61
16:00	21.8	0.003251280	3.32	19.1	0.003347535	3.59	8.3	0.003732555	4.67	8.4	0.00372899	4.66
17:00	21.9	0.003247715	3.31	18.4	0.00337249	3.66	8.8	0.00371473	4.62	8.4	0.00372899	4.66
18:00	21.5	0.003261975	3.35	18.6	0.00336536	3.64	9.2	0.00370047	4.58	8.2	0.00373612	4.68
19:00	20.8	0.003286930	3.42	17.5	0.003404575	3.75	7.9	0.003746815	4.71	8.1	0.003739685	4.69
20:00	19.8	0.003322580	3.52	15.6	0.00347231	3.94	7.4	0.00376464	4.76	8.5	0.003725425	4.65
21:00	19	0.003351100	3.6	15	0.0034937	4	7.2	0.00377177	4.78	9	0.0037076	4.6
22:00	19	0.003351100	3.6	13.8	0.00353648	4.12	6.9	0.003782465	4.81	8.6	0.00372186	4.64
23:00	18.9	0.003354665	3.61	15.8	0.00346518	3.92	6.5	0.003796725	4.85	8	0.00374325	4.7
Average	19.35	0.003338623	3.57	16.49	0.003440671	3.85	7.68	0.003754836	4.73	8.40	0.00372884	4.66

D

R134a Pressure - Enthalpy Table





Key Modelling Assumptions

E.1. Power-to-Gas

- Electrolyser
 - ...
- Storage
 - Constant temperature and pressure inside the hydrogen storage tank.
 - Static and dynamic losses are ignored.
- Controller
- Static Generator

E.2. Power-to-Heat

- Heat Pump
 - Influence of part load efficiency is ignored.
 - Heat exchangers are supposed at hot start in equilibrium with the external sources and heat exchange is ideal.
 - Refrigerant massflow inside heatpump is assumed to be constant.
 - Isenthalpic flow across the expansion valve; and isentropic efficiency for the compressor.
- Storage
 - Constant temperature and pressure inside the hydrogen storage tank.
 - Static and dynamic losses are ignored.
 - Uniform temperature in the hot water reservoir (stratification is not considered)
 - No external heat loss from the reservoir wall
 - The total amount of hot water in the reservoir is conserved (No water consumption during heating process).
- Controller
- Static Generator

E.3. Multi-Energy System

- Power converters are ideal.

F

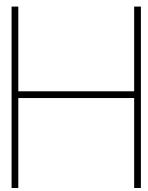
ENTSO-E Day-ahead Market Prices (€/MWh)

Hour\Day	7.02.2019	23.03.2019	7.05.2019	23.06.2019	7.08.2019	23.09.2019	7.11.2019	23.12.2019
00:00	46.25	35.53	42.32	28.1	37.03	27.66	39.07	24
01:00	45.21	34.94	40.98	26.94	33.17	27.2	35.95	30.81
02:00	41.24	34.9	40.8	31.62	31.53	27.38	33.4	30
03:00	38.05	33.1	40.03	36.39	30.92	26.33	32.67	30.16
04:00	37	33.05	40.03	37.62	30.74	25.33	32.9	25
05:00	39.04	34.6	42.71	32.12	32.87	31.31	35.25	2.59
06:00	48.06	36.64	51.59	31.53	36.68	38.37	42.49	24.5
07:00	50.77	38.86	60.16	34.8	42.77	48.99	48.12	30.6
08:00	54.79	38.43	63.9	32.64	44.71	50	51.29	37.58
09:00	53.7	40.36	57.53	32.59	44.98	49.84	48.56	37.56
10:00	53.17	37.34	58.87	24.8	43.93	49.99	47.54	37.4
11:00	50	36.62	56.4	24.8	44.31	49.27	46.36	37.3
12:00	49.45	36	54.07	19	42.16	45.48	43.91	35.94
13:00	46.09	31.1	48.94	14.9	40.09	43.37	44.57	34.9
14:00	42.58	30.1	48	16.86	37.93	40.13	45.61	35.9
15:00	43.32	31.1	46.77	22.55	35.83	40.59	46.83	37.42
16:00	46.28	32.58	47.1	24.59	35.75	41.7	48.68	37.18
17:00	51.65	38.71	48.94	32.13	39.5	50.1	51.17	40
18:00	49.76	41.27	59.22	32.44	42.7	52.69	48.19	40.93
19:00	45.4	44.99	65.68	41.18	43.15	61.3	46.72	39.22
20:00	43.19	42.25	67.87	47.87	42.62	52.85	44.98	35.98
21:00	45.7	39.1	55	32.95	41.94	49.21	37.8	34.63
22:00	43.55	40.35	50.98	34.19	40.55	42.85	37.3	33.14
23:00	42	37.93	45	34.4	37.64	32.71	34.1	32.4

G

Modelica Power-to-Gas Model Parameters

Parameter	Value
Rmem	-
A	-



Modelica Power-to-Heat Model Parameters

Parameter	Value
Pnom	-
A	-

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