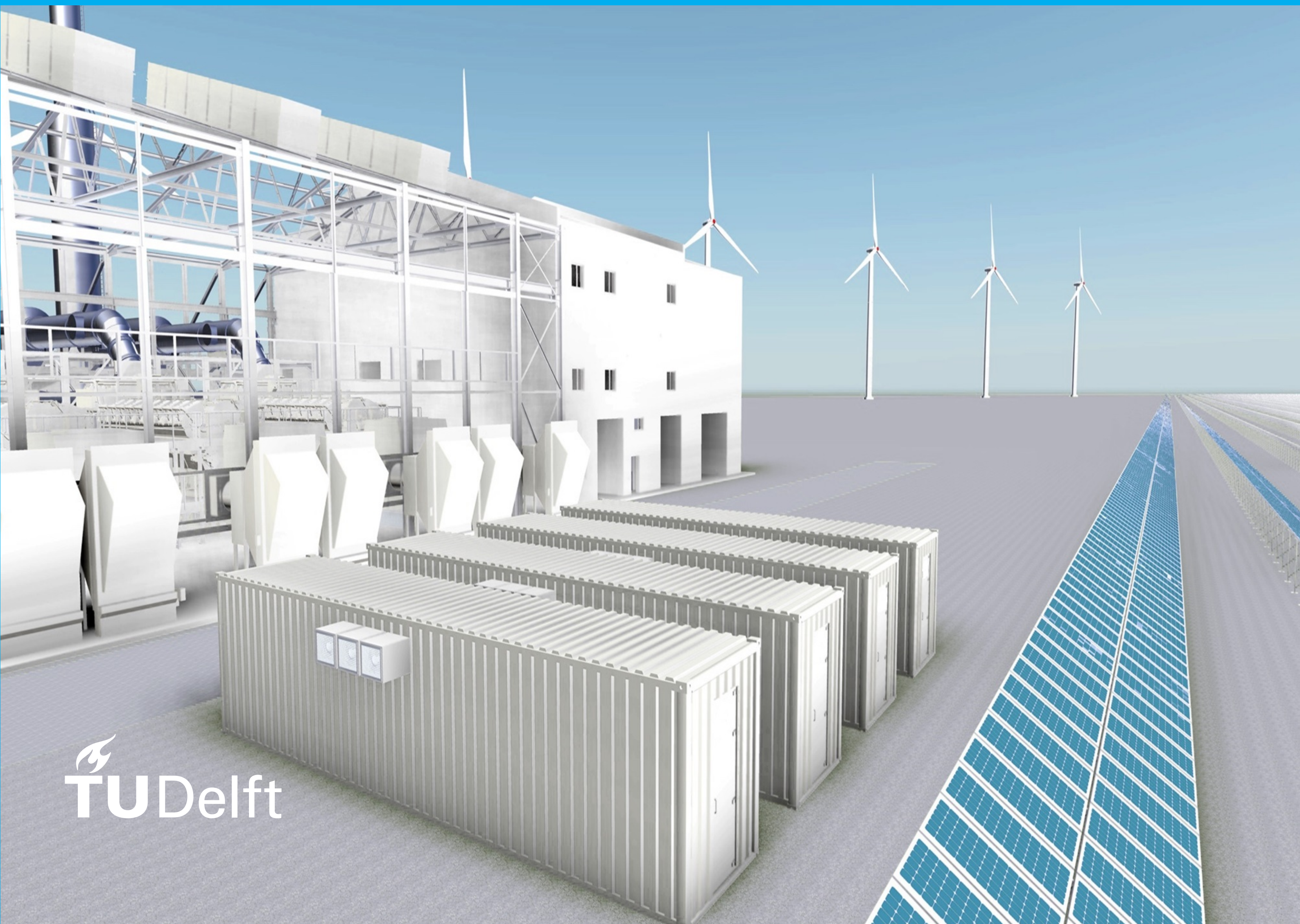
Investigating Hidden Flexibilities Provided by Power-to-X Considering Grid Support Strategies

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.

TU Delft

Preface

First of all, I would like to thank PhD. Digvijay Gusain and Dr. Milos Cvetkovic for not only teaching me the answers through this journey, but also giving me the perception of asking the right questions that lead simple ideas into unique values.

I would also like to thank my family Alican, Huriye, Uğur, Gökhan who have been supporting me from the beginning of this journey and more. You continue inspiring me to find my own path and soul, even from miles away. Your blessing is my treasure in life... My friends, Onurhan and Berke. You encourage me and give me confidence to be my best in any scene. You are two extraordinary men who, I know, will always be there when I need.

Finally, I would like to thank TU Delft staff and my colleagues in TU Delft for making this journey entertaining and illuminative for me.

B. Caner Yağcı
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°C and pursue efforts to keep it to 1.5°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.

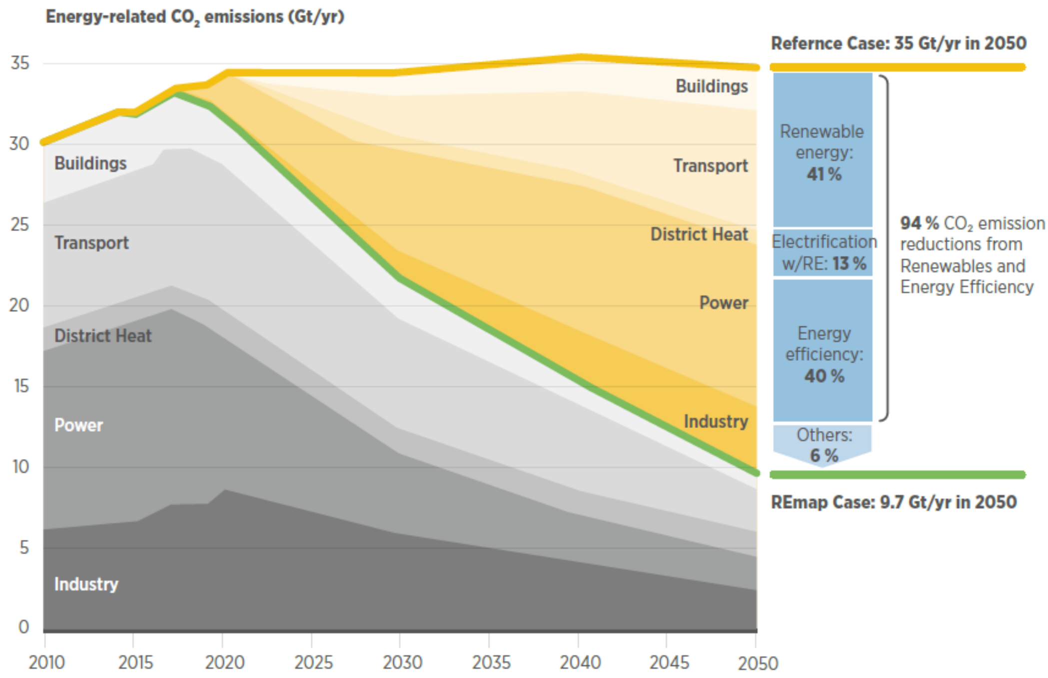


Figure 1.1: Energy-related carbon dioxide emissions with current policies compared to accelerated uptake of renewables (REmap), 2010–2050 [14]

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 CO_2/kWh, and can even reach 0 kg CO_2/kWh if electricity from wind or sun energy is employed. It is useful for comparison to note: oil-based heat generation: 0.31 kg CO_2/kWh and Gas: 0.24 kg CO_2/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 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 response 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

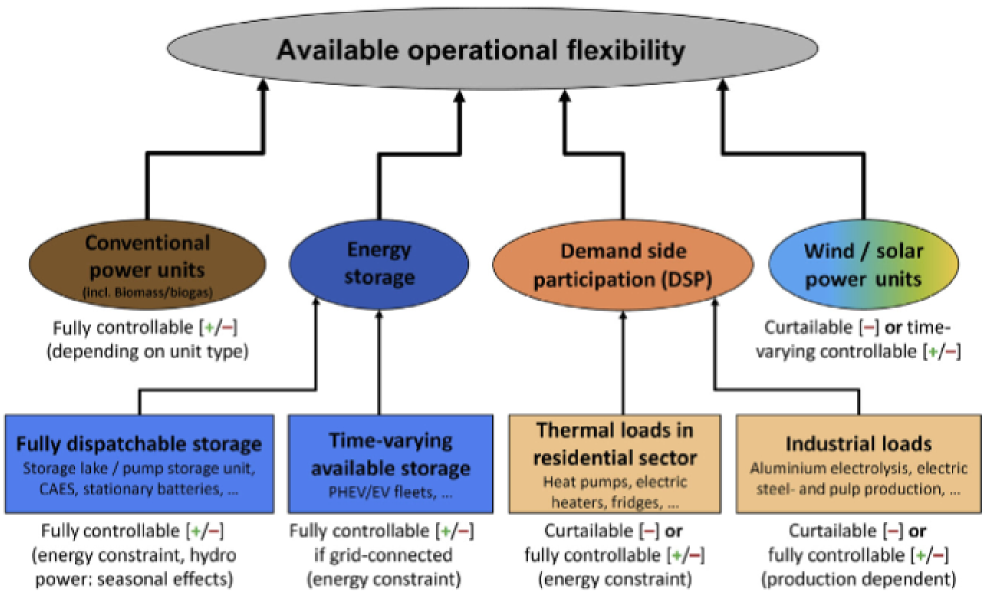


Figure 1.2: Sources of power system flexibility [31]

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 increse in operational cost

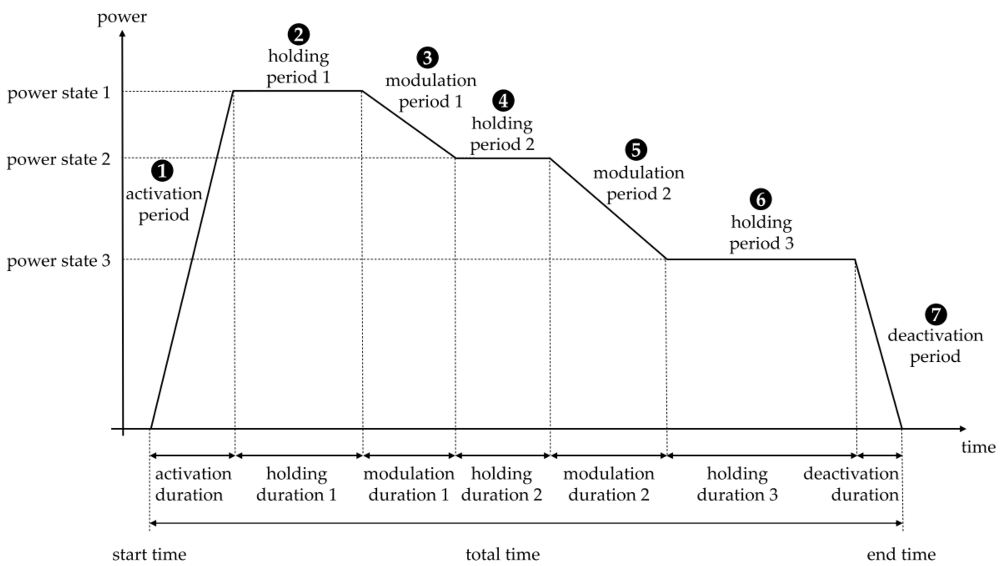


Figure 1.3: An exemplary flexible load measure with the corresponding parameters [27]

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.

