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Economic Feasibility of Pipe Storage and Underground Reservoir Storage Options for Power-to-Gas Load Balancing

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Abstract

This paper investigates the economic feasibility of power-to-gas (P2G) systems and gas storage options for both H_2 and renewable methane. The study is based on a techno-economic model in which the net present value (NPV) method and Monte Carlo simulation of risks and price forward curves for the electricity and the gas market are used. We study three investment cases: a *Base Case* where the gas is directly sold in the market, a *Storage & Arbitrage Case* where temporal arbitrage opportunities between the electricity and the gas market are exploited, and a *Storage & Balancing Case* where the balancing markets (secondary reserve market for electricity, external balancing market for natural gas) are addressed. The optimal type and size of different centralized and decentralized storage facilities are determined and compared with each other. In a detailed sensitivity and cost analysis, we identify the key factors which could potentially improve the economic viability of the technological concepts assessed. We find that the P2G system used for bridging the balancing markets for power and gas cannot be operated profitably. For both, temporal arbitrage and balancing energy, pipe storage is preferred. Relatively high feed-in tariffs (100 € MW^{-1} for hydrogen, 130 € MW^{-1} for methane) are required to render pipe storage for P2G economically viable.

Keywords: Underground reservoir storage; Power-to-gas (P2G); Load balancing; Synthetic natural gas (SNG)

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1. Introduction

Power generation in Germany is shifting from fossil and nuclear fuels to renewables, thus increasing supply fluctuations and challenging the security of electricity supply. Besides distributed generation, demand response, and new or upgraded transmission lines, energy storage is expected to foster the balancing of the power system (e.g. [1-6]). In this context, power-to-gas (P2G) is a relatively new concept which enables to transform surplus power to hydrogen (H_2) by electrolysis or even to renewable methane (CH_4) by additional methanation (e.g. [7,8]). The resulting product can then be marketed directly or stored in designated pipe storage or underground reservoir storage facilities. The conversion to hydrogen has an efficiency of about 75–80%; a further conversion to renewable methane yields a 60–65% efficiency, and a power-to-gas-to-power process would have an even lower efficiency of around 36% [9]. P2G combines the volatile supply characteristics of power from renewables with the seasonal demand characteristics of gas, the latter of which is partly kept in special storage facilities to supply the gas markets without interruption also during the cold season. A key financial risk for investments in a P2G system stems from the price risks emanating from power purchases and gas sales. Adequate storage options can help to mitigate these price risks and enable P2G applications in the future. Hydrogen, as an intermediate production input, requires relatively large storage volumes, resulting in higher investment costs and thus lower profitability. In contrast, methane (CH_4) requires 4–5 times less storage volume than hydrogen, enhancing its economic viability. P2G may also be used for temporal arbitrage in the spot market, or for ancillary system services offered to the transmission system operator (TSO).

The main focus of our study is on the identification of the most feasible technologies and systems for future P2G market applications, and their differentiation. Specifically, we compare P2G systems which are solely based on H_2 generation with such using the additional step of methanation to produce renewable methane (also called synthetic natural gas, SNG) (e.g. [10]). The economic analysis tackles both the alternative storage requirements for the different technological systems, and operating regimes and modes concerned, as well as the decision concerning the economically most appropriate storage medium. A more detailed description of the technical and economic parameters as well as the economic assessment can be found in [11].

The remainder of this paper is organized as follows. Section 2 introduces the methodology used. Section 3 presents the main results, including those from a sensitivity analysis for the

Base Case and the two variants investigated. Section 4 contains the discussion, and Section 5 concludes.

2. Methodology

Three investment cases for a P2G system are performed on different energy markets. The *Base Case* investigates the general production costs of hydrogen and methane, the procurement of power, and the direct sales of gas on the respective spot markets. Stochastic modeling of price forward curves (PFCs) for power and natural gas is pursued in order to account for uncertainty. The *Storage & Arbitrage Case* expands the *Base Case* by including gas storage for temporary arbitrage between the electricity and the gas markets, with the aim of maximizing the economic gain. Project-specific storage facilities (salt cavern / gas tank / pipe storage) (for useful reviews on these technologies see [12,13]) are compared with storage capacity reservations in a decentralized storage market. The optimal storage operation is investigated with regard to size and type. The *Storage & Balancing Case* investigates the economic viability of a P2G system used to engage on the balancing markets, such as the secondary reserve market for electricity and the external balancing market for natural gas in Germany [14]. This latter case includes some variations also used in the *Storage & Arbitrage Case*. Fig. 1 shows the structure of the P2G system model used.

The economic assessment is carried out using different approaches and steps. All projects are assessed over a 20-year production period, and investments are all made in year 1 (i.e. we consider a project lifetime of 21 years). An economic model is set up that is based on the net present value (NPV) method. Several economic indicators that can be derived from the NPV formula are used to evaluate the cases studied. Specifically, the net cash recovery (NCR, before or after corporate tax – BT or AT) reflects the economic value generated by the project at the end of its lifetime for the case of zero discounting (a zero interest rate), the profit-to-investment ratio (PIR) – calculated as the ratio of the present value of the expected future cash flows and the initial investment in the project – is a profitability index of the project, and the internal rate of return (IRR) indicates the interest rate that would accrue if the project only had a zero NPV. In the sensitivity analysis presented in Section 3, we use a discount rate of 10% for the NPV computations. Key input parameters, such as the electricity price, investment costs or production costs, are varied to check the robustness of the project's economic feasibility. Furthermore, depreciation schemes and tax rates have been altered to identify the pre-tax versus the post-tax outcomes, enabling to study the fiscal impact on the projects. A

Monte Carlo simulation with 5000 runs is performed (using Oracle’s Crystal Ball® software) to include the stochastic variation in the electricity and natural gas prices as well as the uncertain retrieval of balancing energy, and to model the probabilities for the price forward curves (PFCs) of power and natural gas. The probabilistic and average values are based on simulated probability distributions of various input parameters. Price risks within the market, as well as the retrieval of balancing energy, are analyzed through statistical tests. Optimal values for important decision and market variables (size, capacity, stop-loss, take-profit) are derived by means of stochastic optimization (see [15] for a useful overview of simulation and optimization in finance, and [11] for further details on the modeling). Electricity procurement and gas sales for the P2G system are provided by day-ahead trading on the spot market, assessed by PFCs or through the offer of capacity service on the secondary reserve market (electric power) and the external balancing energy market (gas). A Brownian motion is applied for simulating the forward prices, enabling to integrate uncertainties stemming from the trading in the futures market. For simplicity, the economic assessment has been based on an operation of 8760 hours per year. In the sensitivity analysis, we especially focus on variations in the energy rate, which provides some insights on the variable costs and production hours within a year.

