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INTEGRATING HIGH RENEWABLE SHARE INTO TODAYS GAS TURBINE POWER PLANT ENERGY SYSTEMS

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ABSTRACT

This paper presents three case studies that integrate renewable power into existing energy infrastructures. The first case study explains how to reduce curtailed green electricity. Due to high intermittency of renewable power supply, large fluctuations of market electricity prices exist and can be used advantageously to generate new revenue streams for plant operators. The second case study shows the strength of combining hydrogen, battery and storage in autarkic decarbonized energy systems via sector coupling. The energy usage factor of the electricity-to-hydrogen-to-electricity chain increases from 30% to 80%. The third case study describes the first-ever demonstration project of a fully integrated Power-to-H_2-to-Power industrial scale installation in a co-generation power plant including an advanced high-hydrogen DLE gas turbine.

Keywords: Power-to-X; hydrogen; energy systems

INTRODUCTION

In a power system with high renewable share as it is considered by most European countries, reliability and stable supply of energy (electricity and heat) becomes increasingly difficult. While Power-to-X solutions as summarized for Europe by Wulf et al. (2018) provide an answer to surplus renewable energy storage and sector coupling, it does not solve the problem of reliable power supply. Utilizing fossil fuels for the past century led to a power system built on conventional plants which are best suitable to serve as this backbone of power security. Curtailment of renewables and "must run" of conventional plants interferes to a certain extend. In today's European energy system this leads to an undesirable situation for the society to pay for not delivered green electricity and the operation of power plants at uneconomic electricity prices. Conventional power plants are increasingly shifting their role to providing fluctuating power to meet predictable and unpredictable short-notice demand peaks and to control and stabilize the grid. To ensure continuous power supply, either the reliable fossil fuel power capacity will have to be kept at a level of maximum demand, or the renewable power generation will have to exceed the power demand whenever possible. This excess energy could be converted and stored to other energy forms for future short term (~minutes/hours) and long-term (~days/weeks) use. Although different forms of energy storage are interchangeable, electrochemical (batteries) storage is more suitable for short term and chemical (hydrogen) storage for long-term. Ban et al. (2019) have presented how power-to-hydrogen integrated into a day-ahead security constrained unit offers the potential to reduce wind curtailments. This paper describes and discusses the integration of hydrogen generation, storage, supply and usage in existing energy infrastructures on a system-wide and local level. Special focus is also set on the economic implications.

The structure of the paper is as follows: First we will discuss revenue stream driven implementation of Power-to-X into an existing energy system, secondly, we will present the integration into an existing, but autarkic setup utilizing sector coupling and at last we will describe the first-ever demonstration project of a fully integrated Power-to-H2-to-Power industrial scale installation in a co-generation power plant application.

NOMENCLATURE

C_X – Cost Power-to-X plant
C_{CO2} – Cost for CO2 certificates
C_{start} – Cost for start
C_{OM} – variable operation and maintenance costs
C_{op} – operational costs

C_{Xop} – operational costs, Power-to-X plant
CCPP – Combine Cycle Power Plant
DLE – Dry Low Emissions
EEX - European Energy Exchange
P_{PPref} – Profit reference plant
P_X – Profit Power-to-X plant
R_{el} – Revenue from electricity
R_{fr} – Revenue from frequency response
R_X - R_X is the revenue from Methanol
R_{Xel} – Revenue from electricity, Power-to-X plant
R_{Xfr} – Revenue from frequency response, Power-to-X plant
WLE – Wet low emissions

CASE STUDY 1: POWER-TO-X FOR FOSSIL POWER PLANTS

Consider a model of an energy system, that is based on today's conventional system setup. It consists of a conventional power plant and a renewable power as the reference baseline. Specifically, for our model as shown in **FIGURE 1**: A conventional power block is a CO_2 emitting power plant in combined cycle or co-generation mode, which can either run on fossil fuels like natural gas, diesel, coal or biofuels like biogas or wood chips.
The revenues generated with the plant are based on sold electricity on the volatile spot market (with a price per MWh) and the product generated (with a price ton of product). The product can be e.g. hydrogen, methanol or ammonia. Furthermore, process steam and district heat can be sold (with a price work per MWh).
This fossil plant is connected to the same power system as the renewable power. Revenues generated with the plant are based on sold electricity.

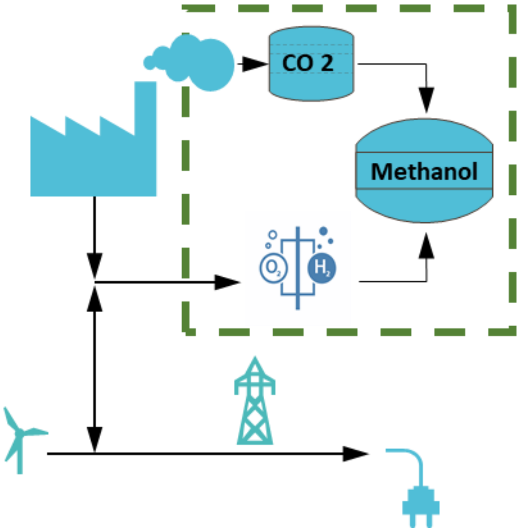

Figure 1: Setup of evaluated power plant with and without methanol plant extension

Due to the volatile behavior of the renewables and the limitations of the electric grid this leads to steep load gradients, necessary shutdowns of the conventional plants that result in reduced lifetime and start costs.

