MODELLIERUNG UND KOMBINIERTE SIMULATION EINES POWER-TO-GAS PROZESSES

Andreas Fleischhacker

TU Wien Institut für Energiesysteme und Elektrische Antriebe, Gußhausstraße 25-29/370-3, Tel.: +43 1 58801 370 361, Fax: +43 1 58801 370397, fleischhacker@eeg.tuwien.ac.at, eeg.tuwien.ac.at

Kurzfassung: Eine Möglichkeit der Speicherung von elektrischer Energie, neben den bestehenden Pumpspeicher- und Speicherkraftwerken, bietet das Power-to-Gas Konzept. Diese Arbeit behandelt zunächst eine exakte mathematische Modellierung einer Power-to-Gas Anlage in Matlab®/Simulink, welche danach in typischen Mittelspannungsnetzen über den Zeitraum eines Jahres simuliert wird.

Das Modell der Power-to-Gas Anlage kann in zwei Abschnitte unterteilt werden. Den ersten Abschnitt, welcher einen Großteil des Modells der Power-to-Gas Anlage ausmacht, umfasst das Modell eines alkalischen Elektrolyseurs. Der zweite Abschnitt beschreibt das Modell einer Methanisierung.

Die Einbindung des Power-to-Gas Modells in zwei Mittelspannungsnetze untersucht, ob der Betrieb mit einem hohen Anteil an regenerativen Energiequellen möglich und sinnvoll ist. Diese kombinierte Simulation führt zu unterschiedlichen Anlagengrößen, welche sich bezüglich der Auslastung, des Energieinhalts, des Wirkungsgrads und der Volllaststundenzahl unterscheiden. Am Ende der Arbeit werden Strategien für den Betrieb einer Power-to-Gas Anlage angeführt.

Da dieser Bericht ein Auszug aus der Diplomarbeit [1] ist, welche in englischer Sprache verfasst wurde, wird der Einfachheit halber, diese Langfassung ebenfalls in englisch erstellt.

Keywords: Modellierung, Power-to-Gas, Sincal, Matlab, Simulink, Mittelspannungsnetz

1 Introduction

Typical electrical energy sources are powerful power plants, providing centrally energy-supply for consumers. In Austria a huge amount of these power plants is fossil fired and delivers the electrical energy by a hierarchic grid structure to the consumer. Today an increasing number of consumers produce energy by photovoltaic. Additionally installed windpower raises too. A part of this renewable energy is often fed back into the grid.

A disadvantage of renewable energy producers is their dependency on nature's behaviour. Therefore renewable energy plants are characterized with much lower full load hours than conventional power plants. As a consequence the residual load power is fluctuating in the positive and negative direction. This problem can be solved with the use of electrical storage systems. Not only short-time but also seasonal storage systems will be required for a sustainable energy supply. According to the study Super-4-Micro-Grid [19] it is not possible to guarantee a 100% renewable energy supply in Austria with only pump storage and storage power plants. Even an extensive expansion of pump storage power plants will not be enough to solve the storage problem.

Another possibility of storing electrical energy is to transform it and store it in the gas grid. An advantage of this method is the higher flexibility of the gas grid in comparison to the electrical grid. The injected gas (energy carrier in the gas grid) has not to be consumed at the moment of injection, while the electrical energy (energy carrier in the electrical grid) has to be consumed at the point in time of generating it. Another reason depicts the much higher storage capacity of the gas grid, because Austria's gas grid provides several pore storages [5]. Energy density of chemical storage systems is much higher, than the energy density of hydraulic power plants. The conversation process of electrical energy into a gas substitute is known in literature as P2G Process [16].

The P2G Process consists of two processes, the electrolysis and the methanation. Electrolysis produces hydrogen using electrical energy to split water. The produced hydrogen can directly be used or can in combination with carbon dioxide be transformed into synthetic methane. Similar characteristics of Synthetic Natural Gas (SNG) to natural gas enable the feeding-in of synthetic methane into the gas grid. Besides SNG it is possible to feed-in small quantities of hydrogen in the gas grid as well [13].

This work is examining the connection of a P2G plant and the electrical distribution grid. Due to today's available literature the dynamic behavior of a P2G plant is unknown. For that reason the first part of the work is the development and verification of a P2G plant's accurate mathematical model. A P2G plant consists of an electrolyser and a methanation. The essential component for the P2G plant's dynamic is the electrolyser. As mentioned at the beginning, renewable energy sources are characterized by a high volatility in energy production. The electrolyser's dynamic has to be sufficient following high energy gradients of the renewable energy sources, to store the maximum of renewable energy. A high-detailed electrolyser model indicates critical parameters e.g. the required standby power and the internal electrolyser temperature[1].