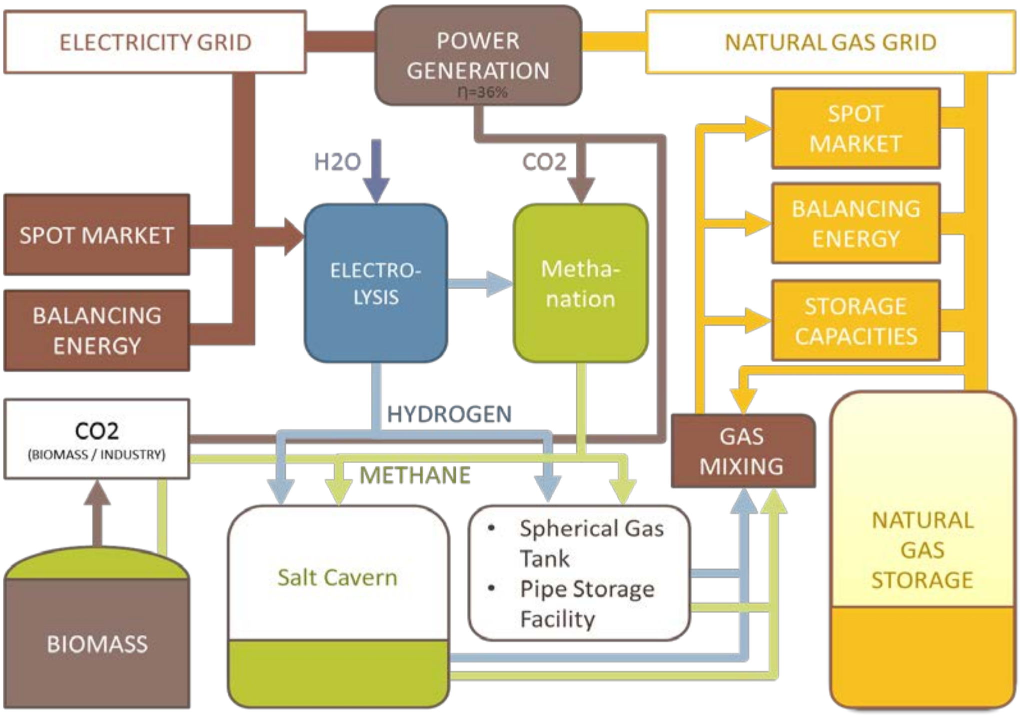

Fig. 1. Set-up of the P2G system model used in the study (power generation efficiency η=36%).

3. Results

3.1. Base Case: Direct sale

3.1.1. Economic evaluation

The P2G system selected is defined for a power-input capacity of 5 MW. The electrolysis plant is run on an efficiency of around 82% and with a cell voltage of 1.8 V, converting the 5 MW of electrical power into 4.1 MW of hydrogen with an hourly volume flow of 1163 Nm^3/h. In an additional step, the methanation plant could convert the 4.1 MW of hydrogen into 3.2 MW of renewable methane, resulting in a total conversion efficiency of 64% (for further details see [2]). In this case, the resulting hourly volume flow would be 290 Nm^3/h.

The annual gas production for the 5 MW system results either in about 36,000 MW for hydrogen or in about 28,000 MW for renewable methane. Further assumptions for the economic analysis are related to the required investment and operating costs (Table 1). The reference P2G system comprises an electrolysis plant with an optional biological methanation facility for further methane processing. In addition, an on-site spherical gas tank for short-term storage is needed as well as corresponding peripherals. Renewable methane in comparison to hydrogen requires only 25% of the geometric volume for short-term (daily) storage and only 25% of compression power. Therefore, costs related to tank storage and peripherals are lower for methane, while construction costs are higher due to the additional methanation plant. Variable operating costs for production of hydrogen contain procurement of electricity in the spot market and water for electrolysis. By assumption, CO_2 for the methanation is being used from a biogas plant at no costs (or benefit in the form of an offset CO_2 tax) and continuously available over the entire year. Fixed operating costs for maintenance and land are higher for methane production, due to higher equipment costs and larger site area needs. Revenues are generated through daily gas sales in the spot market and are higher for hydrogen. In both cases, subsidies in the form of dispensed grid tariffs (7 €/MW) are included for a period of 10 years.

Note that as the yearly operating costs are already higher than the yearly revenues, the P2G system studied yields a negative net cash recovery before tax (NCR BT) and a negative net present value before tax (NPV BT) for both the hydrogen scenario and the renewable methane production scenario (Table 1).The values have been further assessed for the fiscal impact in Germany, which takes the 2012 Renewables Energy Act (EEG), other regulations, and tax payments into account. The annual fiscal and capital allowances are taken care of by a depreciation rate of 10%. The P2G system with additional expenditures for methanation, therefore, provides an increased allowance. However, year by year negative net revenues (revenues minus operating costs) provide neither a basis for investment depreciation nor for tax deductions.