In the Power-to-X setup, shown within the green dashed line in **FIGURE 1**, the power plant is extended with a carbon capture plant, an electrolyser and an e-fuel generation facility, e.g. a methanol synthesis plant. To optimize the feed into the methanol plant, storage tanks for hydrogen and CO_2 are part of the plant, but not shown in the figure for simplicity. Optionally, the plant can be extended with a battery for very fast load shedding and black start capability.

Additional revenues are possible from hydrogen generated using the electrolyser, from the captured CO_2 or from e-fuels (when combining both hydrogen and CO_2 in the methanol synthesis plant). Also improved grid services are possible with the extended and more flexible power plant. For simplicity, the economic analysis for this case, assumes methanol as the end-product.

Profit Calculation

The powerplant operator's profit in the reference case with only the power plant is given for each hour by:

$$P_{PPref} = R_{el} + R_{fr} + C_{op} + C_{start} + C_{CO_2} \tag{1}$$

Where P_{PPref} is the reference plant profit, R_{el} is the revenue from electricity, R_{fr} the revenue from frequency response services, C_{op} are the operational costs that mainly depend on fuel costs as well as operation and maintenance costs, C_{CO2} are the costs for CO_2 certificates. For simplicity the efficiency is averaged for all operating points when estimating the costs for CO_2. C_{start} are the costs starting the power plant. In the model, costs have negative values.

To enable frequency response services, it is assumed, that the power plant's output is throttled by a certain degree of output (kW).

The profit from operating the new power plant set-up including the methanol production facility is given as follows:

$$P_X = R_X + R_{Xel} + R_{Xfr} + C_{Xop} + C_{start} + C_{CO_2} \tag{2}$$

Where R_X is the revenue from selling the methanol (hydrogen), R_{Xel} is the revenue from electric power in case of negative electricity prices and R_{Xfr} is the revenue from frequency response services. C_{Xop} are the operating expenses for the extended plant.

Operation modes of the extended power plant

The economic analysis with above profit calculations derived several potential operational modes for the

extended Power-to-X plant using 2018 as the reference year. Here, for each quarter of an hour in 2018 the margin is determined by comparing the power plant operation cost (dominated by the fuel price per MWh) with the electricity price at the stock market. If this situation is profitable, then the plant is operated at maximum power. If the situation is unprofitable, the plant will be switched off or operated at minimum load. Due to the adaption of power-to-x, for the condition of unprofitable electricity prices either the losses are reduced when the plant operates at minimum load or electricity is drawn from the grid at low/negative prices and revenue can be created by selling the product methanol.
Based on the evaluation of electricity price, operating costs and methanol production economics, several outcomes are possible:

Case A

If the costs for the power plant operation are higher than the price achievable selling power, the power plant is shut down or operated at minimal load. In both cases the electrolyser operates to generate hydrogen reducing the power output of the plant or using electricity from the grid. The electrolyser in the model is assumed to be suitable for intermittent operation, including very short operation times and high loading and de-loading cycles, which is the case for a PEM (Proton exchange membrane) electrolyser, as summarized by Shiva Kumar and Himabindu (2019).

In this case the non-profitable power sold to the grid is reduced or electricity is bought from the grid. Buying electricity will make sense when the market price falls below the profitability threshold of the hydrogen/methanol production. Frequency response with the power-to-X plant is still possible at low or even negative plant load.

In summary, for case A when non-profitable or even negative market electricity prices occur, the total profit of the Power-to-X plant will be higher than the reference plant, as the un-profitability is reduced, i.e., $P_X > P_{PPref}$.

Case B

It is assumed that no revenue can be generated from selling electricity to the grid during periods when the reference power plant starts-up to meet high revenue demand or the price dips under the threshold of profitability. This assumption is reasonable, as the power plant needs a certain time to reach full load. Also, operators usually do not sell electricity the first minutes during start-up, as it is difficult to predict the exact amount of electricity generated. However, in an integrated methanol plant, this electricity can be used for hydrogen generation and methanol production. Therefore, for this period the revenue from the extended plant is higher than the reference plant, i.e., $R_X > R_{PPref}$.

Case C

In case the operational cost is lower than the electricity market price, hydrogen production is paused and all electricity from the power plant is sold to the market to maximize the profit. Here the reference plant profit is higher than the P-to-X-plant profit, P_ref > P_X.

Business Case Evaluation

All cases and their implications are summarized in table 1:

Table 1: Summary of cases

Case	Logic	Profit comparison
A	Unprofitable or negative electricity prices	$P_X > P_{PPref}$
B	Power plant start/operation during unprofitable electricity price dips, with X-production in operation	$P_X > P_{PPref}$
C	Profitable electricity prices	$P_X < P_{PPref}$

The cases for which the profit from the Power-to-X plant is higher than from the reference plant are tied to low to negative electricity prices. These cases occur in the current market mainly, due to excess of energy production, often caused by the priority right of renewables.
There are also periods, when high market electricity prices are present, during peak demand, or low capacity due to bad weather. Those peaks are specifically interesting for gas power plant operators, as gas turbines due to their high flexibility can serve those peaks and generate profit.
Next, the overall economic viability of the extended Power-to-X power plant was evaluated. This depends on the accumulated profits of each of the quarter-hour's periods utilizing the above-described profit calculations considering also the additional CAPEX needed to build the enhanced Power-to-X plant. The additional operational expenses were already included in the calculations.
The overall revenue of the power plant was calculated as described in quarter-hour intervals for the year 2018. The electricity price and the power demand of historical market data from the EEX spot market were used as input variable. Potential regulative or grid charges were not considered in these calculations.

