🏆 reviewed paper

Analysis of rSOC Systems to Support the Energy Supply of Modern Positive Energy Districts

Christof Bernsteiner, Johanna Ganglbauer, Evelyn Hummer, Robert Pratter

(DI Dr Christof Bernsteiner, 4ward Energy Research GmbH, Reininghausstrasse 13A, 8020 Graz, christof.bernsteiner@4wardenergy.at)
(DI Johanna Ganglbauer, 4ward Energy Research GmbH, Reininghausstraße 13A, 8020 Graz)
(Evelyn Hummer, MSc, 4ward Energy Research GmbH, Reininghausstraße 13A, 8020 Graz, evelyn.hummer@4wardenery.at)
(DI Robert Pratter, 4ward Energy Research GmbH, Reininghausstrasse 13A, 8020 Graz, robert.pratter@4wardenergy.at)

1 ABSTRACT

This study evaluates the integration of reversible solid oxide cell (rSOC) systems within Positive Energy Districts (PEDs) to enhance energy self-sufficiency and optimize the use of renewable energy based on seasonal energy storaging. rSOC systems are dual-mode technologies capable of operating as both electrolyzers and fuel cells, enabling seasonal energy storage by converting surplus energy, in this case from photovoltaic (PV) systems, into hydrogen during the summer months and converting it back to electricity and heat during winter. The heat generated is of a high temperature, making it suitable for both heating and hot water preparation.

For the investigation, an own simulation model was developed using Python-based tools, incorporating detailed component characteristics and operating models. The emphasis was shifted towards seasonal operation, as it became evident that there were no benefits to be gained from short-term storage in comparison to battery storages. For the saisonal operation, two operation models have been investigated: continuous operation (Scenario I) and predictive operation based on short-term forecasts (Scenario II). Results show that predictive operation reduces electricity grid dependency by aligning rSOC activity with PED energy demands and PV generation patterns. Parameter studies identified optimal configurations of rSOC power, battery capacity, and battery inverter dimensions to balance self-sufficiency and economic performance. While the system exhibits considerable technical potential, its economic integration represents a significant challenge, caused by high investment costs of rSOC systems and the comparatively low electrical efficiency for hydrogen production and subsequent reconversion into electricity. Consequently, it was not possible to identify an economically viable business model within the prevailing framework conditions, whether for Scenario I or Scenario II. Sensitive analyses taking into account the further development of the technology and the relevant framework contions however, shows, that rSOC has the potential to be an interesting option for use in PEDs in the future.

The investigation was carried out as part of the Cell4Live[1] project, focusing on technical and economic aspects of rSOC systems integrated in PEDs.

Keywords: Fuel Cell, Simulation Model, Positiv Energy District, hydrogen, rSOC-system

2 INTRODUCTION

The efficient energy supply of PED is still a major challenge. Especially when, in addition to the positive energy balance – total annual generation exceeds total annual demand – the degree of self-sufficiency is also considered. If the temporal synchronization of energy demand and energy generation is also addressed, the PED can make a significant contribution to relieving the burden on public grids and benefit from increased security of supply in the event of a power outage.

In this respect, rSOC systems are an interesting technology. They can operate in both electrolysis and fuel cell mode. Therefore, surplus electricity can be converted into green hydrogen and converted back into electricity at a later point in time. In fuel cell mode, heat is released in addition to electricity, which can be used to cover (a part of) the heat demand as well as domestic hot water demand. Thanks to the high storage capacity of hydrogen, this system makes it possible to store energy seasonally, i.e. to shift it from summer to winter. This can significantly increase the self-sufficiency rate of the PED, as photovoltaic systems (PV) are usually the main energy sources of such districts.

[1] Das Projekt wird innerhalb des Förderprogrammes „Stadt der Zukunft“ durch das Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie gefördert, Project description: https://www.4wardenergy.at/en/references/cell4life-1

Within this study, both the technical and the economic aspects of integrating a rSOC system into PED for seasonal storage of renewable electricity from a PV system, with the goal of later supplying the PED with electrical and thermal energy are examined.

3 TECHNO-ECONOMIC MODELLING APPROACH

It has been assumed that the rSOC system is integrated into a higher-level energy supply system, meaning that the rSOC system is not solely responsible for the entire energy supply of the PED. In addition, the focus was on seasonal operation. Therefore, the rSOC system operates exclusively as an electrolyzer during the summer months and as a fuel cell during the winter months. Generally, in both seasons, electricity generated by the PV is first used to meet the PED electricity demand. In electrolyzer mode (see Fig 1), any additional surplus PV electricity is used to operate the electrolyzer, storing renewable energy as hydrogen for seasonal use.