By including the model of the P2G plant in the two distribution grids of [12], it is possible to simulate the "real time" behavior of a P2G model over the period of a year. A subject of investigation is if the operation with a high share regenerative produced energy is possible. In order to guarantee the (N-1) criterion of the grid, the position of the P2G in the grids is investigated. The optimal position of the P2G plant increases the potential of renewable energy sources expansion in the grid. As shown in [12] different P2G plant sizes cause a changed energy content of the P2G plant. An advanced optimization of the P2G plant size, due to maximum efficiency and energy content is another subject of this work. A reduction of the P2G plant size increases the efficiency of the plant and results in higher full load hours. The combined simulation of the P2G plant model and the electrical grid also leads to different operation modes of the P2G plant. The operation modes are differentiated by the required standby power[2]. This work examines the operation mode with a standby power of 15% and the minimum operation load with 30% of the P2G plant's nominal power. An important

[1] Other objects of the electrolysers inquiry are the efficiency, temperature dependency, and cooling demand of the electrolyser.

[2] Alkaline electrolysers are not able to work beyond the standby power [17].

difference of the P2G plant's operation modes is that the hydrogen (H2) purity at the standby mode is to poor for further use[3]. Another difference of two operation modes is the grid's external power consumption, which is much higher at the minimum operation mode. The different operation modes result in miscellaneous full load hours and efficiencies of the plant.

The main target of the Master thesis "Modelling and combined Simulation of a Power- to-Gas Process" is the determination of a mathematical model and its implementation in the numerical software tool Matlab®/Simulink. This high-detailed model enables the investigation of a P2G plant's dynamic and it's limiting parameters. Another part of this work is the implementation of the P2G plant model in two representative middle-voltage grids, a typical rural and a typical suburban grid. These two grids include renewable energy sources. The rural grid consists of PV power plants at the consumers' roofs and a WP park, while the suburban grid only includes the consumers' PV plants without any other renewable energy sources. The operation of the P2G model over a year with the grid's negative residual load power shows the annual energy consumption of the P2G plant at different plant sizes. The P2G plant in these grids operates in two modes, which results in different efficiencies. Another subject of the investigation is the operation of a P2G plant in two modes. Generated SNG via the P2G plant depends on injected electrical energy. The result of efficiency, i.e. the relation of SNG to injected energy, is shown over the period of a year. The achievable full load hours of the P2G plant depending on the grid and the operation mode are a further subject.

2 Mathematical Model of the Power-to-Gas Process

This chapter describes the mathematical model of a typical P2G Process. The model consists of two parts as shown in Figure 3.1. The first element depicts the electrolyser, the gateway to the electrical grid. H_2 produced by the electrolyser reacts with carbon dioxide (CO_2) in the catalyser and produces SNG, water and heat. The heat generation and usage is not investigated in this work.

The model's input

$$x_{in,P2G}(t) = [P_{P2G}(t), N_P, N_S]^T$$

consists of the electrical input power $P_{P2G}(t)$ and the amount of parallel stacks N_P and serial cell elements N_S. The model's output

$$y_{out,P2G}(t) = [\dot{V}_{H_2,AEL}(t),\ \dot{V}_{CH_4,meth}(t),\ \dot{V}_{H_2O,AEl}(t),\ \dot{V}_{H_2O,meth}(t), \dot{V}_{CO_2,meth}(t)]^T$$

[3] The P2G plant's power has to stay at least at the standby power to manage an increasing power input.

consists of the flow rate of hydrogen $\dot{V}_{H_2,AEL}(t)$ and the flow rate of water needed for the electrolysis $\dot{V}_{H_2O,AEL}$. These output variables are produced by the electrolyser. Another part of the output is generated by methanation, the flow rate of methane $\dot{V}_{CH_4,meth}(t)$, water $\dot{V}_{H_2O,meth}(t)$ and CO2 for the methanation $\dot{V}_{CO_2,meth}(t)$ as pictured in Figure 1.

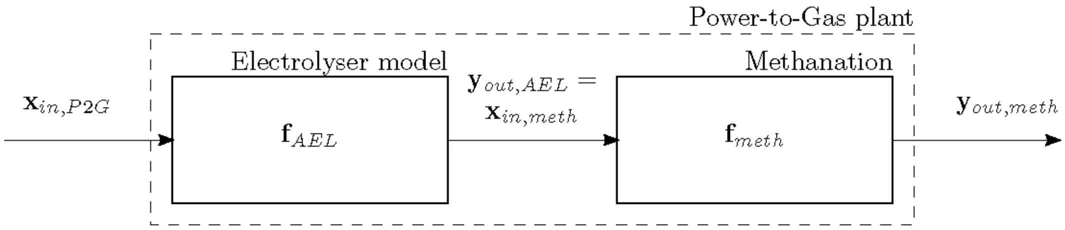

Figure 1: Structure of the P2G Model consisting of an electrolyser and a methanation

2.1 Model of an alkaline electrolyser

According to [4] the electrolysis reaction is

$$2\,H_2O(l) \rightarrow 2H_2(g) + O_2(g), U_{rev,0} = 1.229V$$

to decompose water. $U_{rev,0}$ is the required reversible voltage. The material's aggregate state liquid or gaseous is labelled by (l) or(g).