Calculation example CCPP with methanol synthesis

Based on	CCPP 435MW
average efficiency	37%
starts per year	80
Methanol plant	
Electrolysis	17.5 MW
Carbon capture	2.5 t/h
Synthesis	1.7 t/h

Average el. production price	50.3 €/MWh
El. revenue according EEX	1/4h values 2018
CO_2 Price	25 €/t
Methanol price	400 €/t

Main Results for Power-to-X plant case study

Running a calculation scenario comparing a conventional plant with and without methanol production according to cases A to C with the boundary conditions described above provided following results:
Fuel cost (operating hours) and number of starts are kept constant. The CO_2 saving by capturing and binding it in the methanol production sums up to 1,5% that could account for 0.3 Mio € saving in CO_2 certificates. The electrical power revenue is reduced by 2.3 Mio €, however, the additional revenue stream for the methanol sums up to 3.3 Mio €. The frequency response revenue rises by 0.8 Mio € due to the advantage that even at minimum load the frequency response can be conducted with the electrolysis.

FIGURE 2 shows a graphical comparison between the variants discussed above. It is ordered according to the electricity prices EEX 2018 (blue line) and shows the profit of both variants. The orange dotted line shows the delta in profit of both variants. It is evident that the advantage of the proposed system is most effective during very low and negative electricity prices.

In summary, the advantage of the plant with Power-to-X leads in this analysis to an additional income of 2.1 Mio €/year. Considering that the minimum capital expenditure for a methanol plant including electrolysis and carbon capture is about 2,000 €/kW, it is currently hard to get a payback of the investment in a tolerable time. However, the model is sensitive to many factors that may change favorably in the future. One important boundary condition is the legislation, that is set to increase renewable share in the energy system. For example, the German EEG-surcharge can significantly increase the price for the electricity that is used for the electrolysis. This, as a result, can hinder to install such energy storage plants that are determined to enable the energy transition by enabling a higher utilization of CO_2-free energy carriers.
Technically, this analysis can provide input for renewable energy carrier solutions for the challenging requirements of an energy transition to a CO_2 free future.

CASE STUDY 2: CO_2 FREE POWER GENERATION PLANT

The ultimate target is to decarbonize the power generation and to reach the climate targets as discussed in the United Nations Framework Convention on Climate Change, in an effort to prevent climate change. This second case study – the "CO_2-free power generation plant" – demonstrates how such a plant is designed with a Siemens Energy internal software to reduce total cost of ownership.

Setup of the System

The sustainable transformation of the energy supply system requires that an increasing share of renewables by PV and wind serves the energy demand. Such power supply does not follow the demand, as we are familiar from the current conventional power generation of fossil

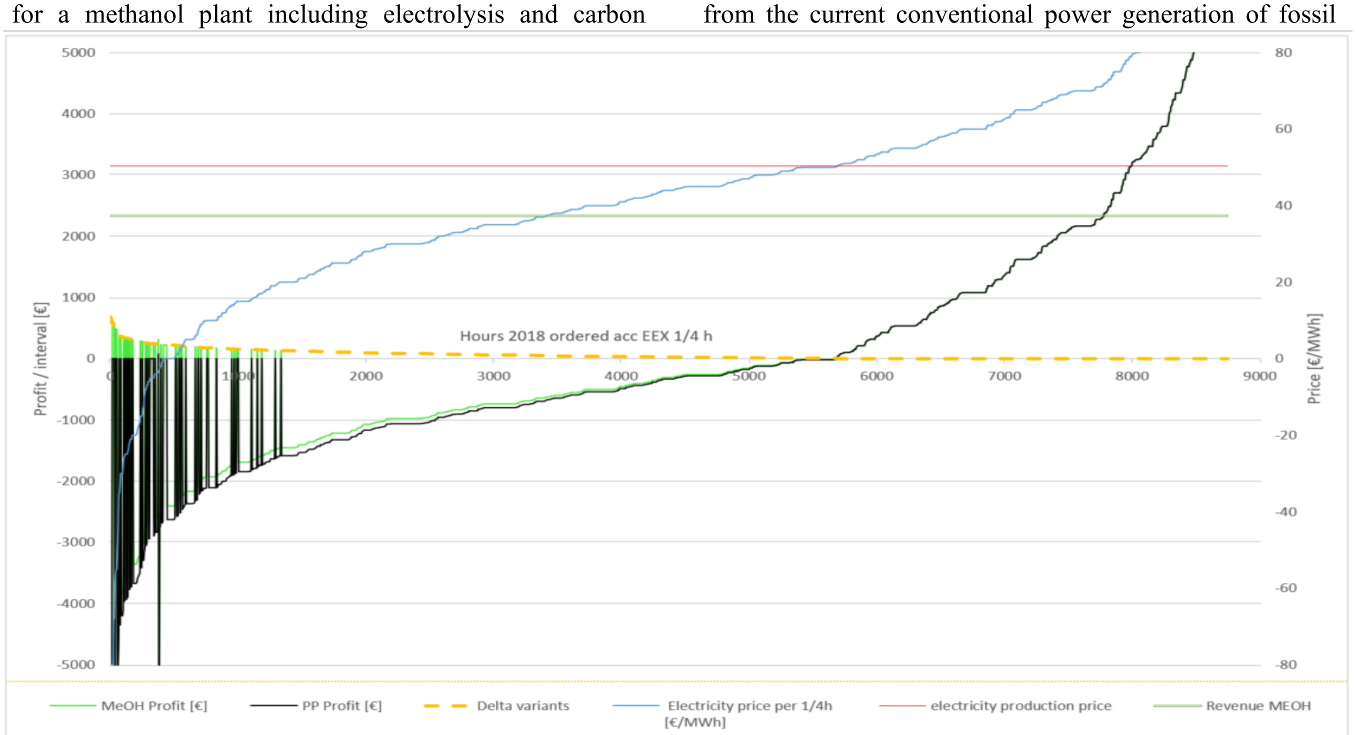

Figure 2: Comparison of profit for standard power plant vs. power-to-x power plant