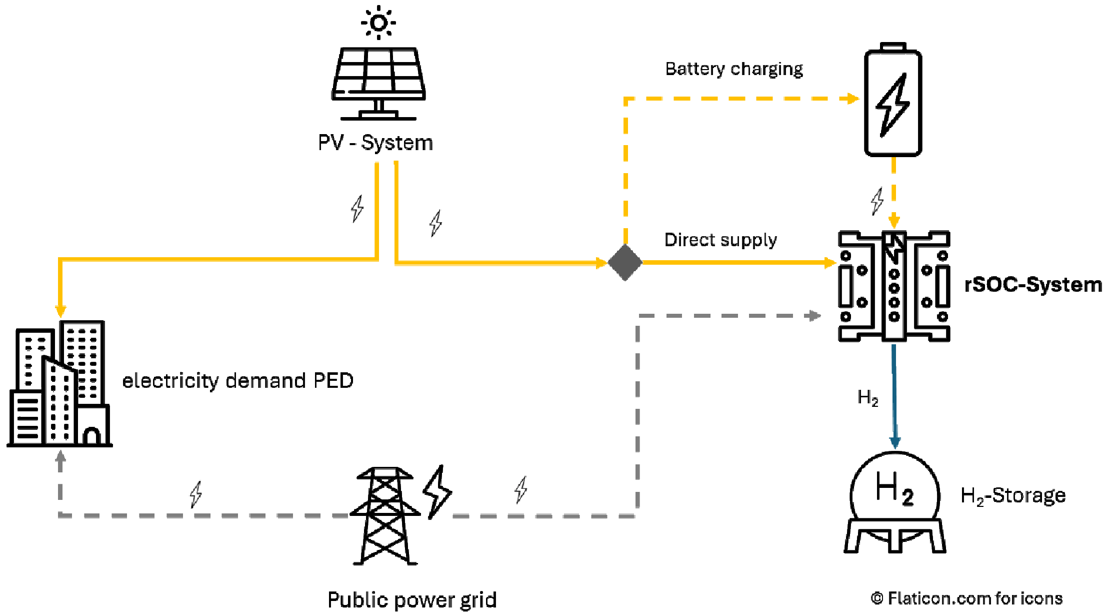

Fig. 1: Schematic diagram of the rSOC-system operating as electrolyzer ("summer operation").

