1. Welcome to my Master thesis green light presentation. In this project I am investigating the hidden flexibilities provided by industrial power to X considering grid support strategies.
2. I have divided my presentation into five main parts. These are Introduction, methodology modelling , results and conclusion. Let's start with the introduction.
3.

Significant number of RES integrated to the electricity network and more expected to be connected in the future. Highly volatile nature of these generation units introduces a great challenge for grid operators to balance the electricity supply and demand. In order to increase the percentage of RES in generation units, the flexibility of power system must be increased........ 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 industries, such as chemicals, petrochemicals, food, steel and so on; large-scale electrification of industry leads to more sustainable and flexible multi energy systems. However, a technical analysis of MES including their optimal control and available flexibility must be implemented. ……………In the previous projects, PtX models are simplified by single equations with constant or linear relation between the power input and the energy output.

However, in reality, 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 incorrect efficiency characterization of device. …………….Correct efficiency characterization of PtX is crucial to analyze flexibility of power system. Inaccurate efficiency models of PtX may lead to increased transmission losses, higher operational cost or miscalculation of MES capacity ……………..Another important problem is, conventional energy management systems only consider generation side with limited amount of information. However, operation of multi-energy system needs to be coordinated to optimally use the available resources. Therefore, a good combination of Market DR and Physical DR is necessary to use the network optimally. However, 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 PtX owners.

4.

Electrical systems are able to deal with variability and uncertainty in both supply and demand of energy up to certain point, and this is called energy system flexibility. Different flexibility classifications can be found in the literature and flexibility can be quantified in multiple ways depending on the nature of study being conducted. In this project, flexibility is the ability of a component or a collection of components to respond power fluctuations in power systems. Here, I analyze PtX devices, and the flexibility offered by them to support power system. 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, power set-point of PtX can be controlled in order to provide power balance for electrical power system and to store this energy for low power generation times. Figure here shows the power consumption of a flexible load with flexibility parameters. Basically, a flexibility service consists of activation and deactivation periods where ramp up/down characterization is important and holding duration where efficiency characterization of the model is important. In this project, I address the effects during holding duration by means of the correct efficiency characterization of PtX and additional information obtained from detailed models during flexibility analysis is defined as the hidden flexibility of PtX.

5.

The objective of this project is to investigate the impact of model fidelity of PtX in flexibility analysis. Additionally, impact of comprehensive energy management system to optimally control economic flexibility dispatch is investigated. In order to reach this objective, specific characteristics of PowertoGas and PowertoHeat technologies are studied and modelled using OpenModelica. Later, energy management system (EMS) is designed for the optimal deployment of flexibility and co-simulation is used to combine these models. My first research question is……. This one is about MES design and power to X selection. When it comes to electrification of the industry there are so many technologies from various energy domains. Therefore this part explains why I have decided to model PEM electrolyser and Electric Heat pump. My second RQ is……. This one is about modelling of PtX. As I mentioned before, flexibilities provided by PtX can be concealed in the simulation results due to modelling approximations. Therefore I have created different models of the same PtX technology and compared them, in order to investigate modelling of PtX with respect to the requirements of flexibility analysis. My last RQ is…… This one is about agent based hierarchical energy management of MES and co-simulation. Here, I have combined my PtX models with pandapower optimal power flow solver for the energy management of my MES.

6.

So my first problem was to decide which PtX to model and where? Here you see my Multi-energy System. To talk about PowertoGas, hydrogen is one of the most convenient energy carriers because it can be stored at high energy densities for a cheap price and it can be formed into various hydrocarbons that used in variety of sectors. But with respect to fuel-cell models very limited amount of electrolyser models developed for control and flexibility analysis. Therefore I have decided to consider PEM Electrolyser. Another convenient electrification option is power to heat with electric heat pumps. Heat pumps are able to utilize surplus energy from variable RES at high coefficient of performance values and this makes PtH an economical option. Therefore I have decided to model electric heat pump with electrolyser and compare these two PtX options in a MES. Additionally, I have determined the location and the capacity of my RES according to the references for Port of Rotterdam and obtaned the hourly power output of these RES from an online resource.

7.

Energy demand profiles are the scheduled, hourly hydrogen and heat demand of PtG and PtH. They define the operational commitment of PtXs in the industrial area. This data was necessary to determine the minimum active power consumption of PtX. Here, I have used Felten, Baginski, and Weber (2017) model to perform this task based on the local ambient temperature. The benefit of this approach is that it only requires historical ambient temperature data to generate the time-series scheduled energy demand profiles. Here Q_{base}

or H_{base} is the base demand of PtX which occurs above the reference temperature $T_{Reference}$, and Q_{max} is the maximum demand corresponding to the minimum temperature $T_{min.}$ Demand in district heating networks is sensitive to ambient temperature changes. On the other hand, industrial hydrogen demand is expected to have less volatility during operation. As a result, figure here shows the ambient temperature dependency of district heating and industrial hydrogen demand in this study. As you can see, industrial hydrogen load has less variation with respect to varying ambient temperature than district heating load this is because the slope of this linear line, in figure on the right side, is smaller for Power to Gas than Power to Heat. So let's move on to modelling.