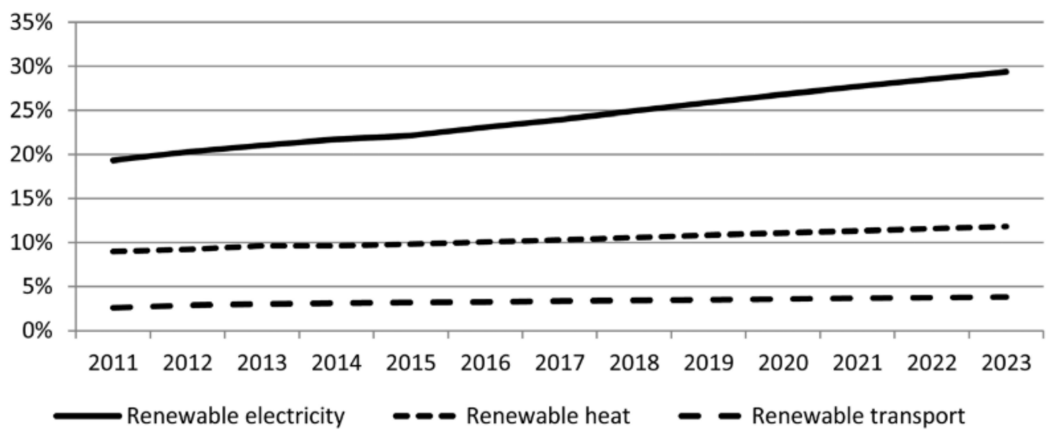


Figure 1.4: Shares of renewables in the energy mix of the power sector, the transport sector, and heat [25]

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?
  - What is the amount of excess RE (flexible capacity) in industrial area?
  - Which PtX option has the best performance for the grid and the most profit for the PtX owner?
- What is essential to model in order to describe the flexibility potential as precisely as possible?
  - Which assumptions can be made and which physical effects should be considered?
  - What should be the modelling considerations for accurate flexibility results?
- What should be the energy management strategy of MES for the optimal use of resources?
  - How different energy domains combined and optimized?
  - How complex simulations can be created for energy management of MES?
  - How to distribute excess energy between flexible loads?

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 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.

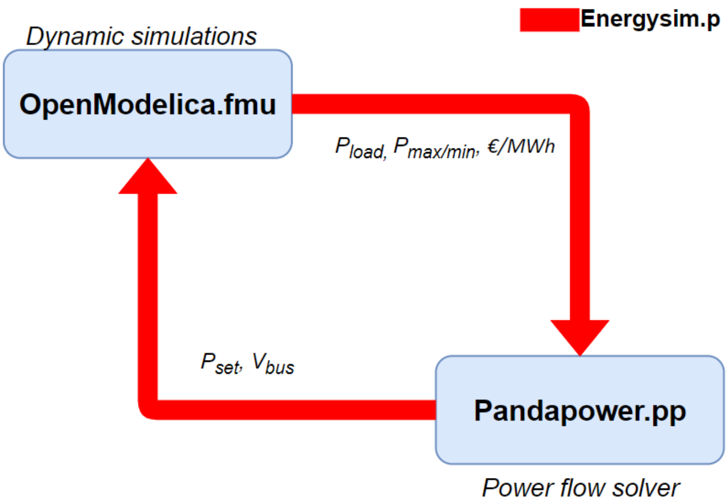


Figure 1.5: Communication between simulation tools

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. PandaPower 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. Acasual 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 hierarchical 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

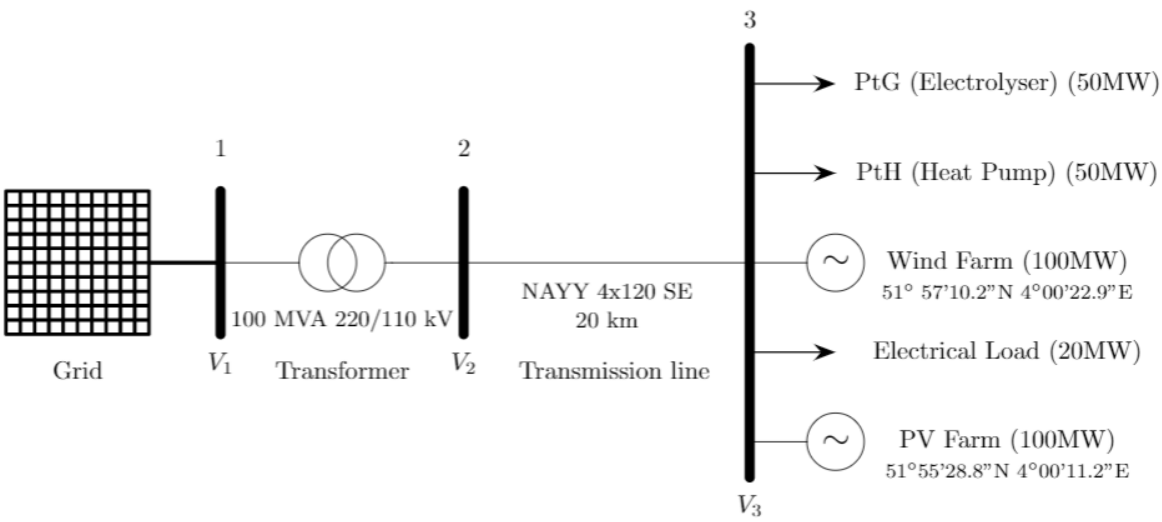


Figure 2.1: Pandapower electrical network

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 o hot water accumulator (storage tank) is connected to P2H(district heating network). The accumulator holds … m_3 water.

Figure 2.5 shows the considered heating network.

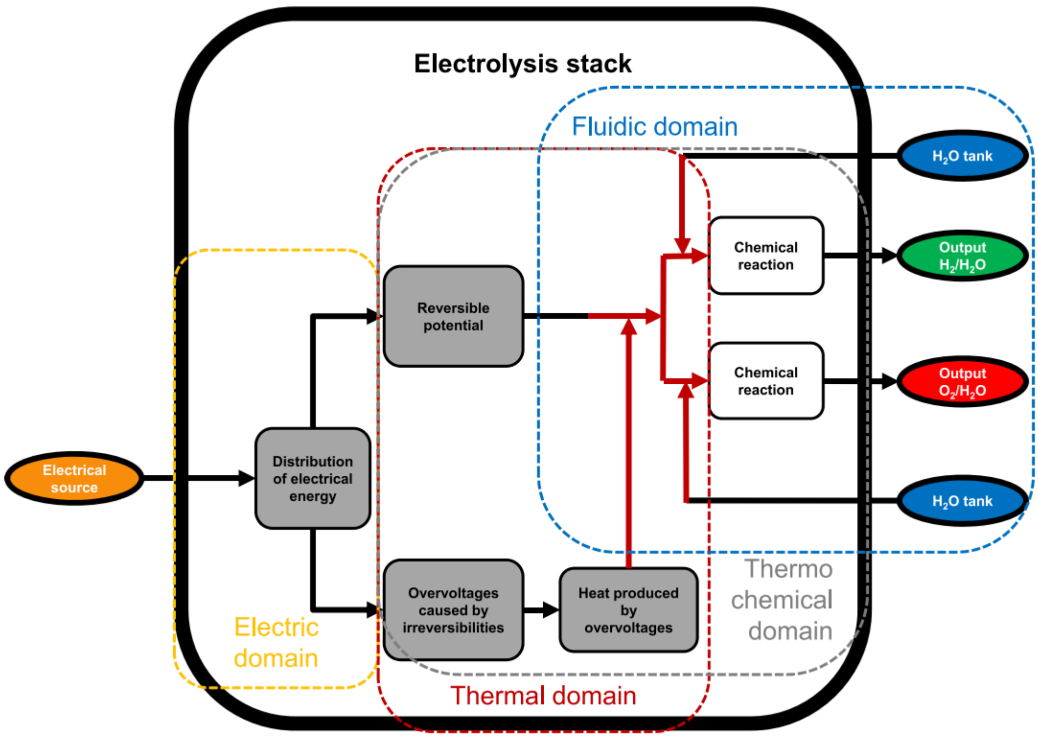


Figure 2.4: Coupled multiphysic phenomena involved in an electrolysis stack [19]

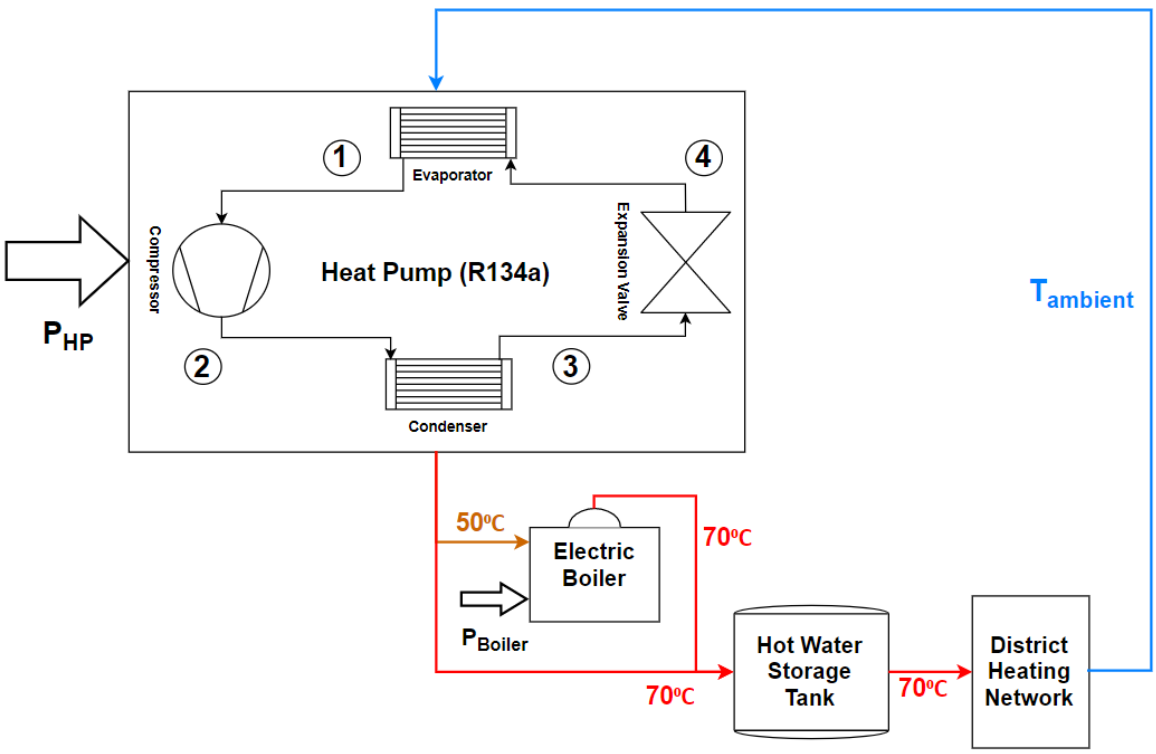


Figure 2.5: Heating Cycle of Water

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 information 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