Hydrogen and renewable methane (SNG) are considered as renewable gases within the biogas definition and exempted for 20 years from power tax and grid tariffs for both gas and electricity. However, the P2G system currently receives no exemption from the EEG levy and is being treated as a non-privileged end consumer, since the stored energy is not fed back into the electricity network. Therefore, significant costs for the input electricity in the order of 35.9 €/MW arise. This further burdens the cash flow and creates even more negative values after tax (Table 2).

Table 1

Input assumptions and before tax results for the *Base Case* scenario.

Cash flow items	Unit	Hydrogen	Renewable methane
Yearly production			
Energy	(MW)	36,078	28,104
Volume	(m^3)	10,191,552	2,540,163
Investment			
P2G system	(1000 €)	2997.8	4376.0
Storage	(1000 €)	327.3	239.1
Peripherals	(1000 €)	335.1	246.9
Construction costs	(1000 €)	270.8	366.6
Yearly operating costs			
Fixed	(1000 €)	676.2	731.0
Variable	(1000 €)	2010.8	2010.1
Yearly accruals	(1000 €)	19,4	26.2
Yearly revenues			
Gas sales	(1000 €)	937.2	730.1
Network fee	(1000 €)	25.3	19.7
NCR BT	**(1000 €)**	**(-44,991)**	**(-53,414)**
NPV BT	**(1000 €)**	**(-17,955)**	**(-21,912)**
Specific production costs	(€/MW)	99	133

Abbreviations: P2G – power-to-gas, NCR – net cash recovery, NPV – net present value, and BT – before tax.

3.1.2. Sensitivity analysis

Selected technical- (cell voltage, methanation efficiency), market-, and other economic parameters are varied in a NCR BT sensitivity analysis for a range between ±50%. The results for both hydrogen and methane production are presented in Fig. 2 (see [11] for more details).

Table 2

Tax deduction and ‘after tax’ results for the *Base Case* scenario. Negative net cash recovery after tax (NCR AT) and net present value after tax (NPV AT) results are given in brackets.

With tax	Unit	Hydrogen	Renewable methane
Fiscal Allowance			
Depreciation	(1000 €)	387.0	525.3
Tax			
Corporate tax	(1000 €)	-	-
Industry tax	(1000 €)	-	-
EEG levy	(1000 €)	1576.8	1576.8
NCR (AT)	**(1000 €)**	**(-76,905)**	**(-85,327)**
NPV (AT)	**(1000 €)**	**(-30,152)**	**(-34,107)**
Specific production costs	(€/MW)	143	192

Abbreviations: EEG – German Renewable Energies Act, NCR – net cash recovery, NPV – net present value, and AT – after tax.

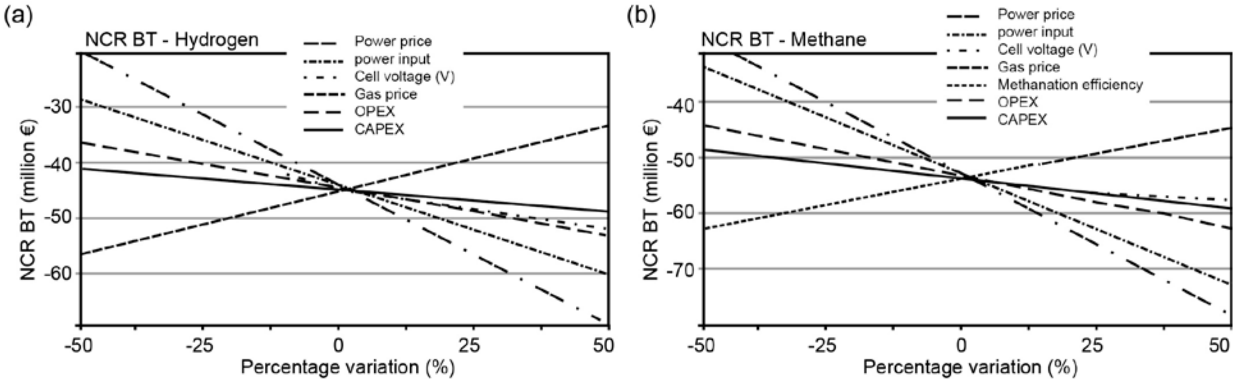

Fig 2. (a) Sensitivity analysis for variations in selected system parameters of a 5 MW P2G system for hydrogen production. The diagram highlights that the operational expenditure (OPEX), capital expenditure (CAPEX), and cell voltage have the lowest impact on the net cash recovery before tax (NCR BT). Note that the cell voltage reduction lowers the NCR BT -12.5%. (b) Sensitivity analysis for variations in selected system parameters of a 5 MW P2G system for renewable methane production. Note that, overall, the NCR BT turns out to be lower for methane production than for hydrogen production.

In both cases the variations of the power and gas prices have the greatest impact on cash recovery. More specifically, a reduction in electricity prices or an increase in gas prices will reduce the negative net cash recovery (NCR BT). Power price changes have a stronger impact than gas price changes, mainly due to conversion loss differences (only 82% of the energy is stored in hydrogen and 64% in methane). Changes in operating costs and investment costs have a significantly lower impact on the outcome than changes in the gas and electricity prices. A variation in power input also has some strong impacts. The positive changes can be attributed to technology changes which would deliver more power for the same investment and operating costs. Increases in conversion efficiency would yield a higher gas output, which is comparable to higher gas prices. As the hydrogen system has an efficiency of 82%, a maximum technical increase by 18% is theoretically comparable to an increase by 18% in the price of gas. The same applies for methane production, where a maximum combined efficiency gain of 36% would have the same effect. From the sensitivity analysis and the selected range of change it becomes obvious that a single parameter alone cannot yield a positive NCR BT. A combination of 50% higher gas prices and 50% lower power prices would drive the NCR BT close to zero. In order to achieve a positive net cash recovery after tax (NCR AT) or even a positive net present value (NPV AT), further benefits from lower investment and OPEX would need to be captured. The challenge of such a project is well expressed in the gas price sensitivity. A gas price of 75 €/MW for hydrogen and 100 €/MW for methane is required to achieve a positive NCR BT. This is about three times higher than current gas prices (approx. 25–26 €/MW).