According to [11] total energy demand necessary for electrolysis is the sum of enthalpy change ΔH and thermal irreversibility $T\,\Delta S$. The term $T\,\Delta S$ is the heat demand of the electrochemical process. Therefore the thermoneutral voltage $U_{th} = \Delta H/(zF)$.

describes with the relation $1/zF$ the total energy demand, needed for the electrolysis. U_{th} is larger than the reversible voltage $U_{rev} = -\Delta G/(zF)$.

According to [17] electrode kinetics of one AEL cell can be modelled by a current-voltage relationship

$$U_{cell}(p,T) = U_{rev}(p,T) + \frac{r_1 + r_2\,\vartheta}{A} I_{cell} + s \log\left(\frac{t_1 + \frac{t_2}{\vartheta} + \frac{t_3}{\vartheta^2}}{A} I_{cell} + 1 \right)$$

with ϑ the temperature T in °C with the conversion $\vartheta = T - 273.15$. By splitting the electrolyser model in two submodels as pictured in Figure 2, the electrochemical model can be written by

$$y_{out,AEl,ec} = f_{AEL,ec}(x_{in,AEL}, y_{out,AEL,th}) = \begin{bmatrix} N_S U_{cell} \\ (P_{P2G}\eta_{AC/DC})/N_S U_{cell} \\ \eta_F N_S N_P V_{std}/(zF) \\ U_{th}/U_{cell} \end{bmatrix}$$

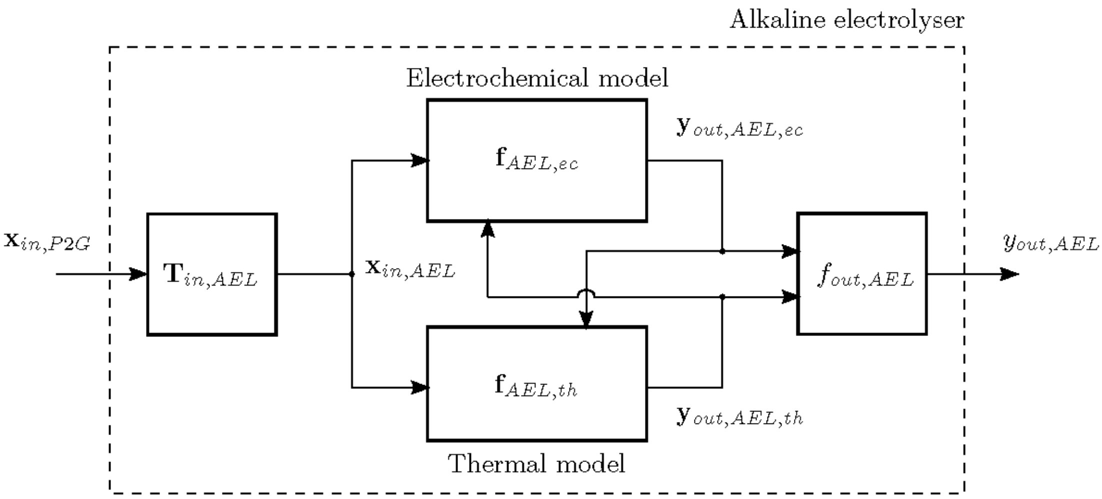

Figure 2: Structure, in- and outputs of the alkaline electrolyser model

with the AC/DC rectifier efficiency $\eta_{AC/DC} = 99\%$ [14], volume of an ideal gas at standard conditions $V_{std} = \frac{0.0224\mathrm{m}^3}{\mathrm{mol}}$ and the faraday efficiency $\eta_F = f_2 \left(\frac{i_{cell}}{A}\right)^2 / \left(f_1 + \left(\frac{i_{cell}}{A}\right)^2\right)$ with the faraday coefficients of [17].

