

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 four main parts. Those are Introduction, methodology modelling and results. Let's start with the introduction.

3.

Significant number of RES are integrated to the electricity network and more expected to be connected in the future. Highly volatile nature of these generation units introduce 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.....One of the most promising ways to increase energy system flexibility is through industrial Power-to-X. Because industrial processes are 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 leads to more sustainable industrial complex and provides the necessary flexibility in new generation energy systems.....In the previous projects, during modelling of PtX, constant or linear relation between the power input and energy output is assumed in order to reduce model complexity. However, in reality, operational performance of PtX such as electrolyser or electric heat pump strongly depends on physical conditions at that moment. During flexibility analysis, this critical modelling assumption leads to incorrect efficiency characters for PtX and losing some of the essential dynamics on simulation results.....Correct efficiency characterization is crucial to understand the flexibility and inaccurate flexibility analysis of PtX may lead to increased transmission losses, higher operational costs or miscalculation of system capacity.....Another important problem is, conventional energy management systems only consider generation side with surplus and excess energy information. However, the planning and operation of multi-energy system needs to be coordinated from both generation and demand side to make optimal use of the available resources. This means, in order to understand MES phenomena, complex analysis must be implemented and this brings a trade-off between model complexity and simulation time. Even though, a good combination of Market DR (price signals) and Physical DR is necessary to run a network optimal. Existing energy management models for MES do not consider energy cost of production (€/MWh). This results with unnecessary trading of electricity and increase in operational cost.

4.

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. Different flexibility metrics and classifications can be found in the literature and various approaches can be taken while defining flexibility metrics according to the needs of analysis. In this project flexibility defined as the ability of a component or a collection of components to response power fluctuations in power systems. From an operational perspective, P2X flexibility becomes relevant in situations where there is excess RE relative to demand in the power system and, therefore, electricity prices are low. In order to compare flexibility potential, key figures that characterize flexibility must be considered. This figure here explains those characteristic parameters of flexibility. 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. Finally my flexibility terms in this project are Hidden flexibility is the effect of modelling simplifications on flexible load (PtX) performance. Here the simplification I have considered is the temperature dependence of PtX. 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. Here besides Physical DR and grid parameters, I also considered levelized cost signals in order to find the optimum operation point of MES.

5.

The objective of this project is to investigate the hidden flexibilities provided by different PtX models, with comprehensive energy management approach. In order to reach this objective, Modelica agents for power-to-gas and power-to-heat are created and combined with Pandapower power flow solver in Energysim. 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 assumptions of PtX. As I mentioned, 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 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 Co-simulation and hierarchical agent based energy management of MES. Here, I have combined my Modelica agents with a power flow solver for energy management of MES.

6.

So my first problem was to decide which PtX to model and Where? Here you see my Multi-energy System. Hydrogen is one of the most convenient energy carriers because it can be stored at high energy densities and it can be transported with existing gas networks. But with respect to fuel-cell models very limited amount of electrolyser models are developed for control and flexibility analysis. Therefore I have decided to consider PEM Electrolyser. Another convenient option is using excess renewable energy in district heating networks and usually electric heat pumps combined with auxiliary electric boilers are recommended for high efficiency. Therefore I have decided to model electric heat pump as well and compare these two PtX options in a MES. Additionally, I have determined the location and the capacity of my RES according to articles about Port of Rotterdam and calculated the hourly power output of these RES from Renewables.ninja.

7.

In order to characterize storage flexibility I had to create timeseries scheduled energy demand profiles. Those are the discharge rate of storage unit in each PtX model. As you can imagine, hourly timeseries heat or hydrogen demand data for industrial networks is rarely publicly available. Therefore I have used the model of Felten, Baginski, and Weber (2017) model to perform this task based on the local temperature. This equation uses the ambient

temperature data to determine the share of the dependency of a demand on temperature. Here  $Q_0$  is the base demand which occurs at temperatures above the reference temperature  $T_R$ ,  $Q_{max}$  is the maximum heat demand corresponding to the minimum temperature  $T_{min}$ . District heating networks is expected to be very sensitive to ambient temperature changes. On the other hand, industrial hydrogen demand is expected to be less dependent on the ambient temperature. Therefore the slope of this linear line is bigger for Power to Heat than Power to Gas. Figure here shows the ambient temperature dependency of district heating and industrial hydrogen demand. As you can see, industrial load has less variation with respect to varying ambient temperature than district heating load.