We did an additional sensitivity analysis for the fiscal impact by varying the EEG levy (Fig. 3), which has increased significantly since the introduction of the Renewable Energies Act in 2000 (EEG 2000) (see [16] for the EEG 2012 considered for this study). The impact of the EEG levy is very similar to that of the power price and, therefore, enhances the negative impact. If the P2G plant was exempted from the EEG levy, the NCR AT in Fig. 3 would be reduced to the NCR BT, as the EEG levy is the only "tax burden" in the after-tax display.

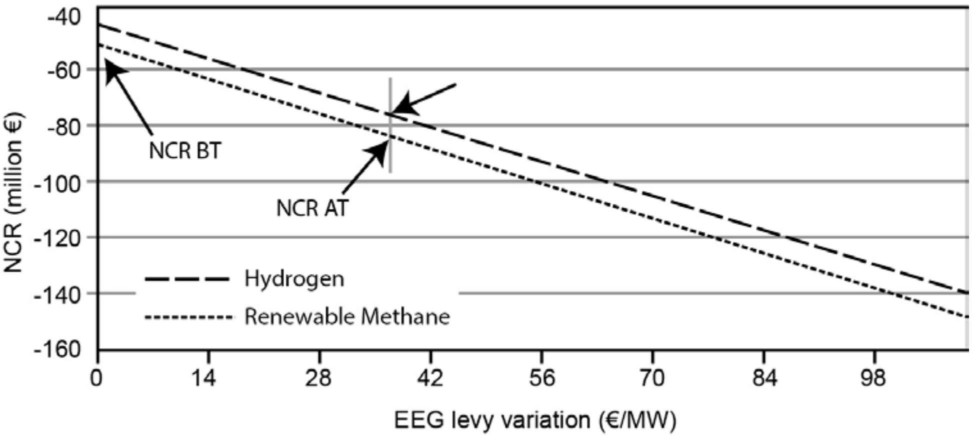

Fig. 3. Impact of variations in the EEG levy on the net cash recovery (NCR AT). Note that the difference between the NCR-BT and NCR-AT is the amount of the levy in absolute values.

3.2. Storage & Arbitrage case: Integration of on-site or decentralized storage

The second investment case *Storage & Arbitrage,* expands the *Base Case* of a P2G system by using a storage device or storage capacities for temporal arbitrage between the energy markets. The objective is to maximize returns by a delay of sales between the spot markets for power and natural gas. Storage operations are optimized in such a way that the NCR as well as the NPV are maximized. The economic comparison focuses on hydrogen and renewable methane production for three types of storage. These are on-site pipe storage facilities, salt caverns, and decentralized storage capacity bookings.

3.2.1. Economic evaluation

Capital expenditures for the electrolysis plant and the methanation facility are equal to the *Base Case*. The storage investment, however, increases significantly above that of the original on-site storage tank in the *Base Case*, especially for the salt cavern (Table 3). The same increases are also visible for peripherals and construction costs as well as for the fixed operating costs. It is obvious from the input data that the investment and operating costs for the salt cavern grow significantly, without any further revenue gains.

Table 3

Cash flow items for the reference scenarios in the *Storage & Arbitrage Case* (negative values in brackets). NCR improvements highlight the deviation of the results relative to the Base Case investment. While decentralized storage capacity bookings provide the best option for hydrogen, pipe storage offers the best (but still negative) NCR BT for methane.

	Hydrogen			Methane		
Cash flow items (in 1000 €)	Salt cavern	Pipe storage	Storage capacity	Salt cavern	Pipe storage	Storage capacity
Investment costs						
P2G system	2997.8	2997.8	2997.8	4376.0	4376.0	4376.0
Storage device	9206	585.5	327.3	7345	798.0	423.4
Peripherals/ Constr. costs	1467	765.0	605.6	1,166	713.6	211.1
Yearly operating costs						
Fixed	1154	725.1	737.4	1125	798	790
Variable	1811	1977	1994	1811	1945	1994
Yearly accruals	72	21	18	62	30	25
Yearly revenues						
Gas sales	863.4	902.0	1023	779.1	1097.2	816
Network fee	22.9	25.0	25.0	18.7	19.5	19.5
NCR BT	**(-64,740)**	**(-46,418)**	**(-43,791)**	**(-65,694)**	**(-46,642)**	**(-51,579)**
NCR improvements	-30.51%	-3.07%	2.74%	-18.79%	14.52%	2.60%
NPV BT	**(-29,018)**	**(-18,697)**	**(-17,411)**	**(-30,798)**	**(-20,843)**	**(-21,287)**
Specific production costs (€/MW)	152	102	99	190	141	134

Abbreviations: P2G - power-to-gas, NCR – net cash recovery, NPV – net present value, and BT – before tax.

All NCR BT figures for the various P2G concepts are still negative (Table 3) but three project concepts have been improved economically through the storage devices. This is caused by the difference to the NCR BT from the *Base Case*, where a better (but still negative) NCR BT and a positive NCR improvement are shown for three concepts. The storage capacity concept improves the NCR by 2–3 % for both gas types, while the pipe storage concept improves only in the methane case, but at a higher level of 15%.

While hydrogen theoretically benefits from decentralized storage, note that a true hydrogen storage model and related costs are likely not properly covered in the assumptions and that such assumptions are also hard to find in the literature. The disadvantages of hydrogen storage in underground storage applications (e.g. lower storage volumes per facility, different compression needs, blending options, etc.) would be passed on to the storage operator, which rationally would integrate these aspects into the costs for his offers. It can be expected that this would increase variable costs by more than 3%, thus offsetting the reported benefits. The greatest economic benefit results for the case of the on-site pipe storage facilities for methane. The NCR BT improves by about 15% through temporal arbitrage. This can be attributed to the flexible use with high extraction rates, which provides the opportunity to sell a large amount of renewable methane volumes at the maximum gas prices.