power plants, but depends on local not plannable changes, such as clouds causing shading and doldrums. Hence, power supply becomes fluctuating as well as the demand side, which could be optimized by digitalization and adjustments in the demand for instance, by stopping certain machines in factories. However, flexibilization technologies will have a more important role in future energy systems like energy storage, transformation of electricity to other energy forms, as well as consuming over capacities in other sectors and demand-side-management. Thus, there will be an interplay of various technologies to ensure security of energy supply, as shown in **FIGURE 3**.

The target of this use case is to apply above concept to ensure the security of supply of a university campus with electricity and heat demand. Such energy supply system is fully based on renewable energy from wind and sun thus provides CO2-free power. Ideally, such renewable energy is used directly by the consumers – here indicated by the grid. Excess energy could be stored in a battery or via electrolysis into hydrogen. On the one hand, the battery technology is optimal for short term storage. On the other hand, hydrogen storage comes at lower specific cost with respect to the amount of energy stored (per kWh) than battery storage, thus is superior for long-term storage by using simple gas tanks, pipelines, caverns or depleted gas fields. The re-electrification is realized via a combined cycle power plant in a combined heat and power cycle. Thus, leveraging the generated heat to serve a heat demand via district heating networks so that the energy usage rate from electricity-to-hydrogen and back to electricity and heat is significantly higher than the pure re-electrification efficiency. Such energy usage rate is further increased by using the heat generated by the electrolysis process to serve the heat demand. This requires the use of a high-temperature heat pump to increase the temperature level to meet the demand requirements. A heat storage adds the flexibility to serve heat demand considering a potential time shift between heat generation and heat demand. An electric heating device is added to the system to cover peak heat loads, which occur only for a few hours and could also be generated, when excess electricity is available, or electricity has a low price.

In this case study, the main focus is on the security of supply of the university with green electricity and heat, but as shown in **FIGURE 3** further options for sector coupling like serving energy to the mobility sector in form of electricity for battery-powered vehicles or hydrogen for hydrogen-powered vehicles as well as to industry demands is possible.

The main challenge is to design the energy system by defining the energy transformation and storage technologies as well as the sizing of those. Only an efficient and cost-effective system would allow to realize such CO_2-free power plant, which requires mathematical optimization. The main input parameters for the simulation are:

1. Location and operation specific data like climate data, space for renewables as well as demand load profiles for electricity and heat

2. Technology data such as selection of theoretical applicable technologies, pre-selection of technologies and the expected sizes, physical models of the technologies, CAPEX and OPEX cost, technical limitations like load ramps and part load behavior

The optimization considers an hourly resolution of a complete reference year including short term and seasonal

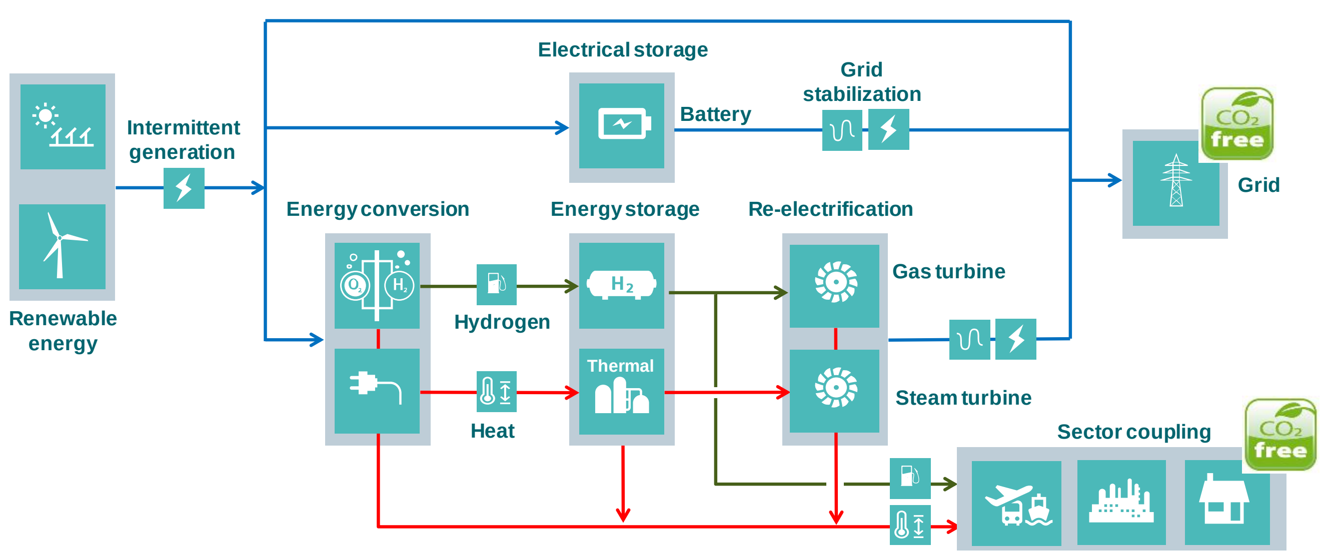

Figure 3: Basic concept for CO_2-free power supply of electricity, heat and other sector coupling applications

fluctuations in supply and demand. The optimization target is the reduction of life cycle cost, the sum of capital and operational cost. An important boundary condition is the limitation of the CO_2-emissions to zero. An alternative is to allow CO_2-emissions and with it e.g. natural gas fired power plants but to penalize the CO_2 emissions with a CO_2 tax thus leading to a solution considering the CO_2 cost.