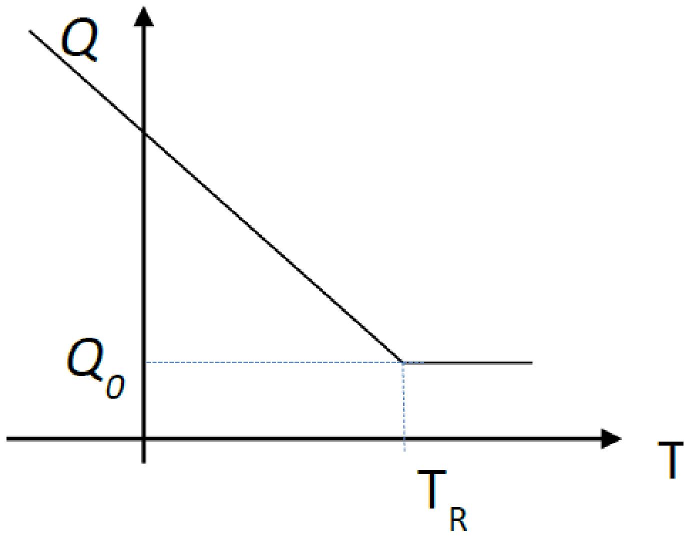


Figure 2.6: The relation between ambient temperature and hydrogen & heat demand [36]

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

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

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

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

$$Carbon\ penalty[EUR/kW] = CO_2\ emission\ factor\ [g\ CO_2\ kW^{-1}]\ x\ Carbon\ price\ [EUR\ g\ CO_2^{-1}] \tag{2.4}$$

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. Analysis

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

2.5.1. Multi-Energy System Analysis

MES analysis is carried out in order to understand the flexible capacity of MES in a specific area with selected flexible loads.

2.5.2. Power-to-X Model Analysis

Efficiency characters of different models and their performance is compared in order to investigate the effect of temperature assumptions on device performance.

2.5.3. Power System Analysis

In order to investigate the influence of modelling considerations on power system flexibility analysis, created PtG and PtH models are combined with power flow solver using co-simulation.

- **Base case:** 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.

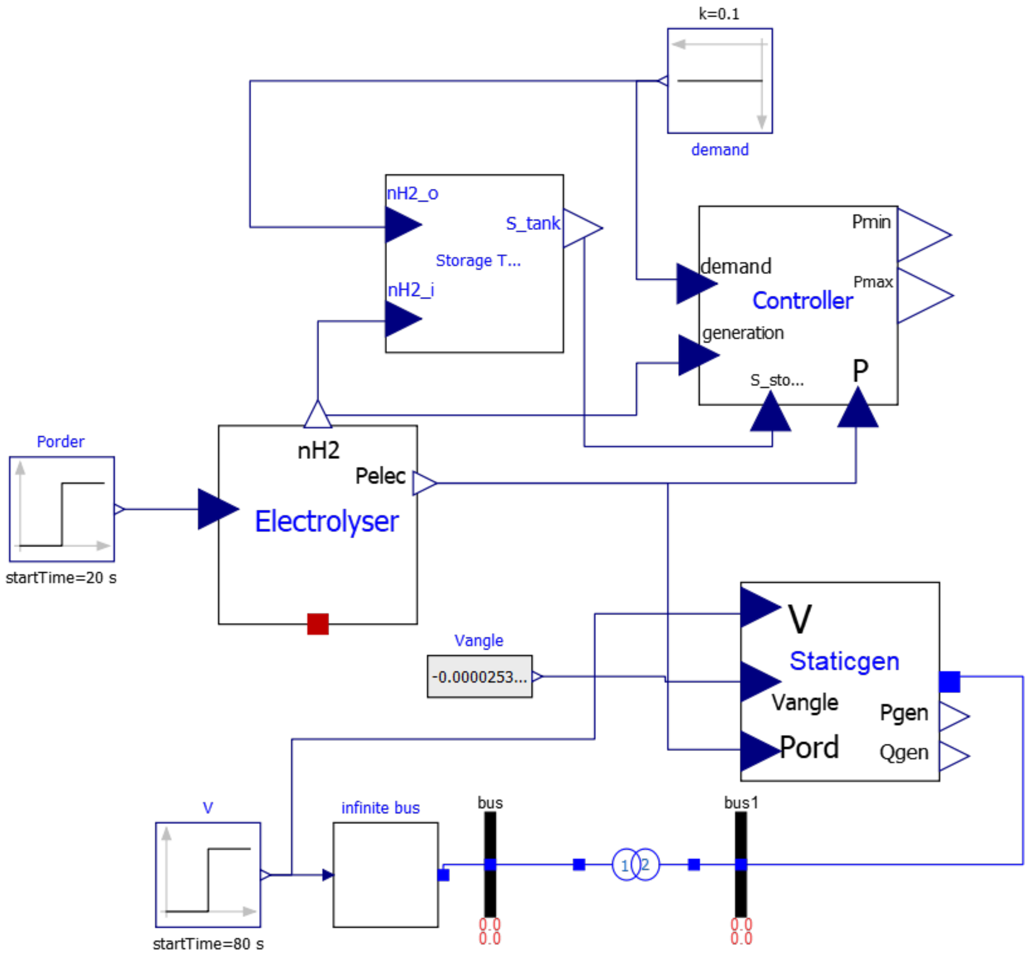


Figure 3.1: Power-to-gas model in OM

Electrolyser

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

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

Electrochemical:

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

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

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

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

$$V_{ohm} = R_{mem} \cdot i_{dens} \qquad [V] \tag{3.5}$$

$$R_{mem} = \frac{1}{\sigma_{mem}} \delta_{mem} \tag{3.6}$$

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

Thermal:

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

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

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

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

Pressure:

$$pp_{H2O} = 6.1078.10^{-3} \cdot exp\left(17.2694 \cdot \frac{T - 273.15}{T - 34.85}\right) \qquad [bar] \tag{3.12}$$

$$pp_{H_2} = p_{cat} - pp_{H2O} \qquad [bar] \tag{3.13}$$

$$pp_{O_2} = p_{an} - pp_{H2O} \qquad [bar] \tag{3.14}$$

Massflow:

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

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

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

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

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

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

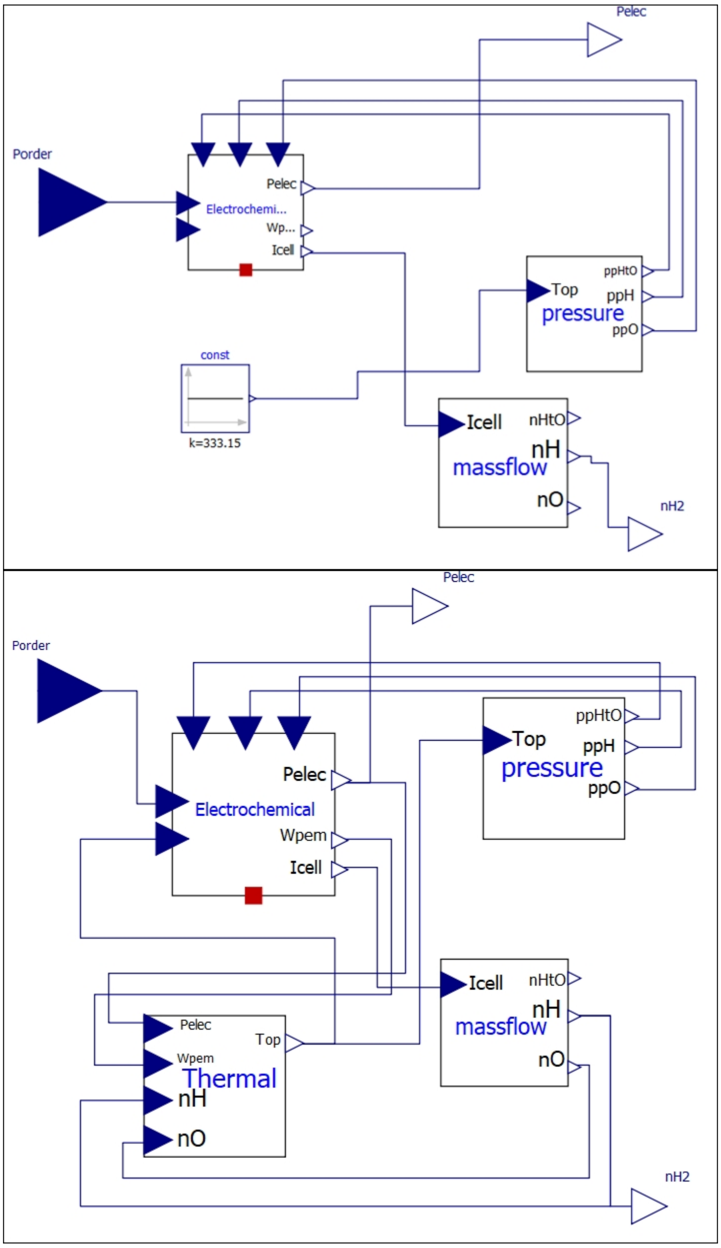


Figure 3.2: Electrolyser model "A" (upper) and model "B" (lower) model in OM

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) $[kg/m^3]$	0.06953	1.104
F (faraday constant)	96485	96485

Adjustable Power Level Controller

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

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

Figure 3.3 illustrates the implemented controller model in OM.

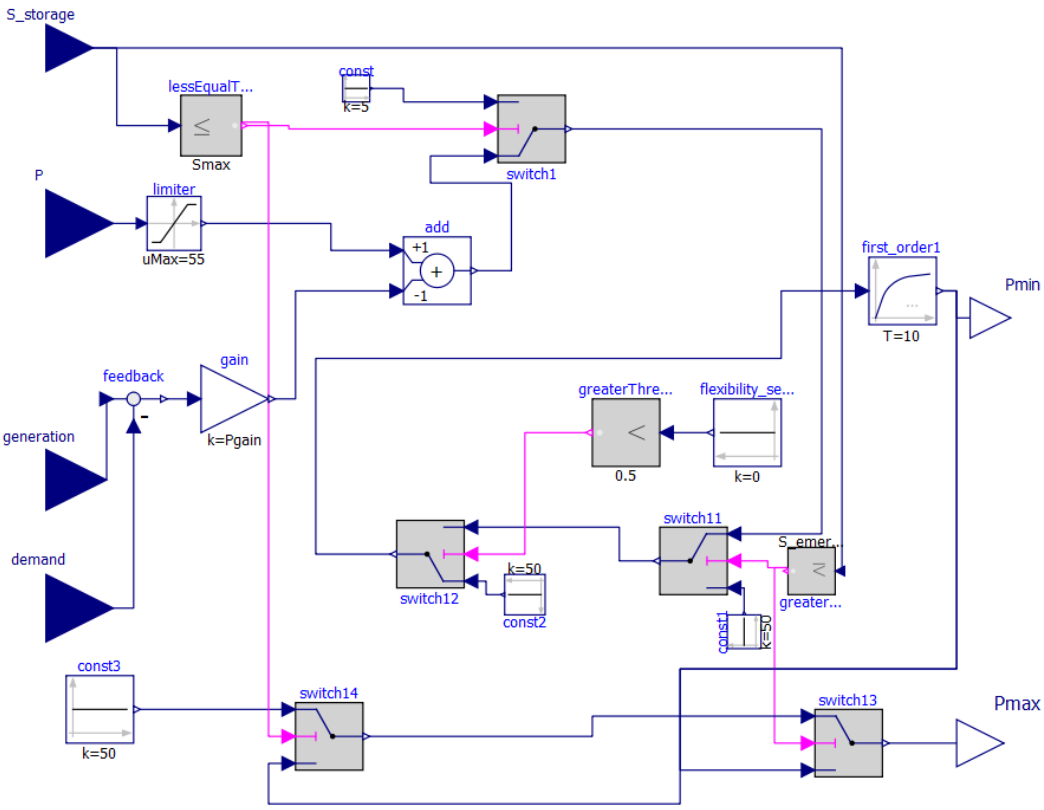


Figure 3.3: Adjustable power level controller in OM

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 $T_{ambient} and T_{condenser} = 50, 70°C$ is shown in 3.3.