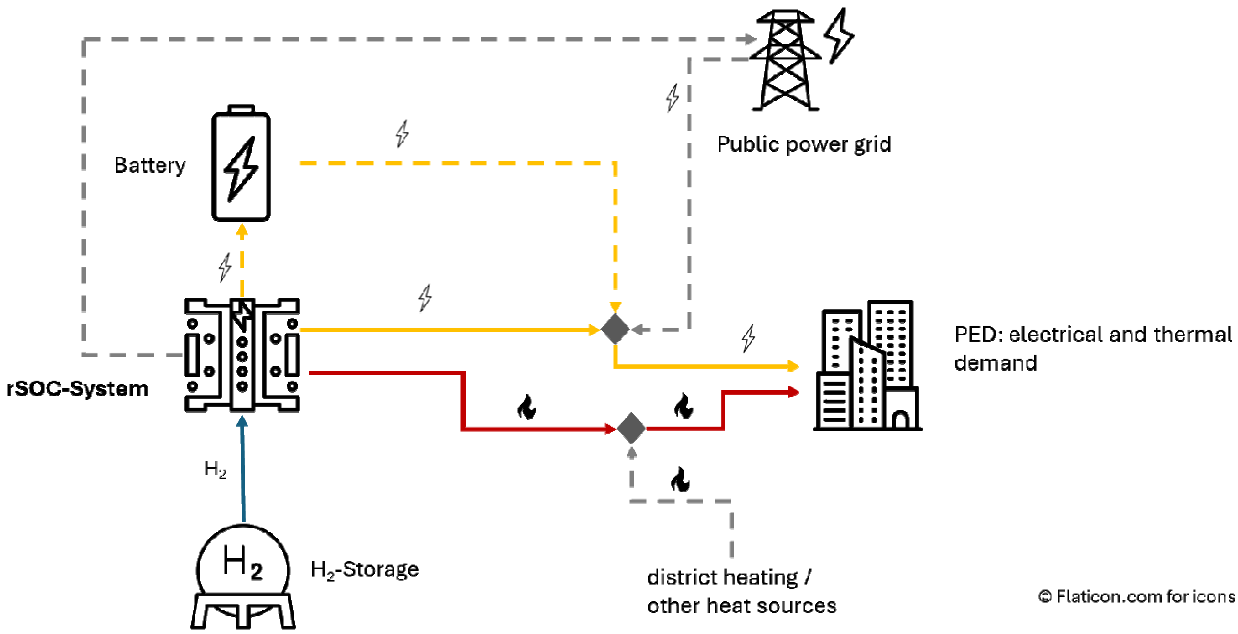

Fig. 2: Schematic diagram of the rSOC-system operating as fuell cell ("winter operation").

During the winter months, the stored hydrogen is reconverted by the rSOC system into both electricity and heat. The generated electricity is used to cover household electricity needs, while the heat from the rSOC system is used for heating and domestic hot water preperation (see Fig 2). Moreover, the rSOC is coupled with a battery to further optimize the operation of the system and minimize the share of grid electricity used for the operation of the rSOC system.

To calculate the energy flows between the components (rSOC system, battery, hydrogen storage, electricity grid) and to determine the optimum dimensions of the system for specific PED, a simulation model in Python was created. This model is based on the so called houshold infrastructure and building simulator “hisim” (Pflugradt, 2020). The respective models of the components were interconnected according to the PED requirements and extended regarding the technical and physical properties of real components (e.g. efficiency of the rSOC system, energy requirement for storing hydrogen in a pressurized storage tank). The operation of the rSOC system is investigated within two scenarios:

- In Scenario I, the rSOC system operates continuously, independent of PV surplus and electricity demand of the PED. The rSOC system is operated in electrolysis mode during the summer months and in fuel cell mode during winter. When the system was being dimensioned, care was taken to ensure that the hydrogen produced during the summer months is sufficient to guarantee winter operation. In order to minimise the amount of electricity purchased from the public grid for the operation of the rSOC system in electrolysis mode, the system was equipped with an additional battery storage for day/night balancing. The determination of the optimum size of the battery storage in comparison with the rSOC-system was also investigated within the project.
- In Scenario II, forecasting methods are used to optimize the operation of the rSOC system. The emphasis remains on seasonal operations. Consequently, the rSOC system is still operated in electrolysis mode during the summer months and in fuel cell mode during the winter months. However, the system is not operated constantly, but rather put into standby mode if, for instance, the forecasts indicate that no PV surplus is expected in the subsequent hours in electrolysis mode.

In standby mode, the rSOC unit consumes electrical energy, e.g., to maintain temperature, ensuring rapid reactivation. The model incorporates values from the literature (Mottaghizadeh, 2021; Tomberg, 2023), specifying that 7% of the nominal power is required for electrolysis mode and 10% for fuel cell mode.

In standby operation, the battery state of charge is evaluated against predefined minimum or maximum thresholds, depending on the rSOC mode, to minimize grid feed-in or consumption (see Table 1).

Minimum running & minimum standby time	3 h
rSOC electrolyzer mode: Minimum state of charge of the battery	50 %
rSOC fuel cell mode: Upper state of charge of the battery	90 %
rSOC electrolyzer mode: standby energy demand of nominal power	7 %
rSOC fuel cell mode: standby energy demand of nominal power	10 %

Table 1: Relevant parameters of the Standby mode.

In Scenario II the rSOC system is operated based on predictions for the electricity demand and the electricity production. For the prediction of the electricity demand, a model was developed, which was capable of generating time series forecasts based on historical load data. With this model based on a neural network, good results were achieved for the total energy demand of the PED. However, it should be noted that the aim of the project was not to develop the best possible forecast, but to find a model that is able to deliver sufficiently good results to answer the research question. To determine the energy production, weather forecasts (solar radiation, temperature) from the GeoSphere Austria (2022) were used to calculate the expected PV production for the next three hours (short-term forecasts of GeoSphere Austria).