The result of such an energy system design is customized to the specific application and location as well as features the technology selection and sizing such as the electrolyser size or storage sizes. Additionally, the CAPEX and OPEX costs are determined as well as an optimized operational scheme for the various technologies in an hourly resolution, for example storage loading g as well as operational times of the various technologies.

The used electricity and heat demand profile for the university campus are shown in **FIGURE 4** and represent an annual electricity demand of 50 GWh and a yearly heat demand of 30 GWh.

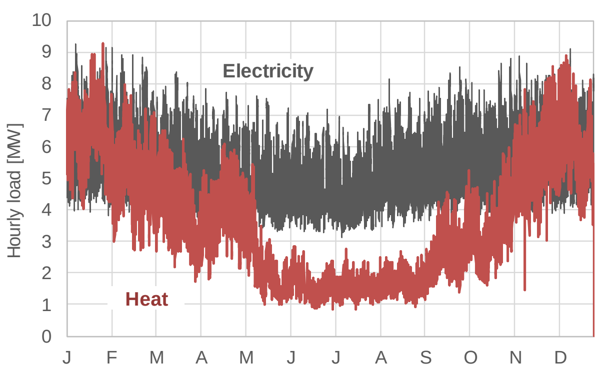

Figure 4: Electricity and heat demand profile of the university campus

For the following components typical technology and cost parameters are used for the initial simulation and are in a second iteration updated with the parameters of specific products such as the Siemens Energy Silyzer 200 electrolyser:

- Wind energy
- Photovoltaic
- Water-Electrolysis
- Gas turbine (operation with natural gas and hydrogen)
- HRSG
- High temperature heat pump (Using the heat generated by the electrolysis or other waste heat e.g. due to the HRSG
- Electric heater
- Battery
- Hot water storage
- Hydrogen storage

Two cost optimized scenarios have been calculated:

- A reference scenario, which allows CO2 emissions.
- A futuristic scenario, which does not allow any CO_2 emission.

Hence, the futuristic scenario resulted in a higher life cycle cost considering today's CO_2 prices.

Technical Evaluation

The results for both scenarios of the energy system design are summarized in **TABLE 2**.

Table 2: Results of the energy system for a fossil and CO_2-free scenario

	Reference scenario	Futuristic scenario
CO_2 emissions	~20.000 t p.a.	none
Wind energy (MW)	6	31
Photovoltaic (MW)	6	30
PEM Electrolysis (MW)	-	10
Gas turbine (MW)	8 (natural gas)	8 (hydrogen)
Steam turbine (MW)	-	-
HT-Heat pump (MW)	-	5
Electric heater (MW)	2	10
Li-Io Battery (MWh)	5	60
Heat storage (MWh)	50	350
Hydrogen tank (MWh)	-	1850

The futuristic scenario without CO_2 emission is more affected by the local weather conditions, which are not constant for different years but have been taken for one reference year. Hence, for the real weather conditions varying from year to year such sensitivity would need to be considered. However, we believe that the presented results give a reasonable indication on the impact of the technology selection and sizing for the two scenarios.

The futuristic scenario requires significantly increased capacity of renewables compared to the reference scenario, as not only the direct consumption needs to be served, but also excess energy is needed for the hydrogen generation for later re-electrification as well as to serve the heat demand due to the various heat generating technologies. Also, the storage capacities are significantly increased, as the natural gas from the pipeline is considered dispatchable so that all storage needs are covered.

The energy balance of the futuristic scenario considers the generation of 99 GWh of renewable electricity (72 GWh Wind & 27 GWh PV) serving 50 GWh of electrical demand and 30 GWh of heat demand. This results in an energy-usage rate of 80%, which is far beyond the efficiency of the electricity-to-hydrogen-to-electricity chain of about 30 to 40%. Such significant improvement has been achieved by a highly innovative sector coupling and energy system optimization. A conceptional layout of a subscale realization is presented in **FIGURE 5**.

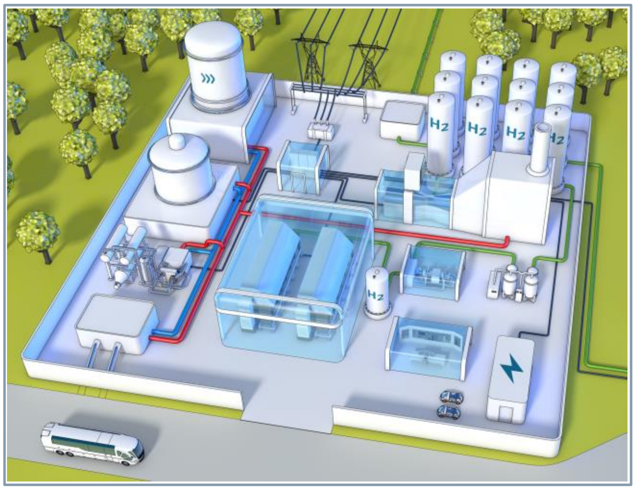

Figure 5: Conceptual layout of an energy systems to supply CO_2-free electricity and heat to a university campus (renewables not shown)

Technical readiness

The technical readiness of the complete energy supply system is given by the available components like the electrolyser - with one exception being the hydrogen gas turbine. For the system, a solution competency is available to plan, build, operate and service such a plant. Further optimization of the system and focused improvements of the components with respect to optimizing the system performance will further reduce cost and improve energy-usage-rate.