8. In order to answer my second RQ I had to create electrolyser models with different considerations. Table here summarizes the features of my Electrolyser models. Model A operates at constant temperature 60 Celcius. On the other hand model B calculates the operational temperature of electrolyser with dynamic thermal sub-model. Both models are semi empirical and have static equations for the electrochemical domain. But thermal submodel has ordinary differential equation which makes the general behavior of the electrolyser system dynamic.

9. Here the difference between both models are explained with equations. Electrochemical, pressure and massflow submodels are same for model A and B. However, for model B, thermal domain is also created with lumped thermal capacitance model. Here, temperature of the electrolyser system is modelled with one equation. The first term on the right side is for heat generated by electrolysis reaction and it depends on cell voltage and current, the second term is for the work contribution of circulation pump and the third one is for the heat removed by cooling system, it has linear relation with the consumed active power. The fourth term on the right side is for the heat lost to ambient, it depends on operation and ambient temperature and the last term comes from enthalpy lost with the products leaving the system, it has empirical equation that depends on temperature. As you can see from the equations adding this dynamic submodel to the system makes the general behavior of the electrolyser dynamic, since each submodel depends on temperature parameter directly or indirectly.

10. Moving to power to heat, this slide summarizes the features of my heat pump models. Figure on the left illustrates the hot water cycle of PtH. With a return temperature equal to ambient, water is pumped to the evaporator of the heat pump. Here assuming constant mass flow rate for circulation pump, the energy output of heat pump is defined by compressor work and coefficient of performance. Basic approach to model electric heat pump is assuming constant COP and no change in temperature, which is model A in this study. However, in reality COP strongly depends on temperature levels of the energy source. Therefore, regression analysis is carried out in order to create a polynomial function of COP depending on the inlet and outlet temperatures. Additionally, COP of a heat pump increases when temperature difference between the inlet and outlet decreases. Therefore, particularly for winter season, heat pump capacity might need to be increased with an auxiliary electric boiler. Here in model C, when the ambient temperature is below 15 celcius,

electric boiler is activated in order to increase the efficiency and heat capacity. So how I calculated this COP equation.

11. Maximum COP that you can reach with a heat pump depends on the choice of refrigerant and the rankine cycle of that refrigerant inside the heat pump. Therefore, Carnot cycle efficiency is calculated using pressure-enthalpy table of Refrigerant R134a. Here the enthalpy at state 1 and state 3 that depends on inlet and outlet temperatures and it is already known from saturated vapor and liquid table. Enthalpy at point two is calculated by linear interpolation of the superheat tables for the refrigerant assuming isentropic compressor work. As a result COP values are calculated for various inlet and outlet temperature conditions and these results are used for curve fitting in order to create fifth order polynomial function of COP that depends on ambient temperature.
12. Here you see the Matlab curve fitting results and the coefficients of fifth order polynomial functions for condenser outlet temperature is equal to 50 and 70 celcius. I have created two different COP equations. This is because, for model C, when the ambient temperature falls below 15 celcius, heat pump output temperature is decreased to 50 Celcius and the rest of the energy is delivered by electric boiler in order to increase supply temperature to 70 Celcius. This means COP equation for 50 celcius is considered when the ambient temperature is below 15 celcius, otherwise COP is calculated assuming heat pump output is at 70 celcius.

13. This slide summarizes my overall PtX models. I have already explained electrolyser and heat pump models. Besides these, Storage model simply calculates the amount of stored energy assuming constant pressure and temperature inside the tank. Static generator model is from iPSL Library and it provides interface with the electrical network. Finally, adjustable power level controller calculates minimum and maximum active power constraints to send higher control level. I will explain this model in detail in the following slides.