For completeness, the after-tax calculation results are also reported in Table 4. As already discussed for the *Base Case*, the net cash flows do not provide sufficient positive cash gains for the application of depreciation or deduction of taxes.

Table 4

After-tax information for the reference scenario *Storage & Arbitrage*. While the decentralized storage capacity provides the best option for hydrogen gas, pipe storage is favored for methane gas.

	Hydrogen			Methane		
Cash flow items (1000 €)	Salt cavern	Pipe storage	Storage capacity	Salt cavern	Pipe storage	Storage capacity
Fiscal allowance						
Depreciation	1361	426	368	1275	595	501
Tax						
Corporate tax	-	-	-	-	-	-
Industry tax	-	-	-	-	-	-
EEG levy	1581	1581	1581	1581	1581	1581
NCR AT	**(-97,370)**	**(-78,029)**	**(-75,402)**	**(-98,323)**	**(-79,228)**	**(-83,670)**
NPV AT	**(-41,562)**	**(-30,785)**	**(-29,499)**	**(-43,171)**	**(-32,155)**	**(-33,375)**
Specific production costs (€/MW)	192	146	142	234	185	178

Abbreviations used: EEG – German Renewable Energies Act, NCR – net cash recovery, NPV – net present value, and AT – after tax.

3.2.2. Sensitivity analysis

In this section, a few selective sensitivity cases are discussed, which are related to the storage of gas in a salt cavern. Most other sensitivities, like variations on the base P2G investment or operating costs, have already been shown for the *Base Case*. They would show similar variations in this scenario. The hydrogen storage example in Fig. 4(a) shows that effects on volume and compression are relatively minor within the selected ±50% range of variation, while the cavern depth as an important cost-affecting parameter has a higher effect. However, overall, these effects are significantly smaller than those shown in the *Base Case*, and improvements will not deliver any major contribution towards a more positive NCR BT.

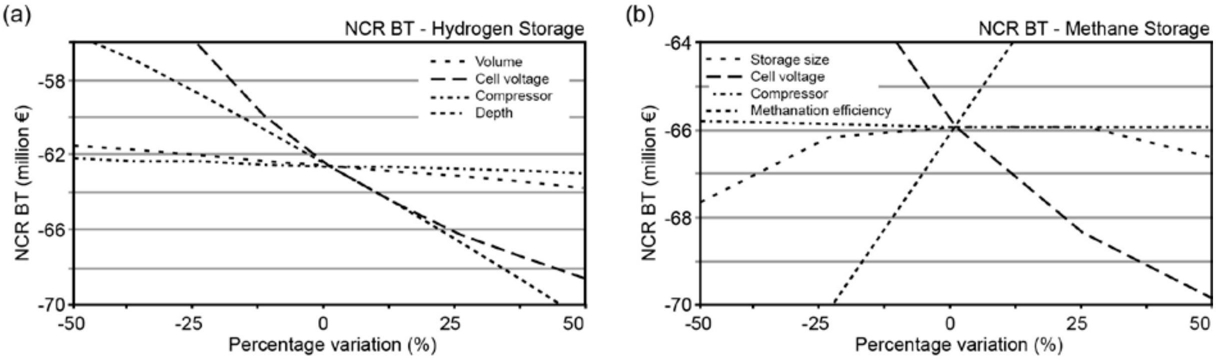

Fig. 4. (a) Comparative sensitivity analysis of the net cash recovery before tax (NCR BT) for variations in storage parameters of a salt cavern as part of a 5 MW P2G system for hydrogen production. (b) Comparative sensitivity analysis for variations in storage size of a pipe storage facility as part of a 5 MW P2G system for renewable methane production.

For the methane case (Figure 4(b)), the storage size has been selected for the sensitivity analysis. Storage itself creates a negative impact on the NCR BT in comparison to the Base Case. An increase in size as well as a decrease would result in an even higher negative impact on the NCR BT. This test confirms the optimization results of the specific cavern size found which creates the minimal loss.

3.3. Storage & Balancing Case: P2G storage operation for load balancing

In the *Storage & Balancing* investment case the storage devices are used to establish a close connection between the control power market and the gas balancing market. Negative reserve capacity is offered on the secondary reserve market for power and positive external balancing energy in one of the German market areas for natural gas (Net Connect Germany, NCG). Note that the procurement of balancing energy in the two German gas market areas (NCG, Gaspool) should be mainly carried out on the EEX spot market and forms the primary position in the merit-order. Hereby, the market areas are irrelevant, as long as procurement is also economical. The economic viability of a P2G system, which operates between these markets, is dependent on the number of lots and the duration for the retrieval of external balancing energy. The economic viability of a P2G system, which operates between these markets, is dependent on the number of lots and the duration for the retrieval of external balancing energy.

The following results provide the general economics of a P2G system using 1 or 2 lots on the gas market (i.e. 30 MW/h or 60 MW/h). The retrieval of power as well as gas is uncertain. However, power deviations are more frequent and more periodic, with a relatively constant average level over the entire year, while P2G storage will be influenced by seasonality. Modeling results have been optimized on a stochastic basis for randomly chosen variables.

Nonetheless, the retrieval of secondary reserve capacity is controlled by the ranking in the merit order (generally the energy system with the lowest marginal cost - i.e. renewable energy technologies with low or zero operating cost), which is dependent on the energy rate offered. An average supply function based on historical data is used to determine the merit order position of the energy system on an hourly basis for an entire year. The higher the energy rate, the higher the probability of retrieval hours within one year.

3.3.1. Economic evaluation

The economic evaluation is based on the optimum facility specification of the P2G system as well as the storage device. The required investment and operating costs have been defined according to the project-specific cost functions. These items, together with resulting revenues – i.e. the NCR and NPV (before tax, BT) – are shown in Table 5. Every P2G system consists of selected numbers of 5 MW plants (4.11 MW electrolysis / 3.6 MW methanation), which are summed up to the corresponding capacity. This is essential due to the fact that the technical limits for an electrolysis plant are given through the feasible volume flow rates.