In fuel cell mode, the activation process involves assessing whether there is an energy demand in the PED after accounting for the energy supplied by the PV system. If an energy demand which cannot be covered by the PV supply is identified, the forecasted PV power generation and PED energy demand during the minimum operational period of the rSOC system are analyzed. Subsequently, the proportion of energy from the rSOC system that can be directly utilized by the PED is determined. If more than 75% of the energy provided by the rSOC system can be consumed directly by the PED without intermediate battery storage, the system is activated. After the minimum rSOC runtime, the battery state of charge and the PED energy demand are checked again. If the upper state of charge level is reached and no electricity power is required by the PED from the rSOC system, it is switched to standby mode.

A similar approach is applied in electrolysis mode. The forecasted PV surplus electricity and PED energy demand during the minimum operational period of the rSOC system are evaluated. If sufficient PV surplus electricity is available and the electrolysis process can operate for at least 75 % of the minimum runtime using only PV surplus electricity (without additional battery discharge), the rSOC electrolysis mode is activated. Once the minimum runtime is reached, it is checked whether the surpluce energy provided by PV or battery charge is sufficient to continue operating the rSOC system actively. If not, the rSOC system is switched back to standby mode.

The model was used to carry out a parameter study and subsequently determine the optimum dimensions of the rSOC system based on the degree of self-sufficiency achieved and the expected net present value. The results were compared with alternative technologies. In addition, a comprehensive economic sensitivity analysis was carried out using selected scenarios in order to determine which parameters have a strong influence on the economic viability of this system and which framework conditions are necessary to ensure the economic use of the rSOC system.

3.1 Input data

The simulations were carried out based on generic energy demand and supply data of a representative PED in Austria and were conducted for an entire year with an hourly resolution. The aggregated energy input data are shown in Table 2. A parameter study with more than 1000 simulations was carried out, each of them considering the operation of the rSOC system for an entire year. In the parameter study, the battery capacity, the inverter power and the electrical power of the rSOC system were varied with the goal to find an optimum between the increase of the autarky rate on the one hand and the net present value of the investment on the other hand.

		Summer	Winter	Seasonal Transition	Year
Electricity demand	in MWh	209	263	455	927
Thermal energy demand	in MWh	82	343	224	649
Photovoltaik supply	in MWh	388	78	461	927

Table 2: Energy data of the PED used for the calculations.

It was assumed that the maximum electricity power demand of the rSOC system in electrolysis mode corresponds to the PV peak power. The electricity power of the battery inverter was at least equal to the electricity power demand of the rSOC system in electrolysis mode, including the power requirement of the hydrogen compressor. The minimum capacity of the battery was sufficient to operate the electrolyser and the hydrogen storage tank for at least one hour.

In both scenarios, the battery serves as short-term energy storage for the rSOC system. The parameter space is limited upwards by the fact that the battery has a maximum capacity to operate the electrolyser and hydrogen storage for 24 hours. In general, it was assumed that the rSOS system in fuel cell mode supplies around half the power demand in electrolysis mode.

		Minimum	Maximum
Photovoltaic peak power	in kW	781	
rSOC system electricity power demand	in kW	55	781
Battery inverter power	in kW	1 x rSOC system electricity power demand	15 x rSOC system electricity power demand
Battery capacity - enables rSOC system operation	in hours	1	24

Table 3: Characteristics of the parameter space. The rSOC system's electricity demand is specified for electrolysis mode, including the hydrogen tank power demand.

4 RESULTS AND DISCUSSIONS

This chapter is divided into two main sections. On the one hand, the effects of forecast-based operation (Scenario II) were analysed in comparison with constant operation (Scenario I) and, on the other hand, the economic efficiency of the use of an rSOC system in PEDs was evaluated in general.

4.1 Comparison of the constant operation with the forecast-based operation

For the following evaluation, the configuration of Scenario I which reaches the best combination between the remaining grid consumption (to be minimized) and the net present value (to be maximized) has been selected. For Scenario II, the same configuration (size of rSOC system, battery capacity and inverter power) has been chosen to make both scenarios better comparable. The optimum configuration of Scenario II would be slightly different, this however does not influence the general findings. As main reference a scenario without rSOC-system was calculated. Meaning, the PED was modelled with the same PV-system and the same energy demand but without any kind of storage system.

It could be shown that the use of forecastes in Sceneario II reduces the the necessary consumption from the public grid by additional 5 % (see Fig. 3) in comparison to Scenario I. The predictive operating strategy ensures that the rSOC system switches from electrolysis mode to standby mode when the photovoltaic supply is expected to be low or absent, e.g. at night or when it is cloudy. Predictive operation also reduces the amount of electricity fed into the grid. If a low electricity power demand from the PED is expected, which does not justify the operation of the rSOC system in fuel cell mode, it is also switched to standby mode.