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

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.

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

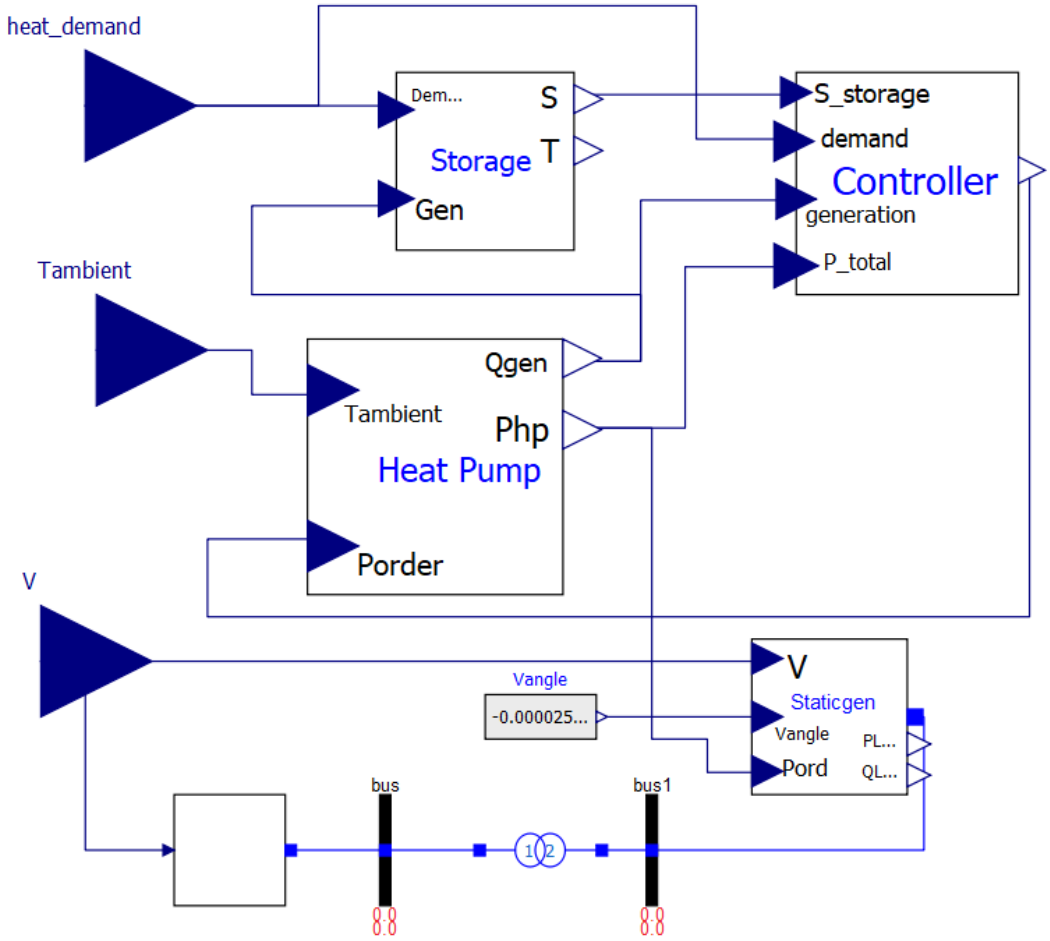


Figure 3.4: Power-to-heat model in OM

Table 3.3: COP results for various ambient and condenser temperatures

$T_{ambient}$	-20	-16	-12	-8	-4	0	4
COP @ $T_{cond} = 50°C$	3.3931	3.6429	3.9268	4.2500	4.6251	5.0604	5.5750
COP @ $T_{cond} = 70°C$	2.4174	2.5586	2.7150	2.8887	3.0837	3.3013	3.5476
$T_{ambient}$	8	12	16	20	24	28	32
COP @ $T_{cond} = 50°C$	6.1957	6.9452	7.8660	9.0564	10.5899	12.7115	15.7889
COP @ $T_{cond} = 70°C$	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

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

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

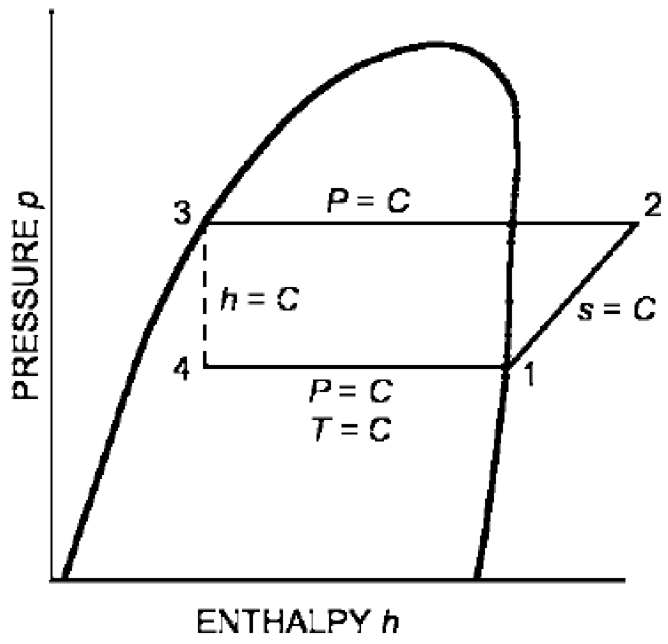


Figure 3.5: Theoretical Single-Stage Vapor Compression Refrigeration Cycle ($C = Constant$) [9]

Table 3.5: 5^{th} order polynomial fuction parameters for $T_{condenser} = 50, 70°C$

$T_{condenser}$ (°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

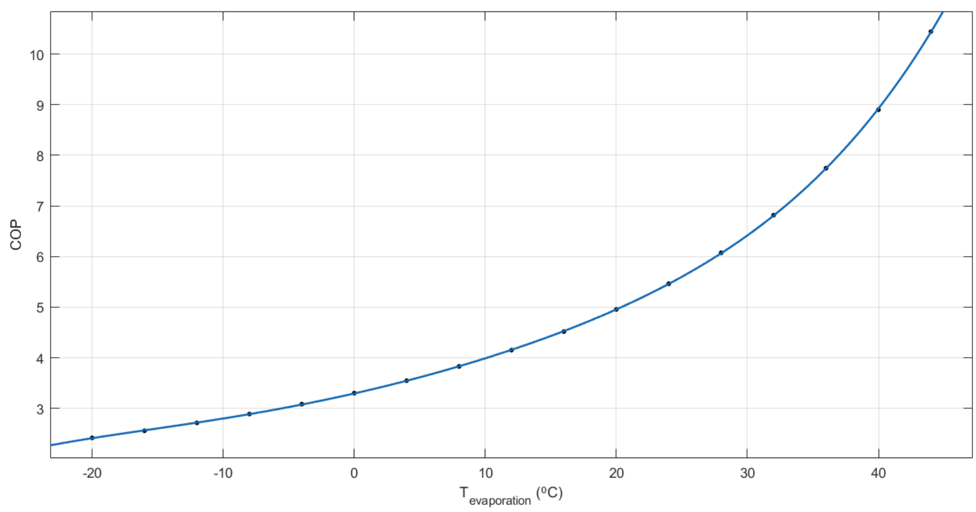


Figure 3.6: COP vs. $T_{ambient}$, $T_{condenser} = 70°C$

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.

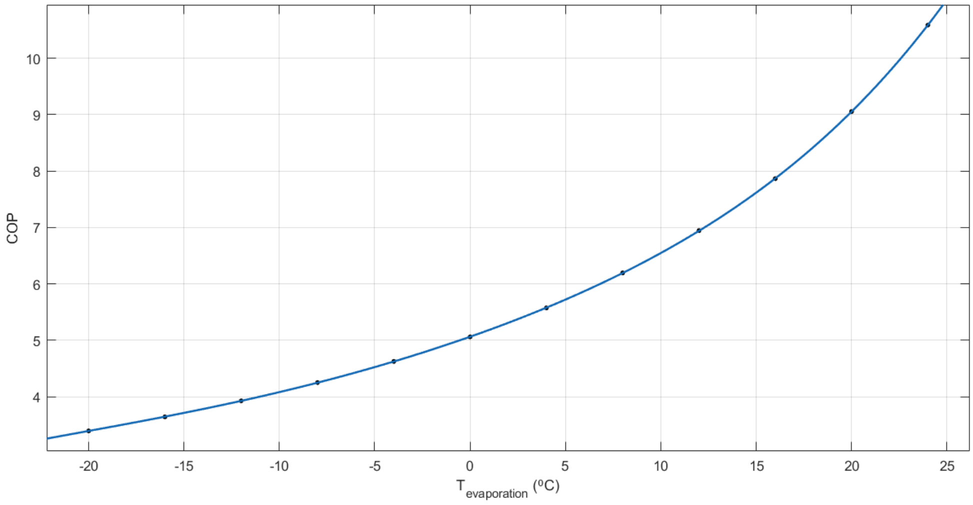


Figure 3.7: COP vs. $T_{ambient}$, $T_{condenser} = 50°C$

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/m3]	977.74
Storage Volume [m3]	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 $t = 0, \ldots$

3.3.1. Formulation of the Optimization Problem

Objective function:

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

Cost function:

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

3.4. Co-simulation Setup

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

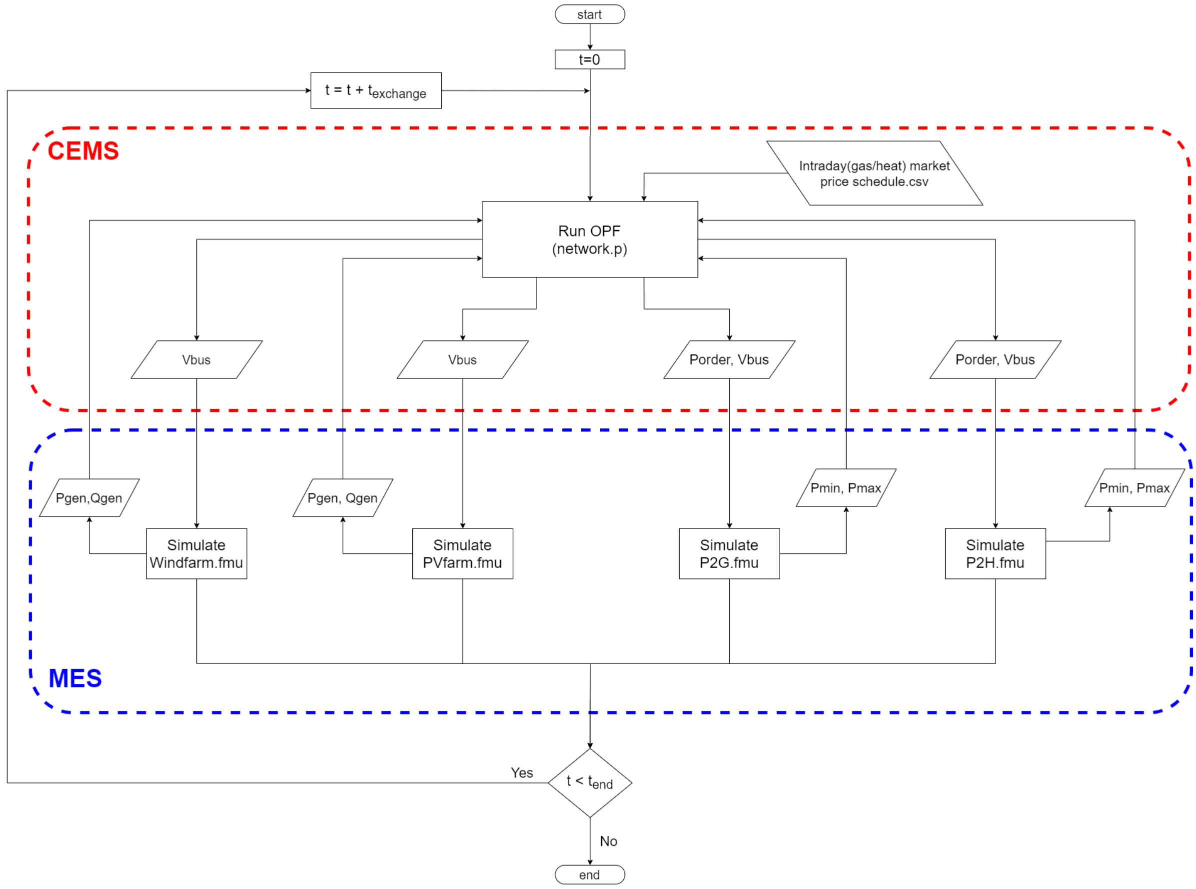


Figure 3.8: Co-simulation flow chart

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)