The thermal model with the internal temperature T and the start temperature T_{start} can be written by

$$y_{out,AEl,th} = f_{AEL,th}(x_{in,AEL}, y_{out,AEL,ec}) = \begin{bmatrix} T_{start} + \int_0^t \dot{T}(\tau)d\tau \\ \dot{Q}_{cool} \end{bmatrix}.$$

$\dot{Q}_{cool} = V_I \int_0^t \Delta T(\tau)d\tau + V_P \Delta T(t)$ defines the cooling demand stabilized by a PI controller. The change of temperature is defined by $\dot{T} = \frac{1}{C_T}(\dot{Q}_{gen} - \dot{Q}_{loss} - \dot{Q}_{sens} - \dot{Q}_{cool})$ according to with the variables according to [1, 4, 17].

2.2 Methanation

The methanation reaction $4H_2 + CO_2 \leftrightarrow CH_4 + 2H_2O, \Delta H_R^0 = -165.12\ \mathrm{kJ/mol}$ [10] and can described by a stoichiometric matrix

$$y_{out,meth} = \begin{bmatrix} \frac{1}{4} & 0 & 0 \\ 0 & \frac{1}{2} & 0 \\ 0 & 0 & \frac{1}{4} \end{bmatrix} \dot{V}_{H_2}/V_{std}$$

The heat produced by the methanation is not investigated in this work.

3 Representative Electrical Grid Models

In this chapter two representative distribution grids of the middle voltage level, that are used for the investigation of the P2G operation strategies, are described. These two grids are adopted from the masterthesis of O. Oberzaucher [12]. First representative results describes a grid in a rural region with agricultural and private household. The second grid represents a suburban region with only private households. The assumption of this work is that every private as well as agricultural household have installed PV plant. A P2G plant in each of the two grids transforms the surplus of renewable energy in chemical energy. The feed-in of SNG in the natural gas grid is not an issue of this work.

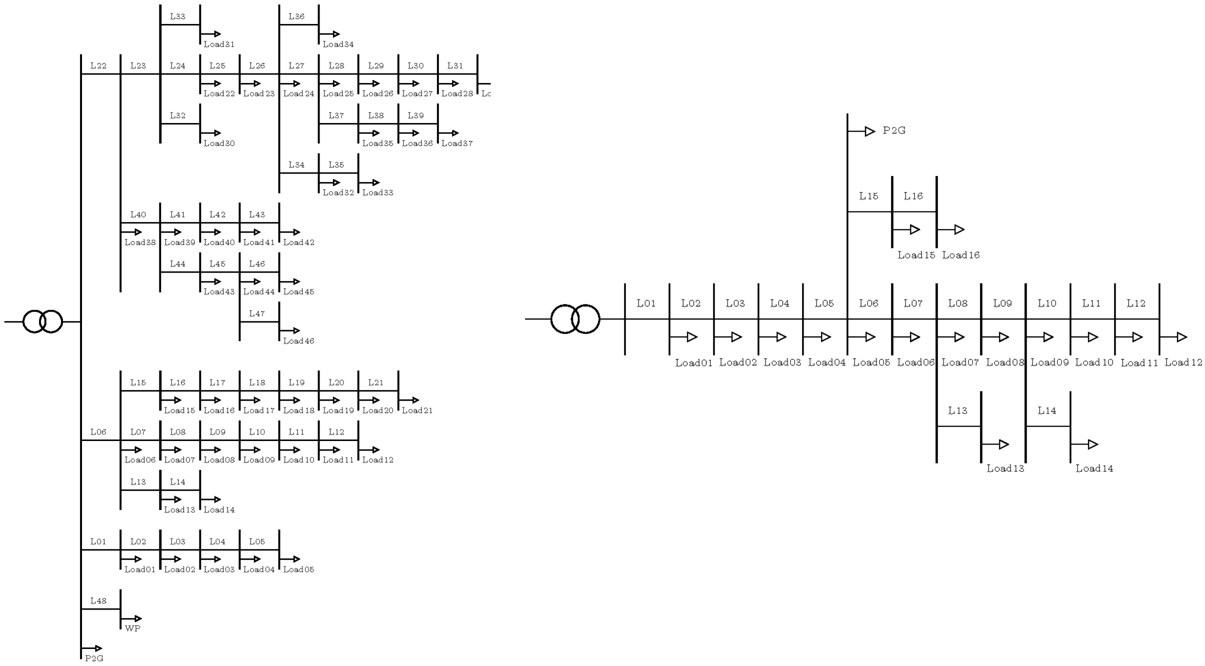

Figure 3: Rural and suburban grid topology

Figure 3 shows the topology of the rural and suburban grid. Simulating the high voltage grid is not a part of this work. The high voltage grid provides power through the slack node for the distribution level, if the renewable energy sources in the distribution grids do not produce enough electrical power. The two grids include a P2G plant. In the rural grid the P2G plant is near the transformer and in the suburban grid in the grid's middle. The rural grid also includes a windpower plant labelled by WP. The transformer represents the gateway to the high voltage grid. The two grids are implemented by PSS®Sincal and the grid parameters are adopted from [12] as well.