In general, the predictive operation of the rSOC system in Scenario II can be seen as to be more grid supportive. In addition to providing seasonal balancing through long-term storage of electricity energy supplied by the PV system, the predictive control of the rSOC system also compensates for daily fluctuations in PV power generation and the PED's electricity consumption.

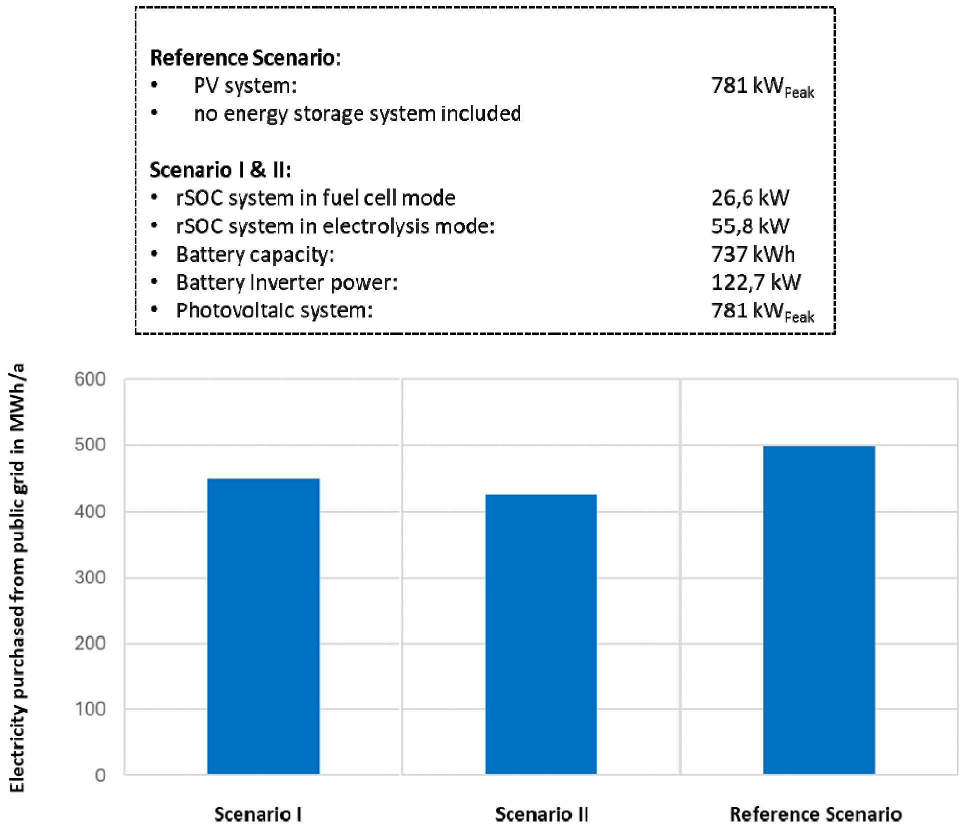

Fig. 3: Remaining share of electricity with needs to be purchages from the public grid, for Scenario I, II and the Reference Scenario.

From the technical perspective, the results of Scenario I show that with continuous operation of the rSOC system, the rSOC system power demand in electrolysis mode should be around 8 % to 12 % of peak power of the PV system to minimize electricity purchased from the public grid. The results of Scenario II show that in forecast-based operation, the rSOC system power demand can be around 10 % to 25 % of the photovoltaic peak power to minimize electricity grid demand. These values are based on a PED where total annual electricity demand roughly meets annual electricity production.

In addition, according to the simulation results, the battery inverter power in both scenarios should be around two to three times the total electrical power of the rSOC system running in electrolysis mode feeding the hydrogen storage. The battery should have a capacity that makes it possible to operate the rSOC system in electrolysis mode for 18 to 24 hours. In continuous operation of the rSOC system (Scenario I), however, a higher battery capacity is beneficial.

4.2 Economic evaluation of the use of an rSOC system in PEDs

For the economic evaluation, the configurations which provide the best results have been chosen for Scenario I and Scenario II, resulting in different dimensions of the main components, as shown in Table 4:

		Scenario I	Scenario II	Reference Scenario	Scenario 100 % grid consumption
PV-System	kWp	781	781	781	-
rSOC System in fuel cell mode	kW	27	31	-	-
rSOC System in electrolysis mode	kW	56	65	-	-
Battery capacity	kWh	737	430	-	-
Batter inverter power	kW	122	215	-	-

Table 4: Dimensioning of main components of the overall rSOC system.