Table 5

Input data and cash flow results before tax of the economic evaluation for the reference scenarios in *the Storage & Balancing Case*. The largest revenues are generated from the external balancing- and secondary reverse market.

Cash flow items	Unit	Hydrogen		Renewable methane	
Capacity		20 MW	40 MW	25 MW	50 MW
Power output		~15 MW/h	~30 MW/h	~15 MW/h	~30 MW/h
Yearly production					
Energy	(MW)	29,468	58,936	27,254	54,508
Volume	(m^3)	8,324,281	16,648,563	2,463,284	4,926,567
Investment costs					
P2G system	(1000 €)	11,005	22,052	20,666	41,373
Storage device	(1000 €)	9853	10,980	1180	2127
Peripherals	(1000 €)	1745	2776	2059	3956
Yearly revenues					
Energy rate external B.	(1000 €)	682	1365	674	1348
Demand rate external B.	(1000 €)	210	420	210	420
Demand rate SR	(1000 €)	1805	3610	2175	4981
Residual gas sale	(1000 €)	231	463	220	440
Network fees	(1000 €)	20.6	41.2	19.0	38.1
Yearly operating costs					
Fixed	(1000 €)	2001	3192	1976	3470
Variable	(1000 €)	368	867	415	1024
Yearly accruals	(1000 €)	114	181	120	239
NCR BT	**(1000 €)**	**(-8342)**	**9812**	**(-1198)**	**19,315**
NPV BT	**(1000 €)**	**(-15,018)**	**(-15,258)**	**(-13,079)**	**(-18,315)**
Specific production costs BT	(€/MW)	191	153	201	200
IRR BT	%	n.a.	2.4	n.a.	3.3
Amortization BT	Years	n.a.	16	n.a.	15
PIR BT		-0.37	0.27	-0.05	0.36

Abbreviations used: P2G – power-to-gas, NCR – net cash recovery, NPV – net present value, BT – before tax, SR – secondary reserve market, IRR – internal rate of return, PIR – profit-to-investment ratio, and n.a. – not applicable.

The revenues comprise the demand rates for capacity offers on both the external balancing- and the secondary reserve markets, the energy rate for gas, the residual gas sales at the end of each storage season and the network fee paid over 10 years with demand rates for the offer of secondary reserve capacity providing the highest contribution to revenues. In all scenarios, revenues are higher than annual operating costs, therefore providing positive net revenues. Fixed operating costs are significantly higher than the variable costs. Note that the investment costs for the system are getting closer to each other as the high cavern costs in the hydrogen cases nearly offset the cost of the methanation plant in the methane P2G system. The higher capacity operations for hydrogen as well as for methane yield a positive NCR BT outcome. The payback time before tax would be around 15 years. The profit to investment ratio (PIR BT) is in the order of 30%, and the NCR BT for the lower capacity units improves significantly in comparison to the *Storage & Arbitrage Case*, but still remains negative. These systems have to be operated for additional years in order to achieve a before-tax payback (21 years for methane and 36 years for hydrogen). For the same offer of external balancing energy, the NCR BT of methane production is about twice as high as for hydrogen. Despite the positive NCR for the higher capacity cases the NPV turns negative in the before-tax assessment already at a discount rate of 10%.

The economic evaluation results after tax show that all earnings are negative, though depreciation and accruals together are higher than the generated profit before tax (Table 6). Therefore, only the EEG levy is applied for the German fiscal system and in all cases provides a negative outcome. Again, an exemption upon request should be provided by the German government.

Table 6

Depreciation and taxes with resulting net cash recovery after tax (NCR AT) for reference scenarios in the *Storage & Balancing Case*.

Cash flow items		Hydrogen		Renewable methane	
Capacity Power output	Unit	20 MW 15 MW/h	40 MW 30 MW/h	25 MW 15 MW/h	50 MW 30 MW/h
Yearly fiscal allowance					
Depreciation	(1000 €)	2260	3580	2239	4745
Yearly tax					
Corporate tax	(1000 €)	-	-	-	-
Industry tax	(1000 €)	-	-	-	-
EEG 2012 levy	(1000 €)	1262	2525	1578	3157
NCR AT	(1000 €)	(-32,207)	(-37,799)	(-30,811)	(-49,967)
Spec. production costs AT	(€/MW)	234	197	273	261

Abbreviations used: EEG – German Renewable Energies Act, NCR – net cash recovery, and AT – after tax.

3.3.2. Sensitivity analysis

The sensitivity analysis focuses on the two higher capacity P2G systems. Figure 5(a) shows the analysis on the 40 MW P2G system for hydrogen, with sensitivities of costs and revenues for a range of parameter variations of up to ±50%.