14. This slide explains the overall analysis considered in order to answer the research questions. MES analysis is carried out in order to investigate the seasonal weather behaviour in the area and to observe the flexible capacity of MES during a year. In power-to-X analysis efficiency characters of each PtX models compared in order to investigate the model fidelity for accurate device performance characterization. Power system analysis is the flexibility analysis of the MES. It is implemented in order to compare the flexibility potential of both PtX options and to evaluate the optimal energy management strategies of MES. In base case, without any flexibility service, flexible demand of MES is measured and possible holding duration for flexibility service is investigated. In the first case, it is assumed that only one PtX is available for flexibility service. During flexibility service, active power set-point of PtX is directly controlled by higher control level in order to use the available excess RE. Here both PtX options are compared with respect to reduction in flexible demand of MES. Also, hydrogen and heat production of models are compared for the same flexibility service. In the second case, it is assumed that both PtX is available for flexibility service. Therefore, in order to optimally distribute the available surplus power, cost signals coming from PtX agents are also considered at higher control level. I haven't explained the methodology of

case 2 yet, because this part is not related to hidden flexibility but the optimal deployment of flexibility.

15. Therefore let's continue with the optimal deployment of flexibility. The role of higher control level is to minimize the operational costs of MES. For this purpose, a constrained, single objective, economic active power dispatch problem had to be created. A major advantage of pandapower is its capability to calculate optimal power flow (OPF) with cost functions. Therefore, it perfectly fit to create such optimization problem. Linear cost signals are calculated in Modelica, depending on the efficiency of PtX, and sent to Pandapower for OPF. While solving this optimal power flow problem pandapower considers: Bus constraint contains maximum and minimum voltage magnitude, branch constraints contain maximum loading percentage and the most important part of this slide operational power constraints where the active and reactive power generation of generators or loads can be defined as flexibility for the OPF. So this means higher control level which is pandapower has to communicate with the PtX agents and learn the adjustable power level which is Pmin and Pmax in order to calculate the optimum operating point. Optimal power flow solver calculates the exact operation point for the next time step considering cost signals within the available range defined by the physical situation of the agents. Therefore, I enhanced the current OPF of Pandapower by adding my models and controlling these boundaries depending on the physical condition of agents. So this P min and Pmax boundaries…

16. … are controlled by the adjustable power level controller of PtX. In a normal operation where there is available space in the storage, minimum active power is controlled such that scheduled energy demand is always balanced by PtX hydrogen or heat production. However, when the storage is full, PtX is forced to work under 0.1 pu until storage energy level is back to acceptable levels. And when the storage energy is below emergency level, PtX is forced to work at 1 pu until it reaches normal operating conditions. Maximum active power value is nominal power during normal operation, however it strictly follows minimum active power if storage is in another state.

17. Linear Euro per MWh cost signal that sent to higher control level for optimal power flow is explained in this slide. This is the c1 coefficient here in this cost function. Levelized cost signals were necessary to analyze the operational cost savings from the optimal deployment of flexibility. The values you see in this table are taken from references. Here, the important part is, in the levelized cost of energy equation instead of having energy produced over lifetime on denominator I have used time instant efficiencies of models. This way cost of energy production of each PtX is compared with respect to their varying efficiencies for the most economic operation.

18. Here is my detailed flowchart for co-simulation. At t=0 optimal power flow solver in pandapower calculates the optimum operation point with the objective of minimizing operational cost. After that the results of the OPF are sent to MES agents. Here PtX models simulate until the next exchange time and send out the adjustable power level and cost binding information to higher control level for the next OPF calculation.

19. Having explained my models and flowchart, I had to combine all models in one environment in order to implement flexibility analysis. Therefore, co-simulation was essential for this study as a result of multi-domain nature of MES and hierarchical control. Energysim allowed me to combine all models and implement this complex simulation in a relatively simple way by exchanging only necessary variables. Figure here shows the macro step time that optimal power flow solver and Modelica agents exchange information, and micro step time that the agents simulate in Modelica.

20. Let's continue with results part. MES analysis is carried out in order to understand the flexible capacity of considered power system. Blue line is the sum of the power output for WF and PV farm and the red line is the sum of active power consumption of model B of each PtX. You will see 8 vertical dashed lines in the following figures as well because I have divided 2019 into 8 sections of 45 days and picked one day from the middle of each section. As a result, I have considered 8 days that represents the year of 2019. If you look at this figure, in this location energy can be stored during summer season and this stored energy can be used during winter or spring. Longer sun hours during summer not only increases the magnitude of RE but also increases the duration of Excess RE time therefore summer season provides opportunity for longer flexibility services. Seventh of February shows that Extreme wind conditions during winter can also provide opportunity for shifting demand. But it should be considered for shorter flexibility services due to smaller time duration of excess RE. So using this figure I have decided to consider Seventh of February for 24 hours power system analysis. Power system analysis is 24 hours to have convenient co-simulation compile time with enough details on results.