Based on the results of [6, 12] the representative installed power for a rural region is built of 90% private households and 10% agricultures. The load of the suburban grid is defined only by private households. The load of a private household is represented by the H0 profile and the agriculture's load by L0 profile of [9]. The sampling time of the used profiles is 15 min.

The used PV power trends are recorded from a PV plant placed at the roof of the Vienna University of Technology. The power production profiles of the wind farm "Haindorf-Inning" between Melk and St. Pölten in Lower Austria are used for the simulation [8].

4 Combined Simulation

This chapter discusses the combined simulation of the P2G model and two representative distribution grids (discussed in Chapter 4). The P2G plant represents a load element in these two grids. By alternating the size of the photovoltaic plants and the P2G plant resulting effects are investigated. The optimal P2G plant size at different PV installation levels is examined too. The combined simulation's aim is to examine the P2G plant's dynamic over the period of a year. In order to reduce the simulation duration the annual results are approximated by three representative months (summer, winter, transitional period). The Simulation is executed by PSS®Sincal in combination with Matlab®.

The power of the P2G plant is calculated by an optimization algorithm implemented in Matlab®. The power peaks of the PV production are capped by reducing installed capacity of the P2G plan to 100, 75, 50 and 25% of the nominal power. This algorithm optimizes the P2G plant's size if a positive surplus power in the grid is available, to minimize the surplus power. If the surplus power is negative the P2G plant is shut down.

Each grid is analyzed, based on two scenarios. The scenarios differ in the level of PV installation. Scenario 1 investigates the maximum installable PV power and scenario 2 the required PV power for the grid's energy autarchy. Because the results of scenario 1 in the suburban grid are equal to the results of scenario 2, the investigation in the suburban grid is not differed in scenario 1 or 2. Another part of this chapter examines two different operation modes of the P2G plant. In the first mode the P2G plant operates at least on the standby power and in the second mode the minimum P2G power is increased to the partial load power.

4.1 The Standby Problem

Under ideal conditions, the P2G plant operates with a constant input power. The P2G plant's input power of this work is produced with renewable energy sources and due to this fact the input power is highly volatile. Most of the today available AEL are able to operate down to $20 - 40\%$ of their nominal power [15]. If the electrolyser's input power is below this value ($20 - 40\%$ of its nominal power) it has to be shut down. In this case the electrolyser is shut down[4], it takes about $30 - 60\ \mathrm{min}$ until the electrolyser is switched on again [18]. The time is needed to purify the AEL with nitrogen [15, 18]. In this time it is not possible to produce hydrogen, if renewable power sources are producing electrical power again.

It is necessary to keep the AEL at least on standby power, because in that case the electrolyser is able to manage an increasing input power. Another reason for the need of standby is the higher life expectancy of the electrolyser, because a periodical shut-down decreases the electrolyser's performance immensely [3].

A possibility to reduce standby losses is to ensure a minimal operating mode of the AEL. That means that the AEL has at least to work at the lower partial load range of $\mathrm{P_{partial}} = 30\%\ \mathrm{P_{n,AEL}} \leq \mathrm{P_{P2G}}$.

The P2G plant's full load hours are much higher at the minimum operation mode than in the standby mode, as shown in Figure 4.

[4] According to [7] the electrolyser usually remains well above the standby power and is only shut-down for maintenance.

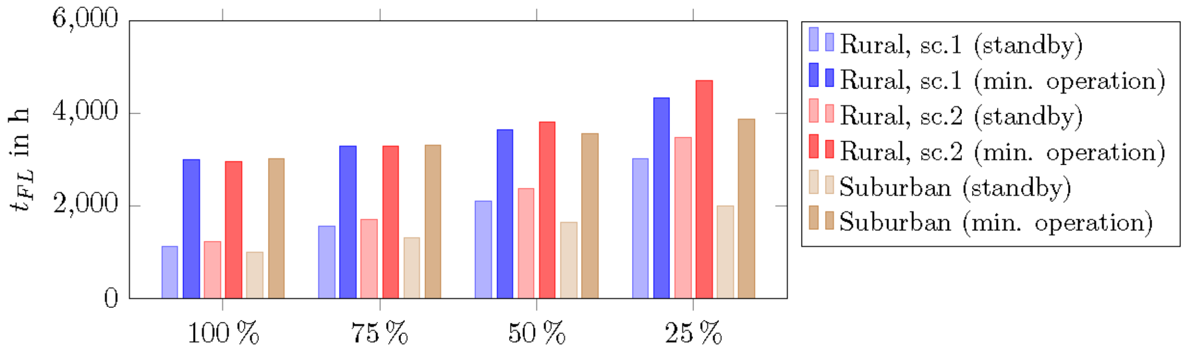

Figure 4: Full load hours of the two scenarios 100%, 75%, 50%25% of the maximum appearing P2G power ˆ PP2G with the standby and minimal operating mode.