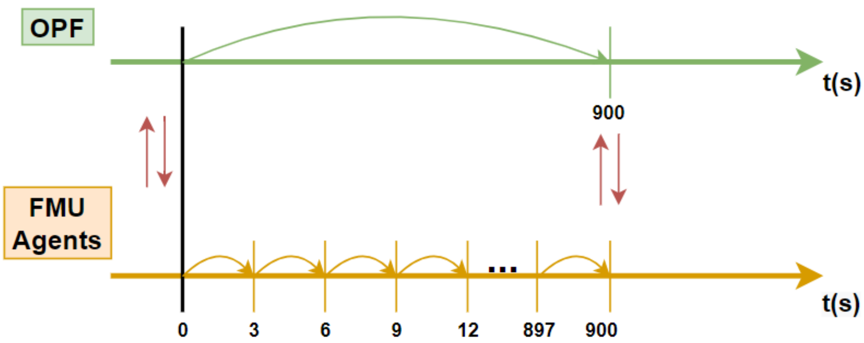


Figure 3.9: Co-simulation synchronization

4

Results & Discussions

4.1. Technical Evaluation

4.2. Analysis

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

4.2.1. Multi-Energy System Analysis

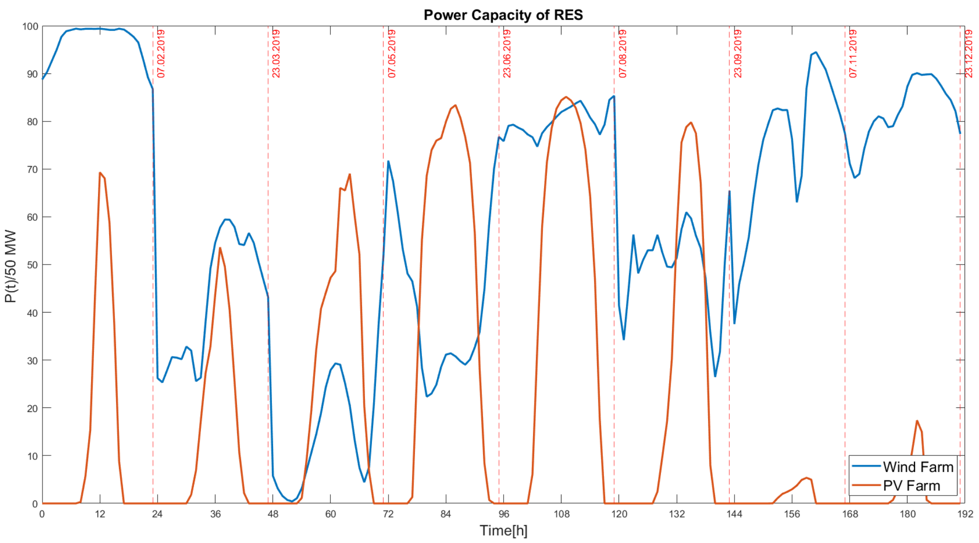


Figure 4.1: Power capacity of renewable energy sources

4.2.2. Power-to-X Model Analysis

4.2.3. Power System Analysis

Base Case

First Case: Hidden Flexibility Analysis

Second Case: Optimal Deployment of Flexibility

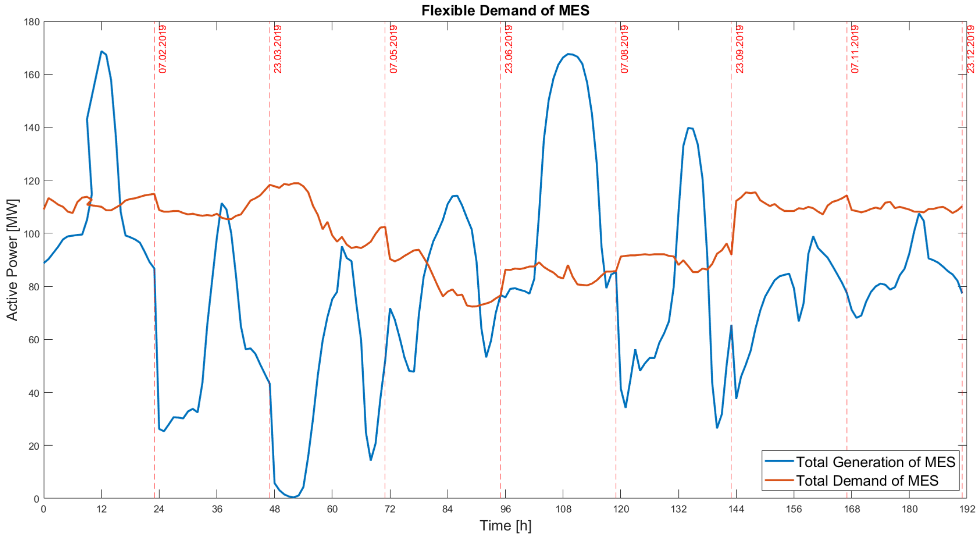


Figure 4.2: Flexible demand of multi-energy system

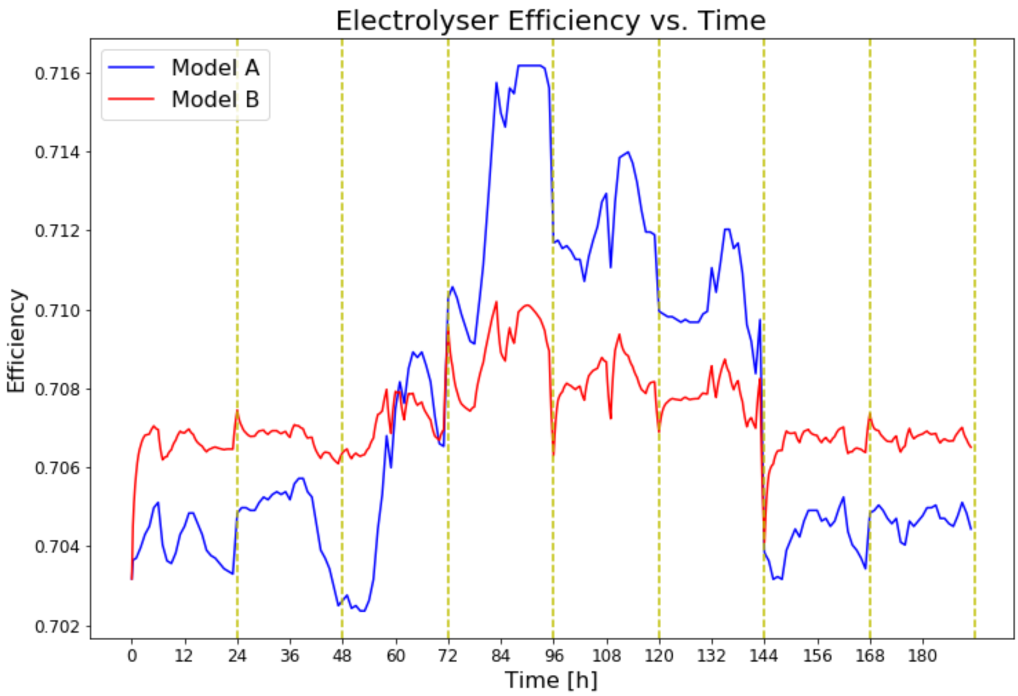


Figure 4.3: Efficiency comparison of electrolyser models

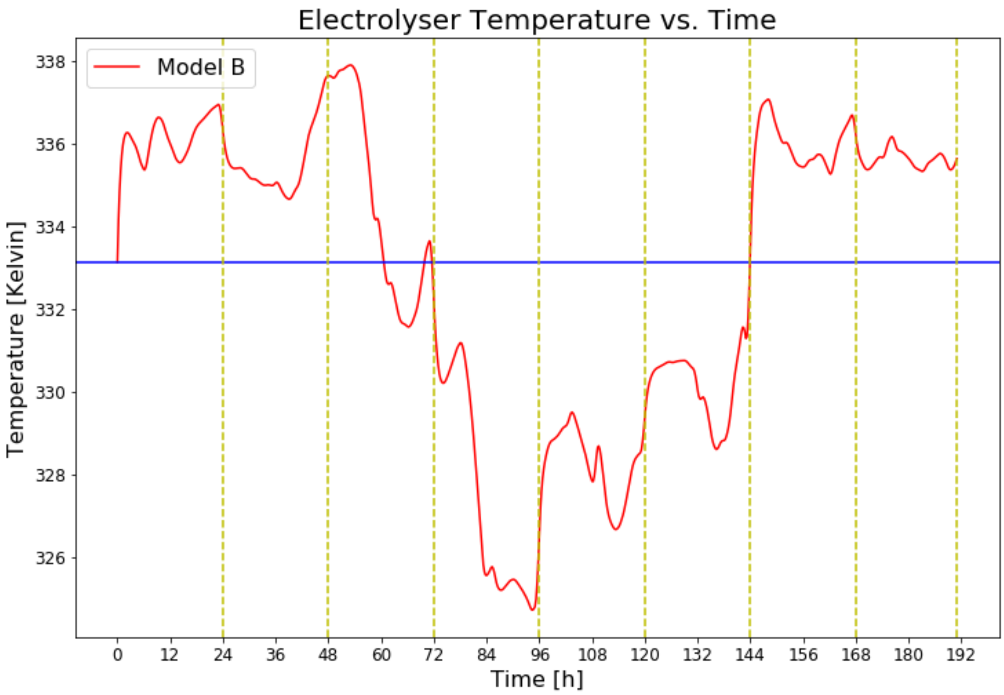


Figure 4.4: Operational temperature comparison of electrolyser models

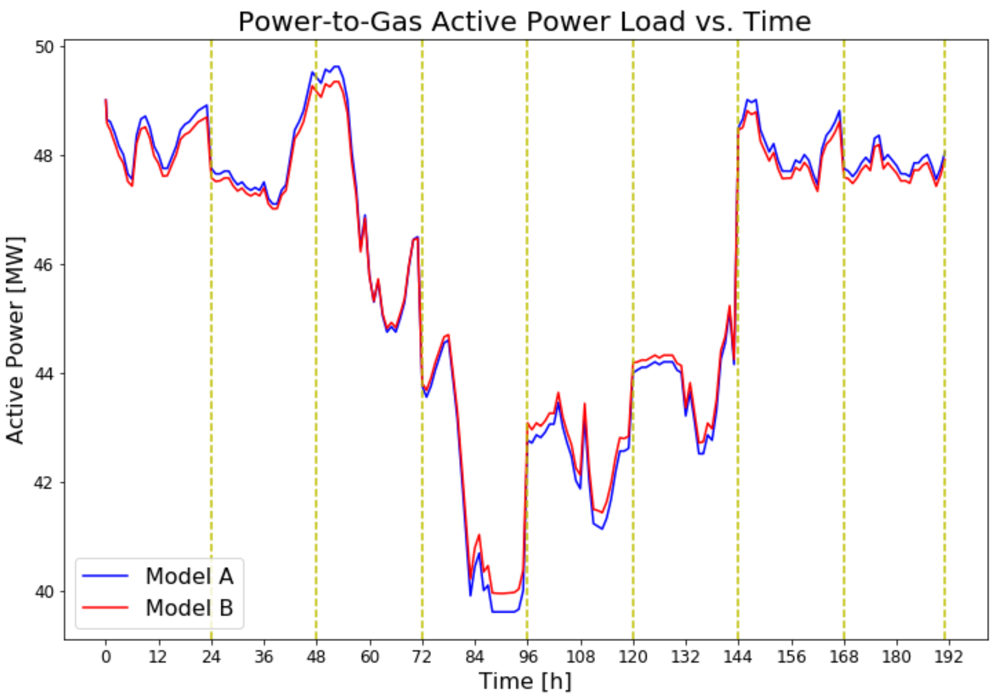


Figure 4.5: $P_{Load,PtH}$ of electrolyser models

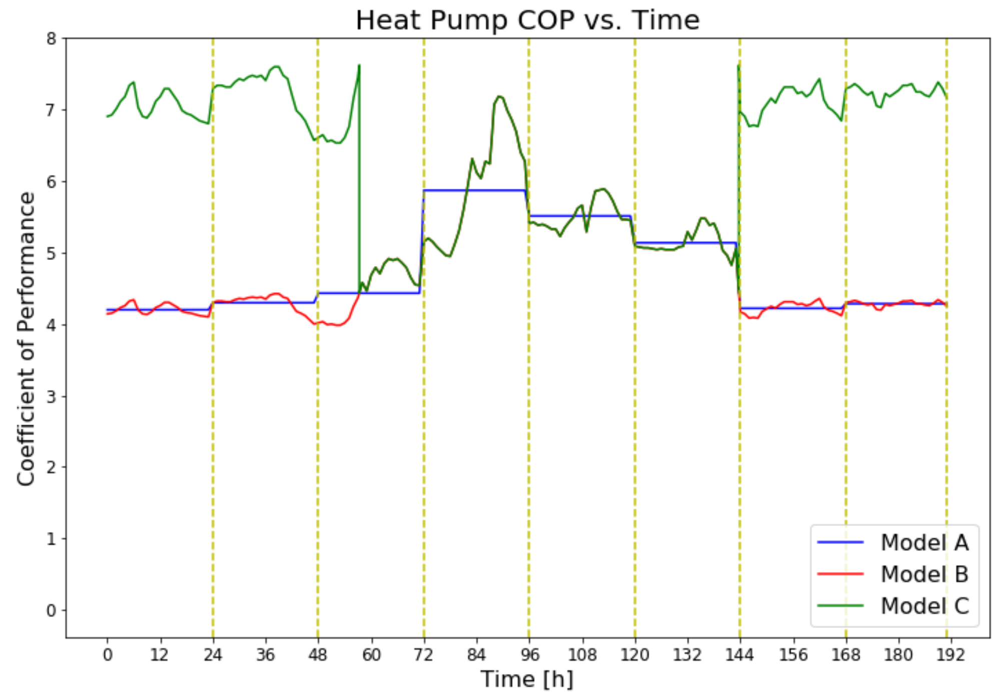


Figure 4.6: COP results of heat pump models

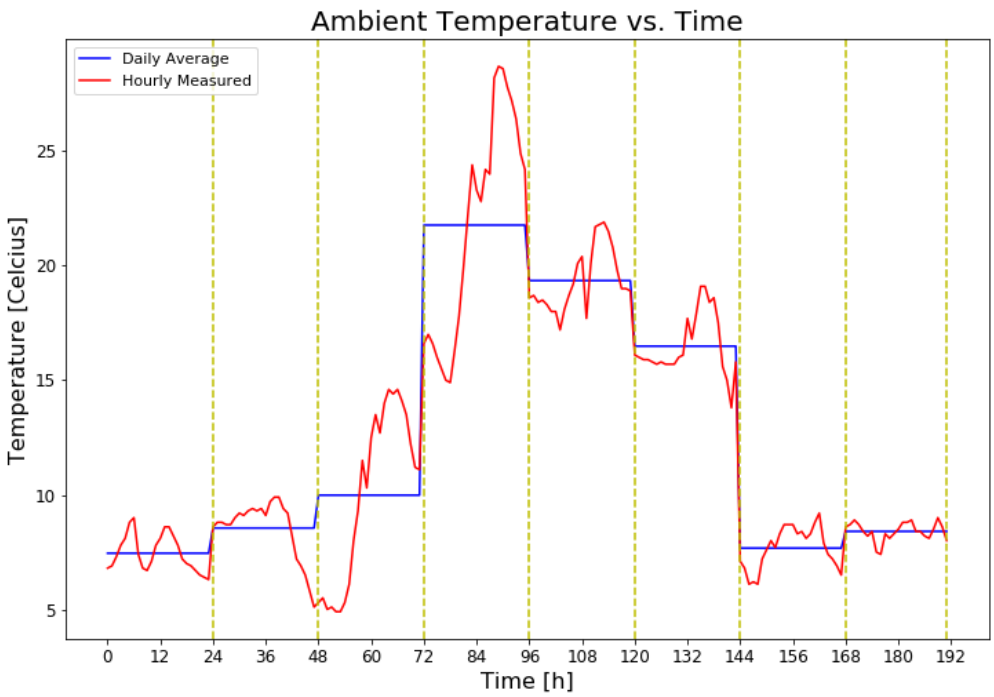


Figure 4.7: Ambient Temperature vs. Time

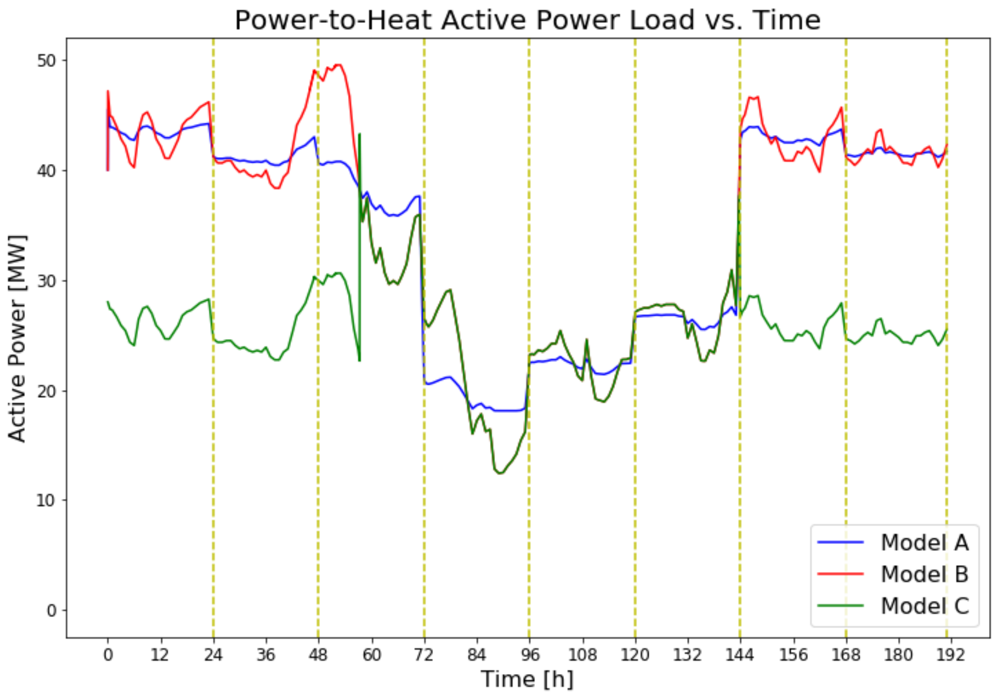


Figure 4.8: $P_{Load,PtH}$ of heat pump models

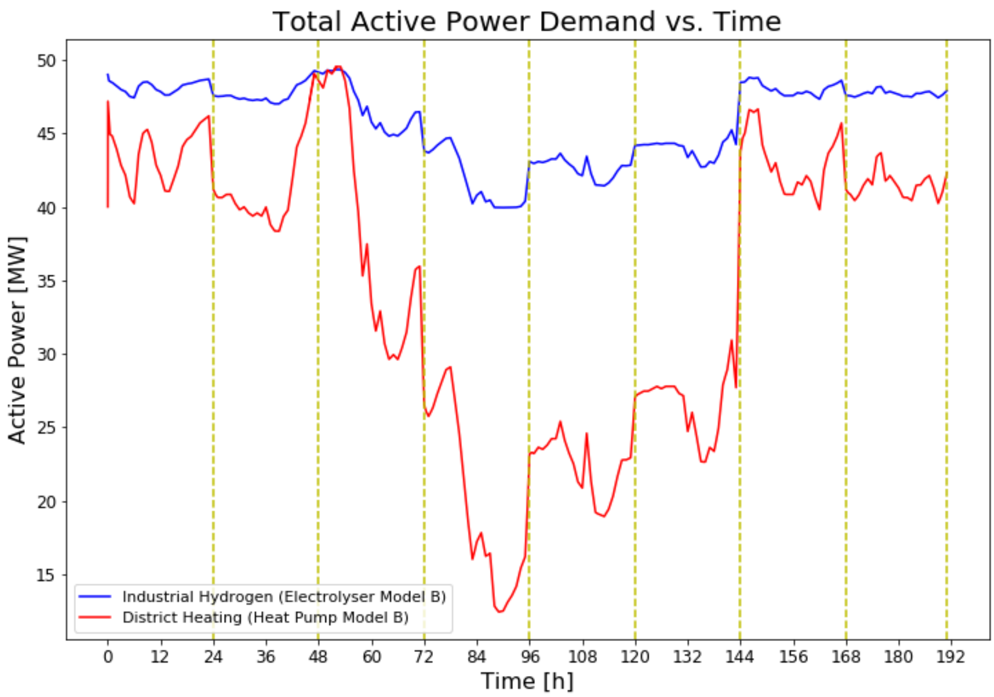


Figure 4.9: P_{Load} results for Model "B" of PtG & PtH

5

Conclusion & 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 is 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.