21. Here temperature evolutions of models and efficiencies are compared for the same energy demand profiles. The effects of temperature evolutions on efficiency curves can be observed in the figures. For electrolyser model A temperature is constant at 60 Celcius and model B it varies between 52 to 65 Celcius. With respect to temperature deviation, maximum efficiency difference is 0.6% which is not very significant. But, thermal submodel is necessary to analyse the required capacity of auxiliaries. If the cooling capacity of the system would assumed to be less than necessary than this would lead to larger temperature differences and therefore bigger variations in efficiency results. For heat pump model A, COP is calculated from daily average temperature therefore it is constant during the day. For model B and C hourly measured ambient temperature is used for COP calculations. Maximum COP difference between model A and B is 1.4 and model B and C is 3. Results show that temperature considerations have significant effect on COP characterization and auxiliary boilers are able to improve efficiency of a heat pump significantly.

22. Here, active power consumption of models is compared. Maximum power consumption difference between power-to-gas models is 0.4 MW which is considerably small for 50 MW capacity. However this number is proportional to the capacity of PtX, as the capacity of the system increase this difference would also increase to more significant numbers. Maximum

power consumption difference between power to heat model A and B is 1.4 MW and model B and C is 5 MW. Those are significant numbers for 50 MW electric heat pump system. Therefore, COP of a heat pump can be assumed constant if inlet and outlet temperatures remain stable during operation. Otherwise, COP must be calculated with respect to temperature levels of the energy source.

23. This slide shows the results of power system analysis case1. The figure above compares the flexible demand of MES when only one of the PtX is available for flexibility service. Here during excess RE, active power set-point of available PtX is controlled such that the amount of excess RE is reduced and the flexible demand curve is approached closer to zero. Since industrial demand is more stable, it offers less flexibility. Therefore the maximum difference between base case and PtG case is 2MW. On the other hand, PtH offers more flexibility due to higher rate of change of heat demand. Maximum difference between the base case and PtH case is 10MW. Figures below compare the hydrogen and heat production of PtG and PtH models. Maximum hydrogen output difference between model A and B is 0.032 meter cube per second. Even though this is a small difference it can be important as the scale of the system increases and it may lead to miscalculation of the required hydrogen storage capacity. For PtH, maximum difference between model A and B is 0.20 m3/s and between model B and C is 0.96 m3/s. The differences are more significant for PtH and model C proves that the auxiliary electric boiler significantly improves the heat pump production capacity during flexibility service.

24. This slide shows the results of power system analysis case2. Figure above shows the levelized cost signals for PtG and PtH. Active power dispatch of available flexibility considered from 10:00 to 16:00. In this time duration, from 10:00 to 10:15, PtG is cheaper than PtH. However, between 10:15 - 16:00 Power-to-gas is more expensive. Figure below presents the resulting active power consumption of PtXs and the amount of excess RE. Flexibility of MES is able to compensate excess RE between 10:00 to 10:45. Therefore, optimal deployment of flexibility is critical for this duration. However, after 45 minutes the amount of surplus power is larger than the total flexible capacity of available PtXs; therefore, both PtX starts to operate at 50MW from 11:00 to 15:45. Between 15:45 and 16:00, active power output of PV farm drops to zero; therefore, flexible capacity of PtXs is again able to compensate excess RE again, without operating both PtX options at nominal power. Table here compares the active power dispatch results of optimal deployment with two different flexibility dispatch strategies in order to see the benefits of optimization. In 50% equal priority scenario, that is the third and fourth column, it is assumed that, available excess RE is always shared equally between both PtXs. In 100% PtG priority scenario, that is the fifth and sixth column, it is assumed that PtG has the highest priority to use surplus power at all times. Therefore, maximum available power is always used for PtG. According to this table and cost signals, optimal deployment of flexibility is able to save 2.75 euro with respect to 100% PtG priority and 0.99 euro with respect to 50% equal priority scenario. Results show that optimal energy management of MES is able to provide significant cost savings annually.

25. To conclude, this thesis has provided a deeper insight into multi-energy system flexibility. This study has shown operating temperature has substantial influence on the efficiency of PtX and the flexibility analysis requires correct efficiency characterization. Therefore, detailed thermal models are necessary to accurately represent the efficiency of PtX otherwise flexibility analysis may result with defective outcomes on active power consumption or energy production output. The second major finding was that the agent based hierarchical energy management is able to optimally operate multi-energy system. This approach reveals a multi-layer structure for the energy management that enables the implementation of local control objectives for the agents individually and a global objective for MES that constrained by the information coming from agents. Lastly, the relevance of co-simulation and Energysim for flexibility analysis is clearly supported by the current methodology. Co-simulation is especially advantageous to represent the multi energy domain nature of MES and to use sophisticated energy management software tools. Also, Energysim facilitates this whole co-simulation setup process. These findings will be of interest to grid operators, industrial PtX owners and researchers of the subject.