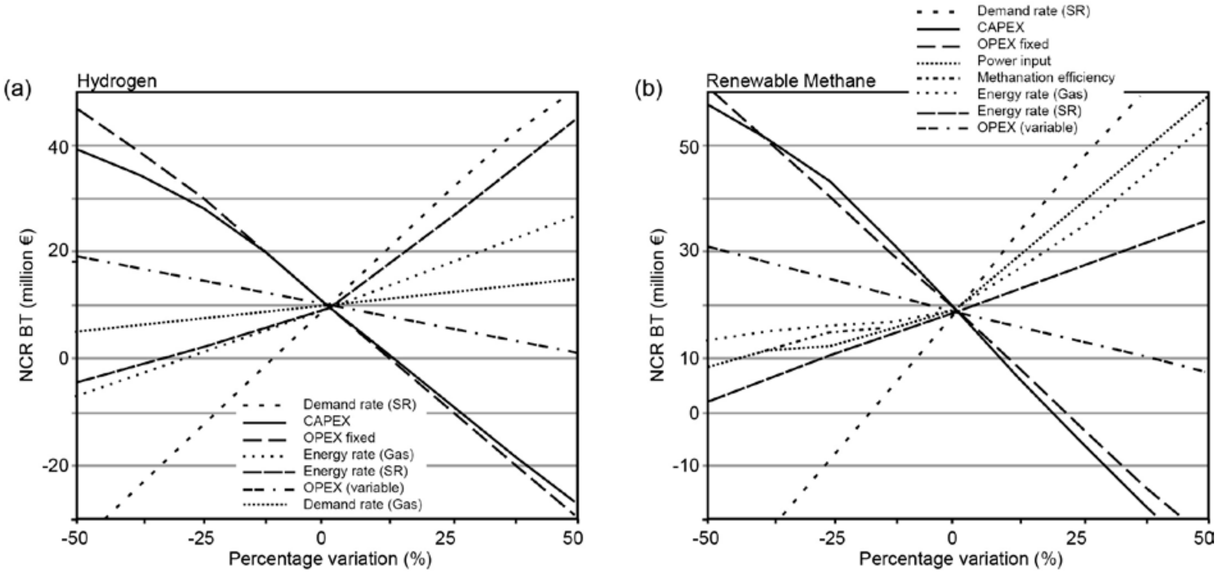

Fig. 5. (a) Sensitivity analysis for variations in selected system parameters of a 40 MW P2G system for hydrogen generation operating between the balancing energy markets. The gas demand rate is the least sensitive parameter to affect the net cash recovery before tax (NCR BT), while the secondary reserve (SR) demand rate offers the highest potential to improve the NCR BT. (b) Sensitivity analysis for variations in selected system parameters of a 40 MW P2G system for methane production operating between the balancing energy markets. Abbreviations used: CAPEX – capital expenditures, OPEX – operating expenditures.

On the revenue side, the NCR BT can best be improved by increasing demand rates for the capacity offered on the secondary reserve market, followed by the energy rate on the secondary reserve market, gas energy rate, and gas demand rate. On the cost side, a percentage reduction on the project’s CAPEX and fixed operating costs would yield the highest improvements for the percentage change, similar to the dimension of the demand rate for the offered capacity on the secondary reserve market. Reductions of variable operating costs generate a lower NCR BT impact.

Generally, it should be expected that increasing energy rates for secondary reserve capacity should have a negative impact, though variable costs and the amount of volume increase. However, it needs to be noted that residual gas volumes are offered on the spot market for natural gas at the end of a storage season. The traded volumes increase with a rising energy rate for secondary reserve capacity, as more and more power is retrieved. The benefits are limited to the trade-off between the energy rate and the natural gas price. Fig. 5(b) provides a similar sensitivity analysis on costs and revenues for the 50 MW P2G system with methanation for generating renewable methane. This sensitivity shows similar parameter behaviors as well as similar dimensions of a positive change in the NCR BT for the increase in revenue-generating parameters and the reduction of operating costs and project CAPEX.

4. Discussion

All P2G systems (~5 MW) assessed in the *Base Case* and the *Storage & Arbitrage Case* have negative net cash recoveries before tax (NCR BT) regardless of the gas type or storage operations (Fig. 6). The integration of a salt cavern for long-term storage even further deteriorates the negative NCR BT. Overall, gas storage only improves the outcome with some smaller benefits reaped through the integration of less expensive gas tanks or pipe storage tanks. The P2G systems operating between the balancing markets in the *Storage & Balancing Case* provide more positive outcomes, especially for higher capacity systems (~50 MW), showing positive NCR BT. Renewable methane shows the highest NCR, due to the increased capacity offered on the secondary reserve market, and reduces storage costs through the integration of a pipe storage facility. Hydrogen production also features a positive outcome for the high capacity plant, although only with a probability of 65%. However, in this case a salt cavern, having higher investment costs, is needed to manage the higher hydrogen volumes. The impact of fiscal payments (after tax) are generally low, as all scenarios show less economic viability.

Considering the standard deviations from Monte Carlo simulations for all NCR values before tax, we find that H_2 and CH_4 show similar values, except for the *Storage & Balancing Case*. The integration of a surface storage device for P2G shows, for all cases, lower standard deviations by more than one third in comparison to the *Base Case*. This means that storage reduces the risk of price differentials, and provides a more robust operation between the electricity sector and the gas sector in economic terms. The option of using a storage device between the balancing markets for power and gas, however, provides increased standard deviations with increasing system capacity. This is due to at least two important factors. First, the retrieval of capacity for both the electricity and gas markets is characterized through uncertain fluctuations in the grids. Second, bid sizes and capacity rates provide price risks and uncertain positions in the merit order for the retrieval of system services.

A further comparison is given through the average specific production costs (Fig. **6**, upper right plot). In comparison to H_2, the generation of renewable methane has higher production costs due to additional capital investment requirements for methanation and due to the lower overall conversion efficiency. The specific production costs also show what gas price is needed to achieve a 10% rate of return from the project or, put differently, that the NPV is just zero at a 10% discount rate. Here, it is obvious that the cases assessed are relatively far off from representing profitable return scenarios.