The re-electrification of 100% hydrogen is technically feasible and is targeted to be demonstrated in the HYFLEXPOWER project discussed below. However, it has not been demonstrated on an industrial scale yet. In general, the EUTurbines association representing all turbine manufacturers announced in the "renewable gas commitment" to deliver gas turbines operating on 20% hydrogen in 2020 and on 100% hydrogen in 2030 (Wetzel and Baron, 2018). The manufacturers put a strong focus on this topic. Siemens Energy offers most of their new turbines with 30% to 60% hydrogen co-firing capability in natural gas considering latest dry low emissions (DLE) technology as well as gas turbines with up-to 100% hydrogen capability with wet low emissions (WLE) technology. Also, the modernization of existing gas turbine power plants is in principle possible up to certain hydrogen co-firing levels, but the effort and economic viability depends on the type and age of the turbine. An additional main component of the system is the production of hydrogen via PEM-electrolysis. Siemens Energy has continuously developed the products in the last years, thus increasing the electrolyser's capacity by a magnitude every 4-5 years. (**Error! Reference source not found.**). Today's largest hydrogen plants operate below 100 MW of electrical energy consumptions. However, developments and projects of larger scale hydrogen production plants for industrial applications are targeted.

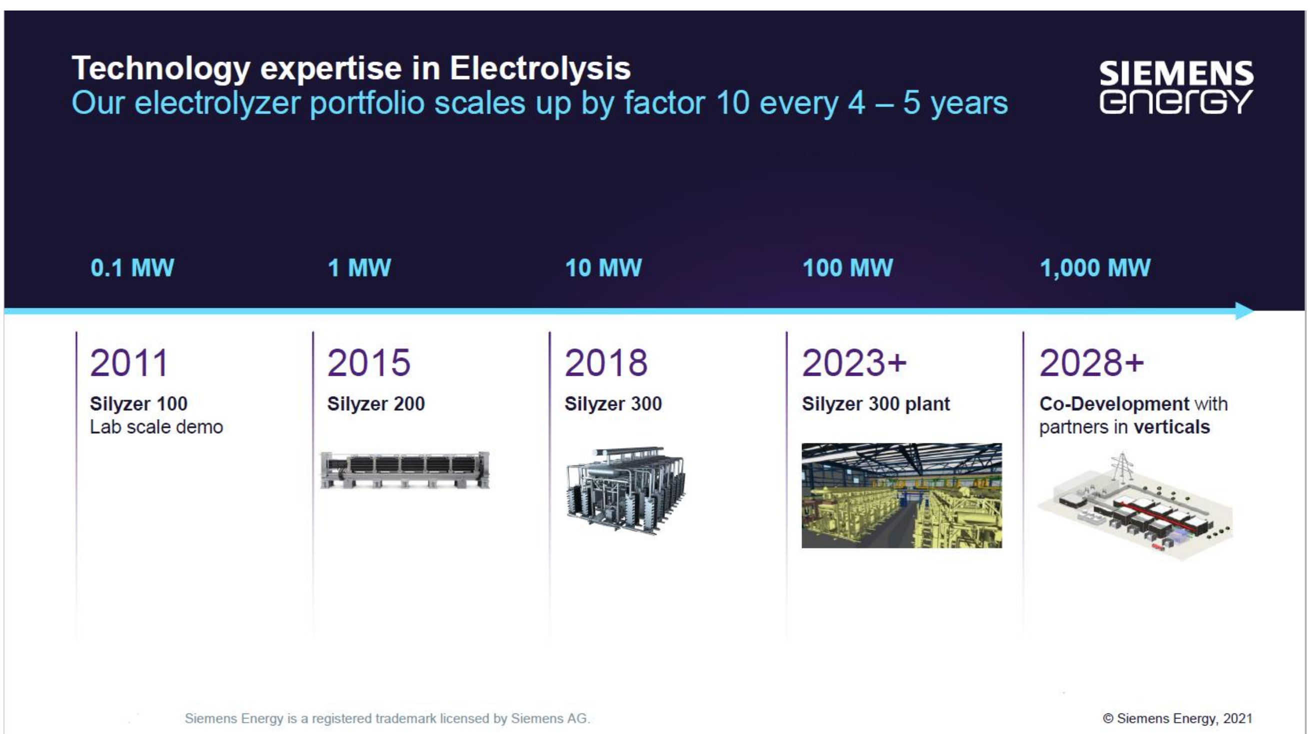

Figure 6: Scaling of PEM-electrolysis (source: Siemens Energy)

Economic viability

The economic viability of CO_2-free re-electrification requires that the total cost of renewable energy generation by wind and sun, electrolysis and hydrogen storage as well as re-electrification is matching the cost of electricity generation by fossil-fired conventional power plants.

The production cost for green hydrogen for a 50MW electrolysis plant are shown for different operating hours in **FIGURE 7**. As additional parameter is the cost for the renewable electricity with 3 €-ct/kWh (green curve) and 6 €-ct/kWh (blue curve) shown indicating the significant impact of the electricity cost. The dotted line shows the impact of compression to 100 bar, whereas the solid line no compression thus 1 bar pressure level displays. For both curves the cleaning of the hydrogen with the DeOxo-process is considered. The conclusion is that for electricity costs below 3 €-ct/kWh and 7000h operating hours the market price of grey hydrogen is met thus indicating a business opportunity. With respect to re-electrification in a gas turbine the price level of natural gas must be met, which is not feasible without subsidies today. All values in this paragraph do not consider the CO_2 cost, which will ease further the price gap of green hydrogen compared to natural gas.