4.2 Standby Battery

The idea of a standby battery is to reduce the power consumption of the high voltage grid for the standby mode of a P2G plant, by installing a second storage system. It can be done by storing the power peaks in batteries, instead of capping the power generation. The capped regenerative energy increases by a smaller installed P2G capacity. For that reason (with a battery) storable energy increases to a maximum with 25% of the nominal power. Figure 5 illustrates that the capped renewable energy for the rural and the suburban grid at 25% of the nominal plant size, is even bigger than the required standby energy.

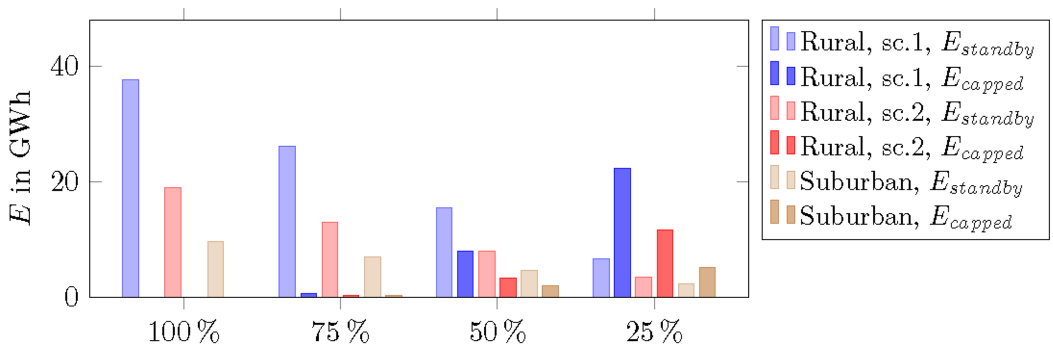

Figure 5: Standby energy $E_{standby}$ and the capped regenerative surplus energy E_{capped}

4.3 Efficiency

The overall efficiency of the P2G plant $\eta_{P2G} = \eta_{AEL}\eta_{meth}$ consists of the AEL's and the methanation's efficiency. The AEL's efficiency is not constant over the full input power range. It is inversely proportional to the input power. Figure 6 shows the average efficiency of the P2G plant. The higher efficiency of a P2G plant in the minimal operating mode is obvious. Although the efficiency of the P2G plant is almost constant in the minimal operating mode, smaller plant sizes are lowering it. The reason is higher full load hours of smaller P2G plants.

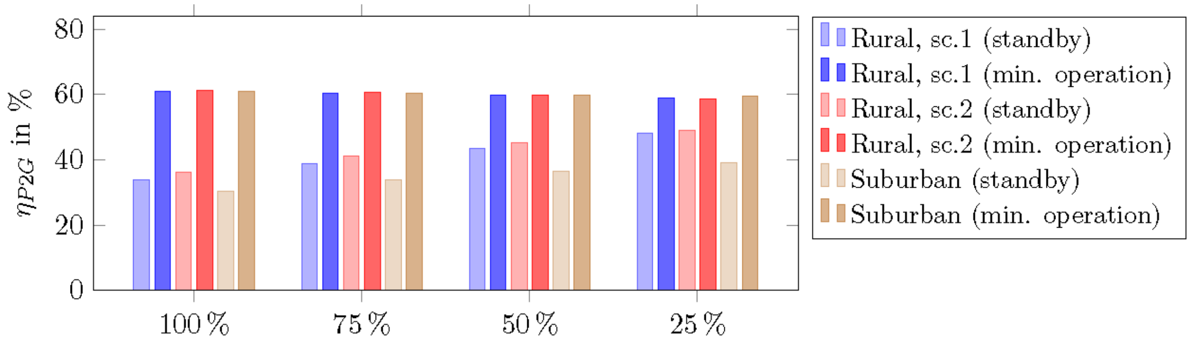

Figure 6: P2G efficiency η_P2G of the rural and suburban grid at standby and minimal operating mode.

4.4 Cycle Number

The dynamic and volatility of the P2G plant's input power determines the cycles of a P2G plant. A cycle is similar to the charge cycle of a battery. In this work one cycle of a P2G plant is defined by raising the input power from $P_{cycle,min} = 30\% \, P_{n,P2G}$ up to $P_{cycle,max} = 80\% \, P_{n,P2G}$. Figure 7 shows the amount of cycles in both modes. The increasing number of cycles by decreasing the plant's nominal power is obvious. The cycles are directly proportional to the life expectancy of a P2G plant. Unfortunately until now no scientific work discussing this relationship is published.