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 submodel. Both models are semi empirical and have static equations for the electrochemical submodel. 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 both model. However, for model B, thermal domain is also created with lumped thermal capacitance model. Temperature of the electrolyser system is simplified 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, second one for the work contribution of circulation pump, third one for the heat removed by cooling system, these two has linear relation with the consumed active power. Fourth one is for the heat lost to ambient it depends on operation and ambient temperature and the last one 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 next slide, 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 my case. 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. How I calculated this equation is in the next slide. Additionally, COP increases when temperature difference between the inlet and outlet of the heat pump decreases. Therefore, especially during winter when the weather is cold, heat pump capacity might need to be increased with an auxiliary electric boiler and this is

usually recommended due to significant increase in efficiency of the heat pump. 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. COP of a heat pump depends on the choice of refrigerant and the rankine cycle of that refrigerant inside the heat pump. Therefore, pressure-enthalpy table of Refrigerant R134a which is the one most commonly used one in sustainable applications is considered for the COP calculations. Here the enthalpy at state 1 and state 3 that depends on inlet and outlet temperatures is already known from saturated vapor and liquid table. Enthalpy at point two is calculated by linear interpolation of the superheat tables for R-134a assuming isentropic compressor work. As a result COP values are calculated for various inlet and outlet temperature conditions and these results are used to create fifth order polynomial function of COP that depends on ambient and output temperature.
12. Here you see the results of Matlab curve fitting and the coefficients of fifth order polynomial function. As you can see I have created two different COP equations. This is because, for model C, when the ambient temperature drops below 15 celcius, heat pump output temperature is switched to 50 Celcius and the rest of the energy is supplied by electric boiler in order to increase supply temperature to 70 Celcius.
13. These figures here summarize my overall PtX models. I have already explained electrolyser and heat pump. Besides these, Storage model simply calculates the available energy storage level by comparing charging and discharging rate. 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 pandapower but I will explain this model in detail in the next slides.
14. Here is my analysis. I have already carried out MES analysis and PtX model comparison and I will show these results today. MES analysis is basically to understand the actual capacity of RES in a specific area and define excess RE times for energy storage. In power-to-X model comparison I have compared the performance of each model in order to investigate the effect of physical conditions on model performance. Next week I will carry out the power system analysis and have my final results. I have considered Power system analysis in order to analyse the effect of models in a MES with external grid and to investigate the optimal energy management strategies of MES. In base case, the amount of curtailed RE is measured. In the first case, models are compared for a given flexibility service and hidden flexibility is quantified by the energy output of PtX that depends on the efficiency characterization of the model. In the second case, in order to investigate the optimal deployment of flexibility I have considered the Market DR and Physical DR at the same time for the hierarchical agent based energy management of MES. I haven't explained this part yet in order to clearly divide it from the hidden flexibility part. Because this part is related to optimal deployment of flexibility.

15. So let's continue with the optimal deployment of flexibility. I have used pandapower for the energy management of MES. Pandapower optimal power flow solver has objective function to minimize operational cost. Therefore it enabled me to consider cost signals at higher control level for the optimal operation of MES. Linear cost signals are calculated depending on the efficiency of device in Modelica and sent to Pandapower. I will explain this in the next slides. 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 modelica agents and learn the adjustable power level which is  $P_{min}$  and  $P_{max}$  in order to calculate the optimum operating point within this range. 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. In other words, I enhanced the current OPF of Pandapower by adding my OM agents and controlling these boundaries depending on the physical situation of agents. So this  $P_{min}$  and  $P_{max}$  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 generation. However, when there is no available space in the storage, PtX is forced to work under 10% load until storage energy level is lower than maximum. And when the storage energy level is below emergency level, PtX is forced to work at nominal power until it reaches normal operation 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 signals that sent to pandapower are explained in this slide. The values you see in this table are taken from a reference paper and carbon emission factors are decided considering green electrolysis pathways and electric heat pump district heating pathways. What is important here, in the levelized cost of energy calculation 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 for the optimal energy management of MES with respect to their efficiencies.
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 calculations.
19. Having explained my models and flowchart, I had to combine all models in one environment in order to implement flexibility analysis. Energysim allowed me to combine all models and implement this complex simulation in a relatively simple way by only using necessary i/o.

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.

20. Finally 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 of 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. 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 the figure, in this area 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 excess RE but also increases the duration of Excess RE time therefore summer season provides opportunity for longer flexibility services. 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 during for power system analysis I will only consider one day simulations with smaller step size.
21. Here temperature evolutions of models and efficiencies are compared for the same energy demand profiles. The effects of temperature evaluations 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 temperature is used for COP calculations. Maximum COP difference between model A and B is 1.4 and model B and C is 3. For model C, besides COP improvement, It is also observed that COP rate of change increases when the heat pump output temperature is switched to 50 Celcius. Results show that temperature considerations have significant effect on COP characterization and auxiliary boilers are able to improve efficiency of a heat pump considerably.
22. As a step towards power system analysis, active power consumption of models is compared. Maximum power consumption difference between power to gas models is 0.4 MW for 50 MW electrolyser system. Which is not very significant. 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 9 MW and model B and C is 19 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.