The green hydrogen production price is expected to reduce in future due to for example:

- Lower cost for renewables
- Lower investment cost for electrolyser
- Lower hydrogen transportation and storage cost due to usage of pipeline, caverns and gas fields
- Carbon taxes

The price for renewable electricity has reached nearly 1 €-ct/kWh in first projects (according to Wirth 2020) and will further decrease in the future. Also, Glenk and Reichelstein (2019) are expecting an exponential cost decline for PEM (based on a multiple source fit), which will support the positive development of the economic viability.
First large-scale projects for H_2 production have been announced currently reaching 100 MW (Project Hybridge, hybridge.net and GetH2, get-h2.de) and the number of announced projects summarized by the German energy agency (Deutsche Energie-Agentur, 2021) indicate the potential to reduce cost by economies of scale and proceeding on the technology learning curve. Further rising CO_2-prices will increase the price for grey hydrogen and natural gas as a fuel.

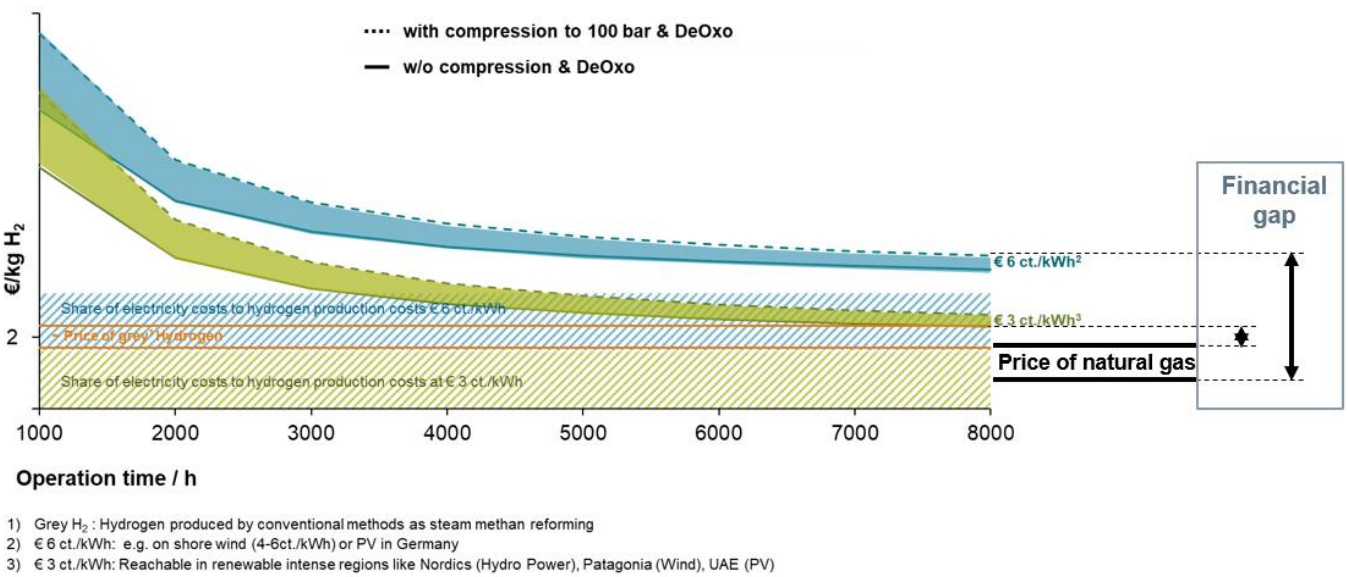

Figure 7: Today's green hydrogen production (Source: Siemens Energy)

CASE STUDY 3: HYFLEX POWER PLANT

The third case study presents the HYFLEXPOWER innovation project currently executed by a consortium led by Siemens Energy. The goal of HYFLEXPOWER is the first-ever demonstration of a fully integrated Power-to-H_2-to-Power industrial scale installation in a real-world power plant application including an advanced high-hydrogen dry low emissions (DLE) gas turbine.

The solution is based on the storage of excess electricity via electrolysis of water and re-electrification of the produced hydrogen in an existing and upgraded thermal power plant. As demonstration pilot site, an industrial facility operated by Engie in Saillat-sur-Vienne, France has been identified. The thermal power plant includes a Centrax CX-400 package installation with a Siemens Energy SGT-400 gas turbine core engine. The SGT-400 is a well proven small gas turbine of the Siemens Energy portfolio, used in power generation and oil and gas applications. The gas turbine power output for this application is up to 12 MW of electricity with the objective to supply energy in the winter season. To this end, a pioneering supply and storage concept for the site will be developed and installed, supplying the consumer with electricity and heat from renewable energy sources. The system solution is realized on an industrial scale by the development, integration and demonstration of innovative single components such as a Siemens Energy electrolyser, hydrogen storage, and a gas turbine package installation that will be upgraded with the aim of operating up to 100% hydrogen. Figure 8 shows the HYFLEXPOWER Power-to-H_2-to-Power concept overview (a) and the site in Saillat-sur-Vienne, France where the HYFLEXPOWER pilot will be built (b).