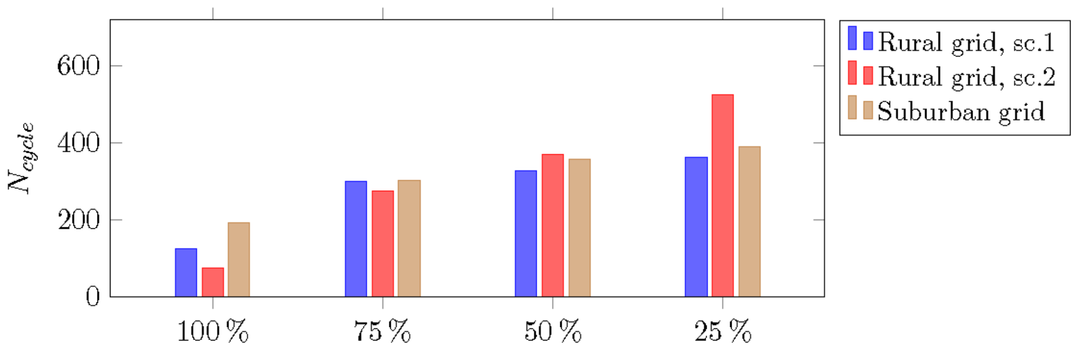

Figure 7: Cycles during a year in the rural and the suburban grid

5 Summary and Outlook

Chapter 2 of this work shows a complete scalable mathematical model of a P2G plant. The high detailed P2G model consists of an AEL and a methanation. The input characteristic of the electrolyser and therefore the P2G plant shows that it is possible to follow each power gradient[5]. The requirement for the AEL's permanent dynamic is the constraint $P_{P2G} \geq P_{standby}$. If this requirement is fulfilled the electrolyser stays at operating temperature and is capable for a dynamic loading. Due to the fact that the time sample of the combined simulation is 15 min, the P2G plant's dynamic can be considered as sufficient.

[5] 1For example the electrolyser NEL P-60 offers a ramp-up time to maximum capacity from stand-by of < 6 s. [2]

Two model regions, a representative rural and suburban grid, are introduced for the combined simulation of the P2G plant which is explained in Chapter 3. The optimal position of the P2G plant in the rural grid is the node next to the transformer, while the optimal position in the suburban grid is the grid's middle node.

The combined simulation of the P2G plant model and the electrical grids is subject of Chapter 4. The beginning of the chapter introduces the program's algorithm, controlled by Matlab® and simulated in PSS®Sincal. An optimization algorithm modifies the P2G plant size considering the relation to surplus power. The optimization algorithm consists of the combination of a simple interval switching procedure and the method of confidence intervals.

As written at the beginning of Chapter 4 three months are simulated. In order to extrapolate the period of a year, the results of summer and winter months are counted three times each and the results of transitional period six times. Two scenarios with different PV power levels are developed for combined simulation. Scenario 1 identifies the maximum PV power due to limiting grid constraints, while scenario 2 calculates the PV power necessary for an energy autarchy operation of the grid.

The result of the annual simulation shows that a reduction of the P2G plant size increases the annual full load hours dramatically. The main problem of an AEL is the minimal required standby power of $\mathrm{P_{P2G,min}} = 15\%\mathrm{P_{n,P2G}}$.The demand on standby power stays constant. For that reason the P2G plant has to be supplied with external electricity at times of low renewable power production as well. Due to this fact, it is not possible to guarantee a purely regenerative operation of the P2G plant[6].

If the AEL operates at standby power, the produced $\mathrm{H_2}$ cannot further be used, because of the low product gas quality[7]. By operating the P2G plant in the minimum operation mode of $\mathrm{P_{P2G,min}} = 30\%\mathrm{P_{n,P2G}}$ it is possible to use the produced hydrogen. For that reason the efficiency of the P2G plant raises significantly by working in minimum operating mode instead of standby power. The problem of minimum operating mode is the increasing external power consumption of the grid, i.e. the external power is not necessarily renewable energy.

The introduction of a standby battery enables the storage of capped renewable energy. The storage of energy is only possible if the nominal power of a P2G plant is smaller than the peak power of the surplus energy. The battery appropriates the coverage of the standby power demand, by decreasing external energy demand. By counting the on-off cycles of the electrolyser, it is illustrated that higher full load hours are accompanied with increasing number of cycles[8].