While the system exhibits considerable technical potential, its economic integration represents a significant challenge. From the economic perspective, unfortunately, no favourable configuration either for the Scenario I nor for the Scenario II could be found in comparison to the reference scenario under the current circumstances. This is mainly due to the high investment costs and the comparatively low electrical efficiency (approx. 55 % (Tokyo Gas Co, 2023)) for hydrogen production and subsequent reconversion into electricity. As shown in Fig 4 the expected net present value for both rSOC scenarios is significantly lower than in the reference scenario, which is supplied exclusively by a PV system and does have its own storage system. Both scenarios have been set in relation to a 100 % grid supply. Meaning that the investment in the PV-system would be amortised within four years, while it is evident that no amortisation occurs in the period under review for the scenario involving the rSOC system.

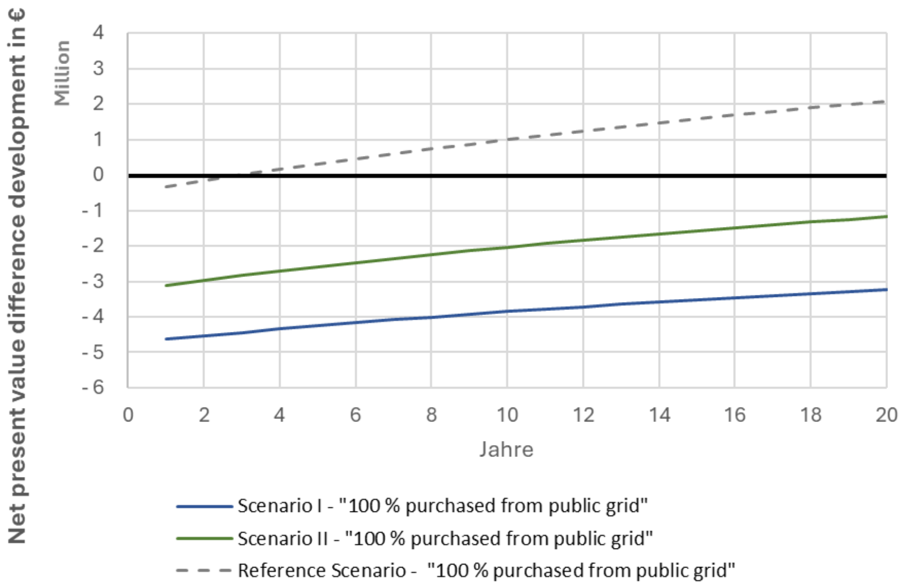

Fig. 4: Development of the net present value for the rSOC-system and the reference scenario (PV system without storage) – both in relation to 100 % grid supply – Basic Scenario.

In the absence of a positive operating model within the prevailing framework conditions, a sensitivity analysis was conducted to ascertain the impact of various parameters on economic outcomes. It has been shown that investment costs and subsidies have the most significant impact on economic efficiency. Given that rSOC systems are a young technology, it is reasonable to assume that investment costs will decrease as the market matures.

Based on these findings, further scenarios predicated on favourable development of the rSOC-technology and the related framework conditions have been defined. The assumptions underlying both the basic scenarios and the "Future Development Scenario" are outlined in Table 5:

		Basis Scenario	Future Development
Investment costs			
PV-System	in EUR/kWp	900	855
Battery Storage	in EUR/kWh	800	680
rSOC-System	in EUR/kW	5000	2000
Hydrogen Storage	in EUR/kWh	835	334
Funding options			
PV-System	%*	30	30
Battery Storage	%*	20	50
rSOC-System	%*	30	50
Hydrogen Storage	%*	30	50
Operation costs			
PV-System	%*	2	1
Inverter	%*	2	0.5
Battery	%*	2	0.5
rSOC-System	%*	3	1
Hydrogen Storage	%*	1.5	0.75
Compressor	%*	1.5	1.5
Electricity tariff	EUR/kWh	0.3	0.3
Feed-in tariff	EUR/kWh	0.08	0.08
Heat tariff	EUR/	0.13	0.13
CO_2 Price	EUR/t_{CO2}	55	55
* % of the related investment costs			

Table 5: Assumptions for the economic evaluation, for the basic scenarios and for the scenario of the future development of the rSOC technology.