Excess capacities from renewable energy sources on the grid, which arise on days with a lot of wind and sunshine and/or low consumption, will be used for the electrolysis of water to generate green hydrogen. The resulting hydrogen will be compressed and stored in pressurized tanks. The chemically bound energy in the hydrogen will then be converted as needed in the SGT-400 gas turbine into electrical and thermal energy. The gas turbine package will be upgraded to allow varying feed from pure natural gas (the main component being methane – CH_4) to 100% H_2. Validation of the Power-to-H_2-to-Power concept including the gas turbine will take place in two experimental test campaigns with increasing H_2 content in the gas feed. The final goal is a validation with up to 100% H_2, demonstrating carbon-free energy production from stored excess renewable energy by project completion in 2024. The stored H_2 can then be used as a load component to compensate supply fluctuations in the power grid and for grid stabilisation. HYFLEXPOWER will demonstrate how the demand for electricity can be met at any time without CO_2-emissions, while at the same time ensuring grid stability. With the outlined concept a corresponding hydrogen-based solution will be demonstrated, which can be extended also on largescale storage and re-electrification concepts. Wind power and photovoltaic generate CO_2 emissions free electric current, which is primarily used directly by the consumer. Excess capacities in such a system – in contrast to today, where they either remain unused or production is curtailed – can be stably stored by transforming them into chemical energy using hydrogen electrolysis. Suited piping and storage tanks ensure that hydrogen is available for re-electrification in case of wind/solar lulls.

CONCLUSION

Gas turbine power plants operating on green hydrogen will be the perfect complementary to renewables for a CO_2-free power generation. The technical readiness is given or will be available in the future with respect to hydrogen gas turbines. Starting the transition now is possible operating such gas turbine power plants on natural gas today and then upgrading the plant to 100% hydrogen capability at a later stage. The overall energy system offers optimization

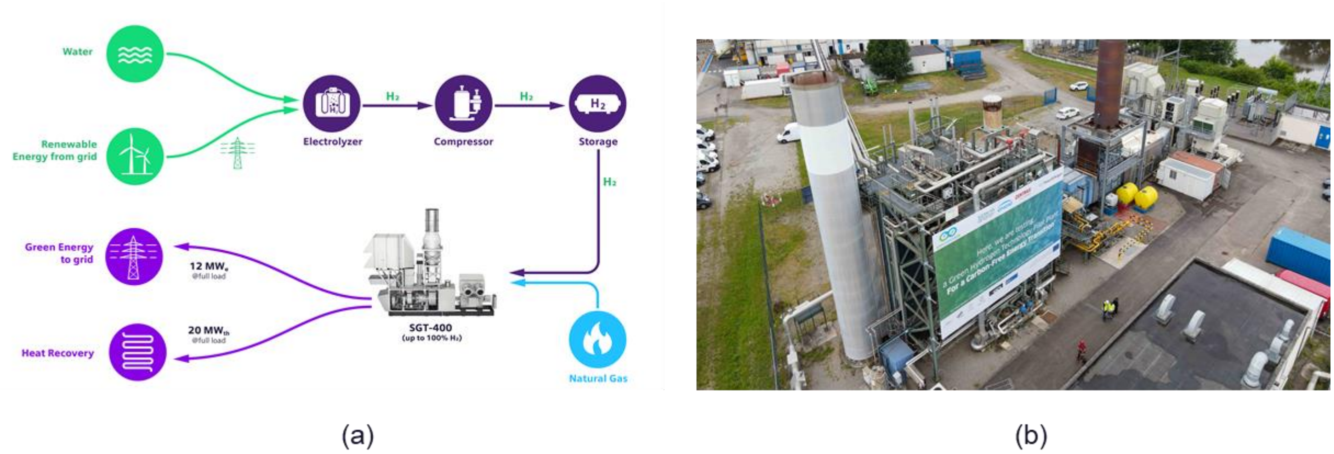

Figure 8: Power-to-H_2-to-Power concept overview (a) and view of pilot demonstration site in France (b) of the HYFLEXPOWER project; source: HYFLEXPOWER

opportunities by using the generated heat to serve heat demand thus lowering the overall energy demand. Especially, the start of the transition to a CO_2-free energy system is challenging, but innovative business and operating models utilizing electrolysers help to increase the flexibility of existing power plants and produce additional products raising revenues. Thus, first business opportunities are available and more futuristic solutions could be realized with the support of public funding to cover the additional cost. In general, the premium for CO_2-free power generation will reduce in the future due to lower renewable's cost and higher cost for fossil power due to higher CO_2 prices or CO_2 taxes, if respective regulations are implemented by governments.

This leads to comprehensive projects demonstrating the whole futuristic energy system such as the HYFLEXPOWER project or the GET H2 project (**FIGURE 9**) demonstrating a hydrogen integration, which will further reduce costs for transport and storage.

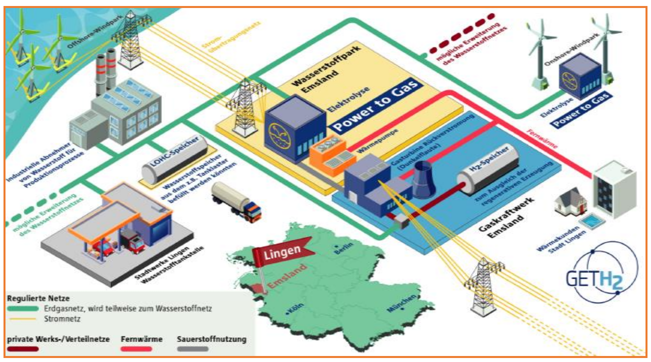

Figure 9: Project layout, picture by GET H2

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