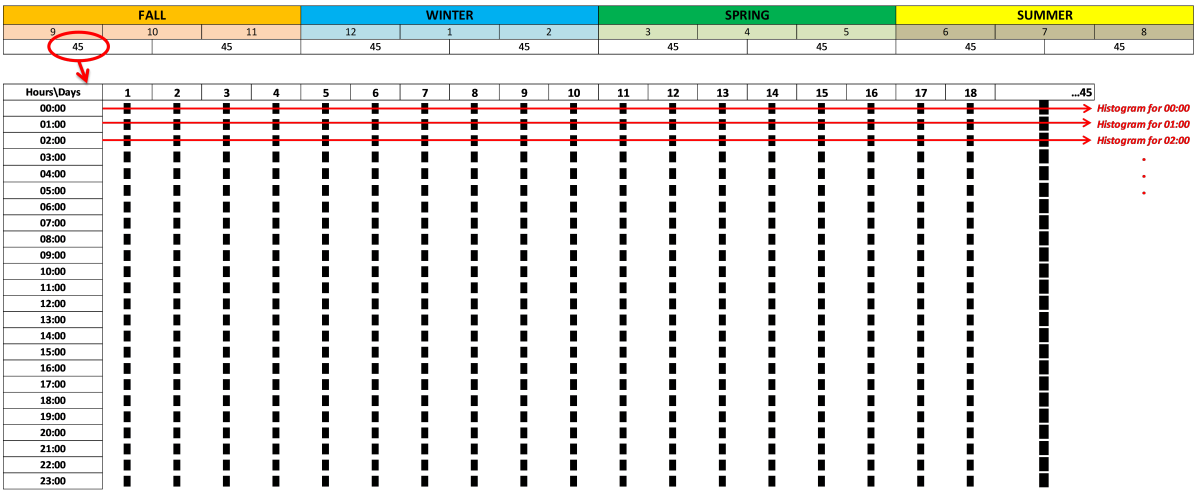


Figure A.1: Historical data processing

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)	Power (kW)	Speed (m/s)	Power (kW)	Speed (m/s)	Power (kW)	Speed (m/s)	Power (kW)	Speed (m/s)	Power (kW)	Speed (m/s)	Power (kW)	Speed (m/s)	Power (kW)	Speed (m/s)
00:00	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	92601.445	12.187	27907.221	6.161	1549.057	2.609	60689.148	8.451	79285.795	10.055	44850.676	7.359	50525.668	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	77857.683	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	31990.499	6.46	6867.586	3.937	28384.259	6.192	74697.25	9.591	52985.806	7.904	79305.323	10.057	80584.682	10.196
08:00	99238.043	17.523	25590.066	5.971	10653.679	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	57882.151	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	4.822	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	4426.706	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

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)	Irradiation (kW/m²)	Power (kW)	Irradiation (kW/m²)	Power (kW)	Irradiation (kW/m²)	Power (kW)	Irradiation (kW/m²)	Power (kW)	Irradiation (kW/m²)	Power (kW)	Irradiation (kW/m²)	Power (kW)	Irradiation (kW/m²)	Power (kW)	Irradiation (kW/m²)
00:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
04:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05:00	0	0	0	0	0	0	1319.422	0.021	0	0	0	0	0	0	0	0
06:00	0	0	0	0	1133.936	0.014	28059.453	0.252	6131.878	0.066	0	0	0	0	0	0
07:00	0	0	1816.785	0.009	9059.934	0.05	55175.157	0.508	32616.535	0.287	0	0	0	0	0	0
08:00	291.983	0.005	6871.221	0.018	19523.916	0.09	68630.187	0.648	57877.971	0.533	2462.303	0.014	26.135	0.001	0	0
09:00	5718.923	0.028	17318.58	0.05	32100.078	0.148	73960.699	0.7	71421.408	0.684	9680.163	0.038	1112.383	0.002	714.301	0.007
10:00	15337.419	0.074	27314.793	0.087	40728.161	0.179	75949.034	0.712	78620.469	0.773	17168.832	0.06	1993.581	0.002	2855.208	0.01
11:00	43767.656	0.314	32821.879	0.106	44094.185	0.17	76473.695	0.708	82635.249	0.829	30349.142	0.135	2428.23	0.002	3496.021	0.008
12:00	69304.444	0.608	43796.938	0.193	47254.563	0.17	79906.414	0.769	84398.683	0.857	56531.02	0.413	2954.324	0.002	5156.988	0.012
13:00	68046.914	0.6	53617.628	0.311	48624.5	0.178	82589.026	0.826	85113.818	0.872	75573.886	0.695	3757.545	0.003	11045.929	0.046
14:00	58793.726	0.503	49577.106	0.289	66037.782	0.417	83392.126	0.85	84351.829	0.862	78800.828	0.754	4917.63	0.007	17395.415	0.113
15:00	37387.539	0.294	40423.999	0.227	65517.127	0.445	80710.341	0.809	82807.878	0.842	79787.169	0.781	5363.456	0.015	14964.246	0.12
16:00	8831.553	0.063	25787.706	0.133	69020.134	0.535	76771.579	0.751	79625.623	0.799	77484.171	0.764	4976.757	0.035	721.25	0.013
17:00	0	0.002	10674.833	0.054	60238.669	0.456	71310.144	0.68	74116.278	0.729	67067.936	0.645	0	0.004	0	0
18:00	0	0	2161.488	0.021	52116.871	0.402	56567.394	0.489	64261.721	0.614	43352.895	0.397	0	0	0	0
19:00	0	0	0	0	20423.694	0.128	28313.547	0.194	46923.725	0.432	7967.569	0.083	0	0	0	0
20:00	0	0	0	0	6726.103	0.052	8406.849	0.05	17515.946	0.161	0	0	0	0	0	0
21:00	0	0	0	0	0	0.001	710.453	0.008	0	0.002	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

C

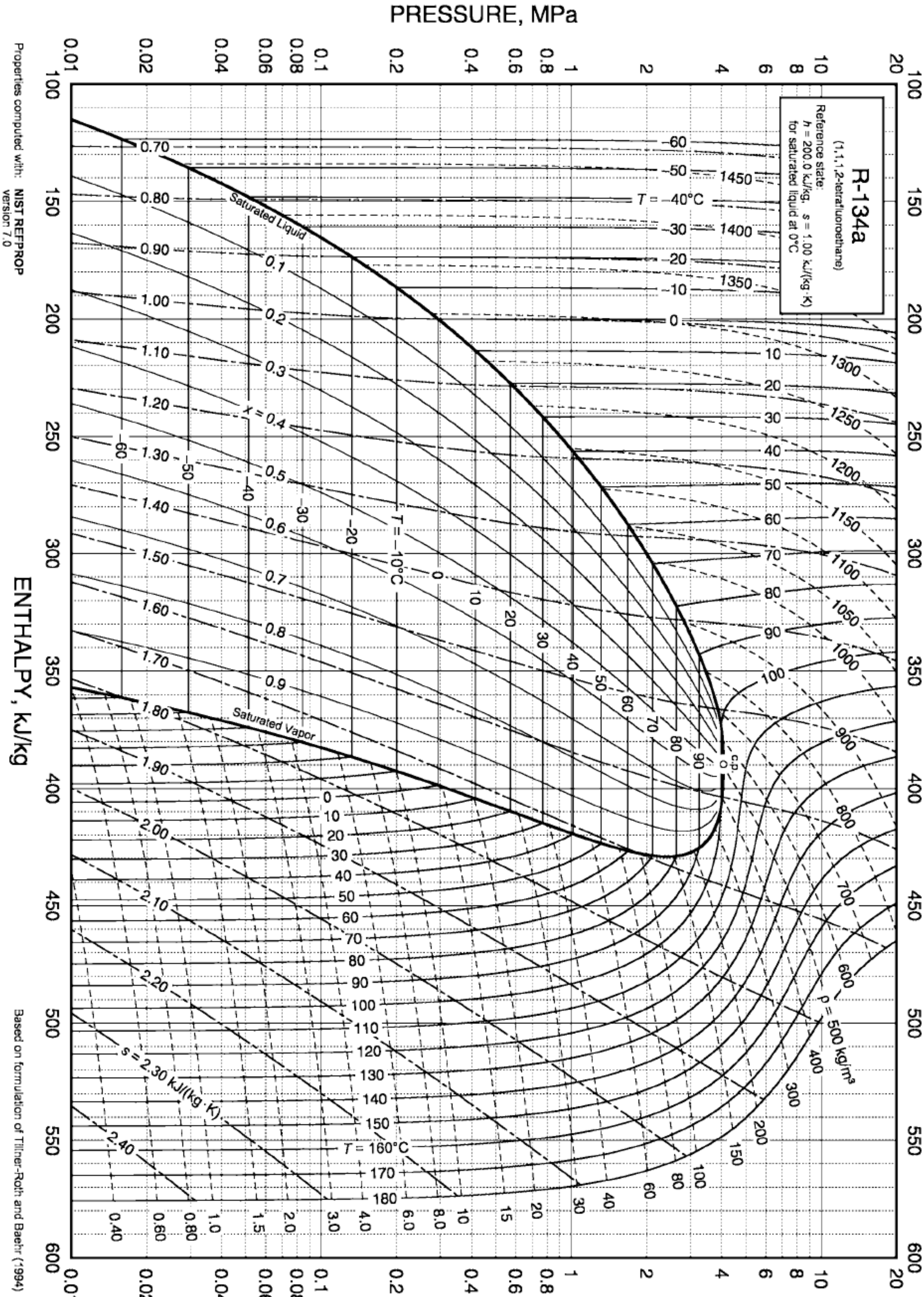
Ambient Temperature & Energy Demand Data

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


PRESSURE, MPa
ENTHALPY, kJ/kg
R-134a
(1,1,1,2-tetrafluoroethane)
Reference state:
h = 200.0 kJ/kg, s = 1.00 kJ/(kg·K)
for saturated liquid at 0°C
Saturated Liquid
Saturated Vapor
c.p.
s = 2.30 kJ/(kg·K)
T = 160°C
ρ = 500 kg/m³
Properties computed with: NIST REFPROP version 7.0
Based on formulation of Tillner-Roth and Baehr (1994)

E

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.
  - Refirigerant 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	-

H

Modelica Power-to-Heat Model Parameters

Parameter	Value
Pnom	-
A	-

Bibliography

[1] World Energy Outlook 2019. *International Energy Agency*, 2019. ISSN 1387-1811. doi: DOE/EIA-0383(2012)U.S. URL https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf.