The results of the scenario for the future development of the rSOC technology are shown in Fig. 5. Significant better results could be achieved with the assumptions made. Compared with an 100 % grid consumption, the Scenario II is economically viable after nine years. Scenario I is expected to reach its amortisation point after fifteen years. In comparison with the reference scenario, however, there is still no amortisation. Nevertheless, the rSOC system has a considerable future potential especially for such PEDs, where a high degree of autarky is essential.

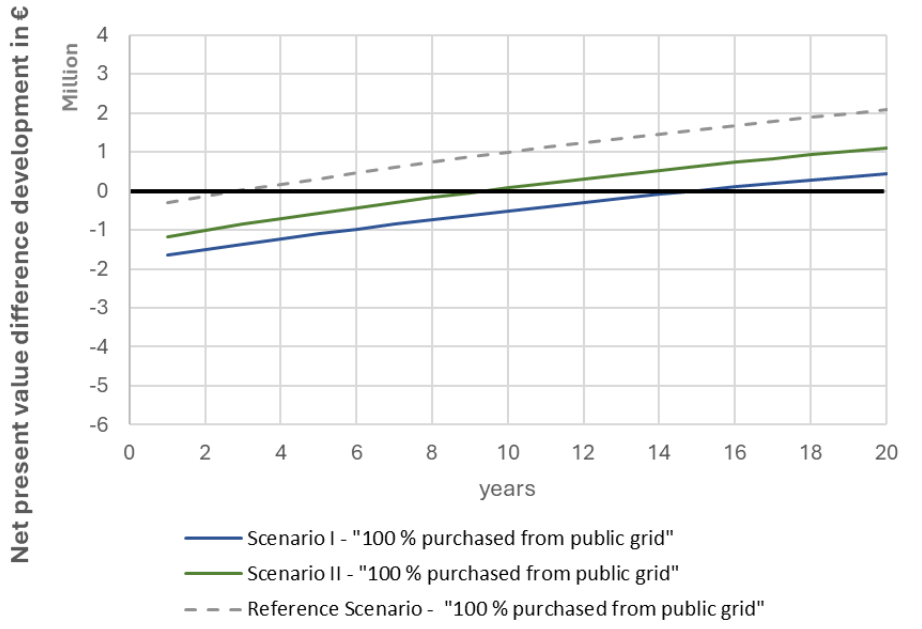

Fig. 5: Development of the net present value for the rSOC-system and the reference scenario (PV system without storage) – both in relation to 100 % grid supply –Scenario for the future development of the technology and the relevant framework conditions.

5 CONCLUSION

Although rSOC systems are an interesting technology for use in a PED from a technical point of view, it was not possible to find an economically viable use case under current conditions. However, as rSOC systems are an emerging technology, it can be assumed that there will be positive development in the coming years, both in terms of investment and achievable efficiency. Therefore, a sensitivity analysis was carried out, which shows that if investment costs and the relevant framework conditions develop favourably, rSOC technology can be an interesting option for use in PEDs in the future. The integration of rSOC systems is particularly favourable if a high degree of autarky should be achieved, as they are well suited for seasonal balancing.

6 REFERENCES

Pflugradt, N. (2020). ETHOS.HiSim – House Infrastructure Simulator [Computer software]. https://github.com/FZJ-IEK3-VSA/HiSim

GeoSphere Austria. (15. 12 2022). Kurzfristvorhersage. https://data.hub.geosphere.at/dataset/nowcast-v1-15min-1km

Mottaghizadeh, P., Fardadi, M., Jabbari, F., Brouwer, J.. Dynamics and control of a thermally self-sustaining energy storage system using integrated solid oxide cells for an islanded building. In: International Journal of Hydrogen Energy. Vol. 46, Issue 49, pp. 24891-24908. 2021.

Tomberg, M., Heddrich, M. P., Ansar, S. A., Friedrich, K. A.. Operation strategies for a flexible megawatt scale electrolysis system for synthesis gas and hydrogen production with direct air capture of carbon dioxide. In: The Royal Society of Chemistry, Sustainable Energy Fuels 2023, Vol. 7, pp. 471-484, 2023.

Ltd. Tokyo Gas Co., “Residential Fuel Cell ENE-FARM | Challenge Zero.” Accessed: Mar. 17, 2023. [Online]. Available: https://www.challenge-zero.jp/en/casestudy/469