[6] If the external power originates from hydro power plants, or other WP plants a purely renewable operation is possible.

[7] the amount of oxygen in hydrogen is to high and otherwise

[8] Only valid in this work, because the input power of the P2G plant is very dynamic, due to the high volatility of regenerative power sources

To optimize storage of electrical energy by a P2G plant, it is recommended

- to operate the P2G together with WP and PV. The nominal power to this two power plants should be similar, to support each other e.g. sunny windless days or cloudy high wind days.
- If only PV is available the P2G plant has to shut down in winter months to avoid the standby problem[9].
- A small P2G plant guarantees high full load hours by a low standby energy.
- A battery (or another optional storage system) is installed to use the surplus power peaks and reduce the external power consumption.
- To increase yearly efficiency the P2G plant is operated above standby power (minimum operating mode).

[9]The restart of a turned off AEL/P2G is very energy-intensive [15]. For that reason AEL are rarely shut down [7]

6 Literature

[1] Andreas Fleischhacker, “Modelling and Combined Simulation of a Power-to-Gas Process,” Masterthesis, Faculty of Electrical Engineering and Information Technology, Vienna University of Technology, 2013.

[2] N. H. AS, NEL P-60, Pressurised Electrolyser - Extreme Flexibility; Technical Specifications.

[3] A. Bergen, L. Pitt, A. Rowe, P. Wild, and N. Djiali, “Transient electrolyser response in a renewable-regenerative energy system,” International Journal for Hydrogen Energy, vol. 34, pp. 64–70, 2009.

[4] P. M. Diéguez, A. Ursúa, P. Sanchis, C. Sopena, E. Guelbenzu, and L. M. Gandía, “Thermal performance of a commercial alkaline water electrolyzer: Experimental study and mathematical modeling,” International Journal of Hydrogen Energy, vol. 33, no. 24, pp. 7338–7354, http://www.sciencedirect.com/science/article/pii/S0360319908012093, 2008.

[5] E-Control, Natural Gas Storage in Austria. Available: http://www.e-control.at/de/marktteilnehmer/gas/gasmarkt/speicher.

[6] C. Groiss, C. Maier, and J. Scalet, “DSM -Potenziale in einer österreichischen Modellsiedlung,” TU Wien Institut für Energiesystem und Elektrische Antriebe, Vorarlberger Energienetze GmbH, 2012.

[7] Hydrogenics, HYSTAT-Wasserstofferzeuger. Conversation with CEO Dr. Bernd Pitschak at the Hannover Messe 2013.

[8] W. Inning-Haindorf, Generated WP from 11/2011 to 12/2012. Available: http://www.energiewerkstatt.org/.

[9] O. Kalab, “Standardisierte Lastprofile,” Wirtschaftkammer Oberösterreich, 2006.

[10] J. Kopyscinski, “Production of Synthetic Natural Gas in a Fluidized Bed Reactor: Understanding the Hydrodynamic, Mass Transfer, and Kinetic Effects,” Eidgenössische Technische Hochschule ETH Zürich, 2010.

[11] A. Löewe, Chemische Reaktionstechnik mit MATLAB und SIMULINK: WILEY-VCH, 2001.

[12] O. Oberzaucher, “Design und Analyse: Systemgekoppeltes Verteilnetz der Zukunft,” Technischen Universität Wien, Fakultät für Elektrotechnik und Informationstechnik, 2013.

[13] Österreichische Vereinigung für das Gas- und Wasserfach, Natural Gas in Austria - Gas quality, ÖVGW-Richtlinie G31.

[14] Siemens, “Sitras TCR - Gesteuerter Gleichrichter für die DC-Bahnstromversorgung,” 2012.

[15] T. Smolinka, M. Günther, and J. Garche, Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien: Fraunhofer ISE, FCBAT, 2011.

[16] M. Sterner, Bioenergy and renewable power methane in integrated 100% renewable energy systems. Limiting global warming by transforming energy systems: Kassel University Press, 2009.

[17] O. Ulleberg, “Modeling of advanced alkaline electrolyzers: a system simulation approach,” International Journal of Hydrogen Energy, vol. 28, no. 1, pp. 21–33, http://www.sciencedirect.com/science/article/pii/S0360319902000332, 2003.

[18] O. Ulleberg, T. Nakken, and A. Ete, “The wind/hydrogen demonstration system at Utsira in Norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools,” International Journal for Hydrogen Energy, vol. 35, pp. 1841–1852, 2010.

[19] T. U. Wien/ESEA, Super-4-Micro-Grid - Nachhaltige Energieversorgung im Klimawandel, Publizierbarer Endbericht: Österreichische Forschungsförderungsgesellschaft, 2011.