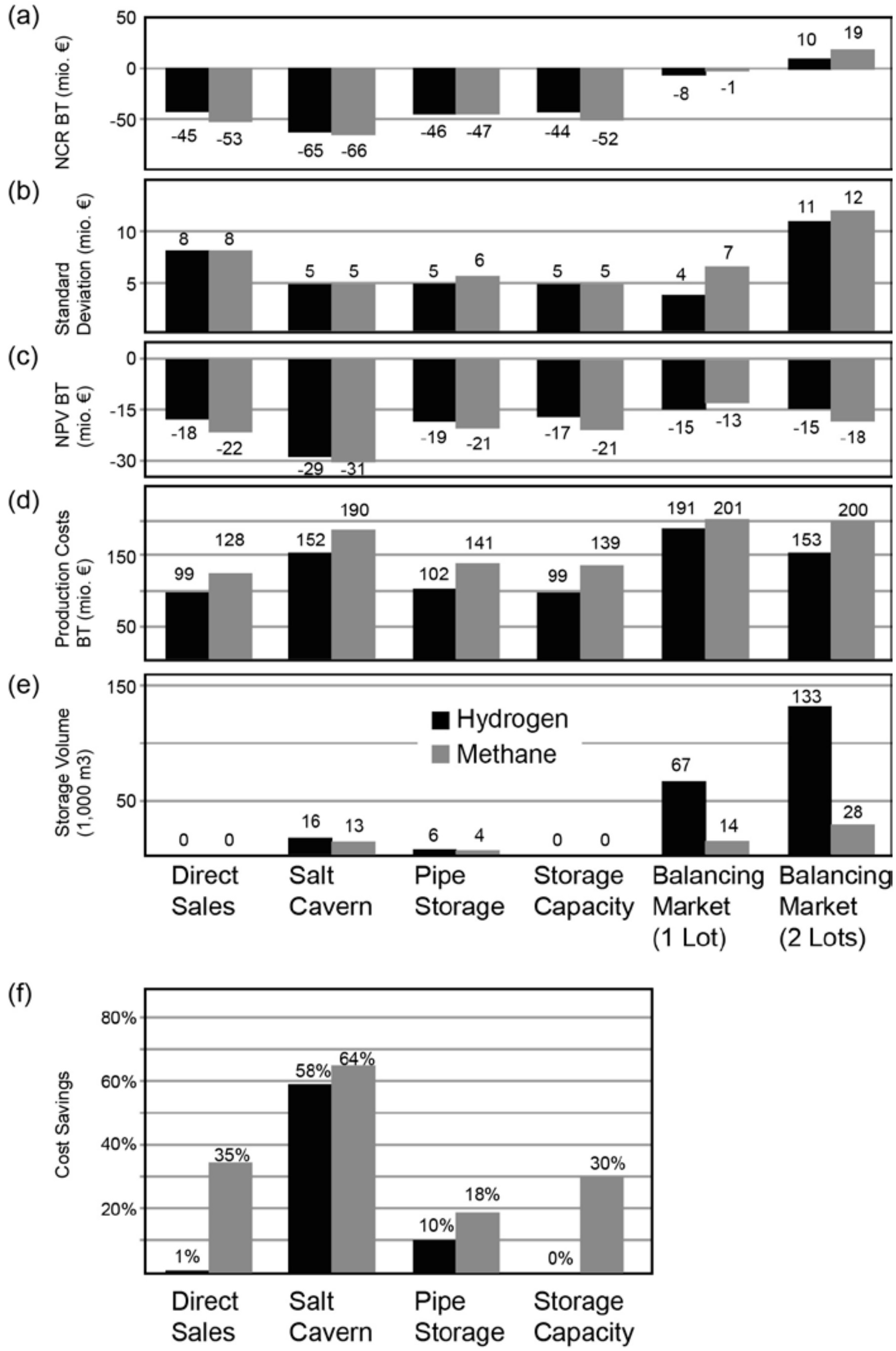

Fig. 6. (a) Comparison of average values for net cash recoveries (NCRs) before tax of investigated scenarios for hydrogen and renewable methane. (b) Comparison of standard deviations of NCRs before tax of investigated scenarios for hydrogen and renewable methane. (c) Comparison of average values of net present values (NPVs) before tax for hydrogen and renewable methane for the investigated scenarios. (d) Comparison of production and storage costs for hydrogen and renewable methane for each scenario. (e) Comparison of storage volume requirements for hydrogen and renewable methane for each scenario. (f) Comparison of cost-saving requirements (CAPEX and OPEX) for the *Base Case* and *Storage & Arbitrage Case* to achieve a 10% project return (NPV AT @ 10% equal zero). Note that the *Base Case* and the *Storage & Arbitrage Case* were assessed without electricity costs.

Finally, we compare storage sizes for a pressure range of 6–18 MPa (Fig. **6**, lower right plot). For the *Base Case*, storage size has only a minor impact on the required geometric volume, as the on-site tank storage has the sole purpose of collecting the daily production volumes. The same applies to the for the decentralized storage capacity of the *Storage & Arbitrage Case*. Cavern storage volume is about three times as high as that of pipe storage. A significant difference results from the optimization in the *Storage & Balancing Case*, where hydrogen requires a five times larger geometric storage volume compared to methane. The only possible solution which could manage this type of operation is given through the integration of a larger salt cavern, which would, however, necessitate significant investments. Pipe storage as an alternative would require a pipe length of several kilometers. In the case of a spherical gas tank application, the installed capacity would require more than 100 units for a 40 MW H_2-P2G system [9].

5. Conclusion

Presently, as was shown for the case of Germany, P2G cannot be economically operated between the balancing markets for power and gas, assuming an investment case at 10% discounting. An operation between the spot markets, with the purpose of direct sales or temporal arbitrage, has high uncertainties, while also creating highly negative economic results. The storage of hydrogen in a storage device is less attractive due to the incompressibility of hydrogen. The results from our analysis suggest to sell hydrogen gas directly and to blend the gas into the pipeline grid. In the case of balancing energy, a high investment in a salt cavern would be required for the storage of larger quantities of hydrogen gas. The storage of renewable methane has a positive economic impact. For temporal arbitrage and for balancing energy a pipe storage facility turns out to be the favored storage solution. Contractual storage capacities would theoretically improve the economic viability of hydrogen, if allowed. For renewable methane, capacity bookings provide little positive impact and lower flexibility. Both P2G technologies are exposed to price risks of the two commodities. Furthermore, balancing energy increases the risk through the uncertainty of retrieval. Predictions of the economic outcome are highly uncertain, so that the results have to be treated with some caution. Finally, we find that to promote pipe storage for P2G, a fixed feed-in tariff of 100 € MW^{-1} for hydrogen and 130 € MW^{-1} for methane would be required.

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