[2] Bjarne Bach, Jesper Werling, Torben Ommen, Marie Münster, Juan M. Morales, and Brian Elmegaard. Integration of large-scale heat pumps in the district heating systems of Greater Copenhagen. *Energy*, 107:321–334, 2016. ISSN 03605442. doi: 10.1016/j.energy.2016.04.029. URL http://dx.doi.org/10.1016/j.energy.2016.04.029.

[3] John Barton, Sikai Huang, David Infield, Matthew Leach, Damiete Ogunkunle, Jacopo Torriti, and Murray Thomson. The evolution of electricity demand and the role for demand side participation, in buildings and transport. *Energy Policy*, 52:85–102, 2013. ISSN 03014215. doi: 10.1016/j.enpol.2012.08.040. URL http://dx.doi.org/10.1016/j.enpol.2012.08.040.

[4] Morten B. Blarke. Towards an intermittency-friendly energy system: Comparing electric boilers and heat pumps in distributed cogeneration. *Applied Energy*, 91(1):349–365, 2012. ISSN 03062619. doi: 10.1016/j.apenergy.2011.09.038. URL http://dx.doi.org/10.1016/j.apenergy.2011.09.038.

[5] Carsten Bode and Gerhard Schmitz. Dynamic simulation and comparison of different configurations for a coupled energy system with 100% renewables. *Energy Procedia*, 155:412–430, 2018. ISSN 18766102. doi: 10.1016/j.egypro.2018.11.037. URL https://doi.org/10.1016/j.egypro.2018.11.037.

[6] Kenneth Bruninx, Dieter Patteeuw, Erik Delarue, Lieve Helsen, and William D'Haeseleer. Short-term demand response of flexible electric heating systems: The need for integrated simulations. *International Conference on the European Energy Market, EEM*, (March), 2013. ISSN 21654077. doi: 10.1109/EEM.2013.6607333.

[7] Van Hai Bui, Akhtar Hussain, and Hak Man Kim. A multiagent-based hierarchical energy management strategy for multi-microgrids considering adjustable power and demand response. *IEEE Transactions on Smart Grid*, 9(2):1323–1333, 2018. ISSN 19493053. doi: 10.1109/TSG.2016.2585671.

[8] Xinyu Chen, Xi Lu, Michael B. McElroy, Chris P. Nielsen, and Chongqing Kang. Synergies of wind power and electrified space heating: Case study for Beijing. *Environmental Science and Technology*, 48(3):2016–2024, 2014. ISSN 0013936X. doi: 10.1021/es405653x.

[9] Tullie Circle. *2013 ASHRAE Handbook—Fundamentals*. 2013. ISBN 1936504472.

[10] Manuel Espinosa-López, Christophe Darras, Philippe Poggi, Raynal Glises, Philippe Baucour, André Rakotondrainibe, Serge Besse, and Pierre Serre-Combe. Modelling and experimental validation of a 46 kW PEM high pressure water electrolyzer. *Renewable Energy*, 119:160–173, 2018. ISSN 18790682. doi: 10.1016/j.renene.2017.11.081.

[11] Digvijay Gusain, Miloš Cvetković, and Peter Palensky. Energy flexibility analysis using FMUWorld. *2019 IEEE Milan PowerTech, PowerTech 2019*, 2019. doi: 10.1109/PTC.2019.8810433.

[12] Kofi E. Hagan, Olufemi O. Oyebanjo, Tarek Medalel Masaud, and Rajab Challoo. A probabilistic forecasting model for accurate estimation of PV solar and wind power generation. *2016 IEEE Power and Energy Conference at Illinois, PECI 2016*, pages 1–5, 2016. doi: 10.1109/PECI.2016.7459241.

[13] Karsten Hedegaard, Brian Vad Mathiesen, Henrik Lund, and Per Heiselberg. Wind power integration using individual heat pumps - Analysis of different heat storage options. *Energy*, 47(1):284–293, 2012. ISSN 03605442. doi: 10.1016/j.energy.2012.09.030. URL http://dx.doi.org/10.1016/j.energy.2012.09.030.

[14] IRENA. *Hydrogen From Renewable Power: Technology outlook for the energy transition*. Number September. 2018. ISBN 9789292600778. URL www.irena.org.

[15] Huiyong Kim, Mikyoung Park, and Kwang Soon Lee. One-dimensional dynamic modeling of a high-pressure water electrolysis system for hydrogen production. *International Journal of Hydrogen Energy*, 38(6):2596–2609, 2013. ISSN 03603199. doi: 10.1016/j.ijhydene.2012.12.006. URL http://dx.doi.org/10.1016/j.ijhydene.2012.12.006.

[16] Peter D. Lund, Juuso Lindgren, Jani Mikkola, and Jyri Salpakari. Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renewable and Sustainable Energy Reviews*, 45:785–807, 2015. ISSN 13640321. doi: 10.1016/j.rser.2015.01.057. URL http://dx.doi.org/10.1016/j.rser.2015.01.057.

[17] Modelica Association. Modelica Language Specification. 2017.

[18] Theresa Müller and Dominik Möst. Demand Response Potential: Available when Needed? *Energy Policy*, 115(February 2017):181–198, 2018. ISSN 03014215. doi: 10.1016/j.enpol.2017.12.025. URL https://doi.org/10.1016/j.enpol.2017.12.025.

[19] Pierre Olivier, Cyril Bourasseau, and Pr Belkacem Bouamama. Low-temperature electrolysis system modelling: A review. *Renewable and Sustainable Energy Reviews*, 78(February):280–300, 2017. ISSN 18790690. doi: 10.1016/j.rser.2017.03.099.

[20] Kazuo Onda, Toshio Murakami, Takeshi Hikosaka, Misaki Kobayashi, Ryouhei Notu, and Kohei Ito. Performance Analysis of Polymer-Electrolyte Water Electrolysis Cell at a Small-Unit Test Cell and Performance Prediction of Large Stacked Cell. *Journal of The Electrochemical Society*, 149(8):A1069, 2002. ISSN 00134651. doi: 10.1149/1.1492287.

[21] Peter Palensky and Dietmar Dietrich. Demand side management: Demand response, intelligent energy systems, and smart loads. *IEEE Transactions on Industrial Informatics*, 7(3):381–388, 2011. ISSN 15513203. doi: 10.1109/TII.2011.2158841.

[22] G. Papaefthymiou, B. Hasche, and C. Nabe. Potential of heat pumps for demand side management and wind power integration in the German electricity market. *IEEE Transactions on Sustainable Energy*, 3(4):636–642, 2012. ISSN 19493029. doi: 10.1109/TSTE.2012.2202132.

[23] Raul Rodríguez Pearson. Pvsystems: A modelica library for photovoltaic system and power converter design. URL https://raulrpearson.github.io/PVSystems/index.html#PVSystems.

[24] M. K. Petersen, K. Edlund, L. H. Hansen, J. Bendtsen, and J. Stoustrup. A taxonomy for modeling flexibility and a computationally efficient algorithm for dispatch in Smart Grids. *Proceedings of the American Control Conference*, pages 1150–1156, 2013. ISSN 07431619. doi: 10.1109/acc.2013.6579991.

[25] Stefan Pfenninger and Iain Staffell. URL http://www.renewables.ninja/.

[26] Stefan Pfenninger and Iain Staffell. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy*, 114:1251–1265, 2016. ISSN 03605442. doi: 10.1016/j.energy.2016.08.060. URL http://dx.doi.org/10.1016/j.energy.2016.08.060.

[27] Paul Schott, Johannes Sedlmeir, Nina Strobel, Thomas Weber, Gilbert Fridgen, and Eberhard Abele. A generic data model for describing flexibility in power markets. *Energies*, 12(10):1–29, 2019. ISSN 19961073. doi: 10.3390/en12101893.

[28] Iain Staffell and Stefan Pfenninger. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy*, 114:1224–1239, 2016. ISSN 03605442. doi: 10.1016/j.energy.2016.08.068. URL http://dx.doi.org/10.1016/j.energy.2016.08.068.

[29] Leon Thurner, Alexander Scheidler, Florian Schafer, Jan Hendrik Menke, Julian Dollichon, Friederike Meier, Steffen Meinecke, and Martin Braun. Pandapower - An Open-Source Python Tool for Convenient Modeling, Analysis, and Optimization of Electric Power Systems. *IEEE Transactions on Power Systems*, 33(6):6510–6521, 2018. ISSN 08858950. doi: 10.1109/TPWRS.2018.2829021.

[30] Bart W. Tuinema, Ebrahim Adabi, Patrick K.S. Ayivor, Víctor García Suárez, Lian Liu, Arcadio Perilla, Zameer Ahmad, José Luis Rueda Torres, Mart A.M.M. Van Der Meijden, and Peter Palensky. Modelling of large-sized electrolysers for realtime simulation and study of the possibility of frequency support by electrolysers. *IET Generation, Transmission and Distribution*, 14(10):1985–1992, 2020. ISSN 17518687. doi: 10.1049/iet-gtd.2019.1364.

[31] Andreas Ulbig, Matthias A Bucher, and Göran Andersson. Operational Flexibility of Power Systems. In *Renewable Energy Integration*, pages 201–216. Elsevier, 2017. ISBN 9780128095928. doi: 10.1016/B978-0-12-809592-8.00015-9. URL https://linkinghub.elsevier.com/retrieve/pii/B9780128095928000159.

[32] United Nations. Summary of the Paris Agreement. *United Nations Framework Convention on Climate Change*, pages 27–52, 2015. URL http://bigpicture.unfccc.int/{#}content-the-paris-agreemen.

[33] L. Vanfretti, T. Rabuzin, M. Baudette, and M. Murad. iTesla Power Systems Library (iPSL): A Modelica library for phasor time-domain simulations. *SoftwareX*, 5(September 2007):84–88, 2016. ISSN 23527110. doi: 10.1016/j.softx.2016.05.001. URL http://dx.doi.org/10.1016/j.softx.2016.05.001.

[34] Clara Verhelst, Filip Logist, Jan Van Impe, and Lieve Helsen. Study of the optimal control problem formulation for modulating air-to-water heat pumps connected to a residential floor heating system. *Energy and Buildings*, 45:43–53, 2012. ISSN 03787788. doi: 10.1016/j.enbuild.2011.10.015. URL http://dx.doi.org/10.1016/j.enbuild.2011.10.015.

[35] John Webster and Carsten Bode. Implementation of a Non-Discretized Multiphysics PEM Electrolyzer Model in Modelica. *Proceedings of the 13th International Modelica Conference, Regensburg, Germany, March 4–6, 2019*, 157:833–840, 2019. doi: 10.3384/ecp19157833.

[36] Jens Weibezahn. Data Documentation 92: Electricity, Heat, and Gas Sector Data for Modeling the German System. *DIW Berlin, 2017*, (ISSN 1861-1532), 2017.