Online-Appendix zu

„Economics of Hydrogen: Scenario-based Evaluation of the Power-to-Gas Technology“

Ubald Bauer

Technische Universität München

Junior Management Science 5(4) (2020) 532-561

Appendix

A.1 Construction of the contribution margin term

The optimized contribution margin is affected by six different price phases:

Phase	Price constellation	PtG operating mode	p^{b+}	p^{+}
1	$p^b(t) \geq p^s(t) \geq CV \geq 0$	PtG facility idle	$p^b(t)$	$p^s(t)$
2	$p^b(t) \geq CV > p^s(t) \geq 0$	Electrolysis from RES power	$p^b(t)$	CV
3	$CV > p^b(t) \geq p^s(t) \geq 0$	Electrolysis from RES & grid power	CV	$p^b(t)$
4	$CV \geq p^s(t) > p^b(t)$	Electrolysis from grid power	CV	$p^s(t)$
5	$p^s(t) > p^b(t) \geq CV \geq 0$	PtG facility idle	$p^b(t)$	$p^s(t)$
6	$p^s(t) > CV > p^b(t)$	Electrolysis from grid power	CV	$p^s(t)$

Table 10: Phase distinction.

In phase 1, the contribution margin is composed exclusively from the revenues from power feed-in, which is remunerated by the wholesale electricity price and the subsidy premium, if a subsidy is granted, such that:

$$CM_1(t|k_e, k_h) = \left(epex^+(t) + sub \cdot premium(t)\right) \cdot CF(t) \cdot k_e. \quad (39)$$

In phase 2, electricity from the RES primarily is converted to hydrogen. Any excess power not absorbed by the PtG facility is fed into the grid. The EEG subsidy is only granted for internally absorbed power if the feed-in requirement is waived. Furthermore, renewable power is subject to statutory fees, captured by $markup^{res}$:

$$markup^{res} = tax^{res} \cdot \left(fees^{res}_{fix} + fees^{res}_{var,i}\right).$$

The contribution margin equals:

$$CM_2(t|k_e, k_h) = \left(epex^+(t) + sub \cdot premium(t)\right) \cdot [CF(t) \cdot k_e - z(t|k_e, k_h)] \quad \text{Revenue for electricity fed into the grid}$$

$$+[CV - markup^{res}] \cdot z(t|k_e, k_h) \quad \text{PtG contribution margin from RES power}$$

$$+sub \cdot (1 - fit) \cdot premium(t) \cdot z(t|k_e, k_h). \quad \text{Premium on internally absorbed RES power}$$

The term is then transformed by aggregating all components with factor $z(t|k_e, k_h)$:

$$CM_2(t|k_e, k_h) = \left(epex^+(t) + sub \cdot premium(t)\right) \cdot CF(t) \cdot k_e$$

$$+z(t|k_e, k_h) \cdot [CV - epex^+(t) - markup^{res} - fit \cdot sub \cdot premium(t)$$

$$+sub \cdot premium(t) - sub \cdot premium(t)].$$

The majority of the term in the second line can be substituted by $p^s(t)$ and the third line is eliminated, such that:

$$CM_2(t|k_e,k_h) = \left(epex^+(t) + sub \cdot premium(t)\right) \cdot CF(t) \cdot k_e + [CV - p^s(t)] \cdot z(t|k_e,k_h). \quad (40)$$

In phase 3, electricity from the RES is utilized for the PtG operations and, in case of excess capacity, grid electricity is absorbed additionally.
Therefore, the resulting contribution margin equals the contribution margin of phase 2 plus the margin from the additional grid power conversion:

$$CM_3(t|k_e,k_h) = CM_2(t|k_e,k_h) + [CV - p^b(t)] \cdot \left(k_h - z(t|k_e,k_h)\right).$$

This results in the term:

$$CM_3(t|k_e,k_h) = \left(epex^+(t) + sub \cdot premium(t)\right) \cdot CF(t) \cdot k_e + [CV - p^s(t)] \cdot z(t|k_e,k_h) + [CV - p^b(t)] \cdot \left(k_h - z(t|k_e,k_h)\right),$$

which can be transformed by resolving the last component and aggregating all terms with the factor $z(t|k_e,k_h)$. Thus:

$$CM_3(t|k_e,k_h) = \left(epex^+(t) + sub \cdot premium(t)\right) \cdot CF(t) \cdot k_e + [CV - p^b(t)] \cdot k_h + [p^b(t) - p^s(t)] \cdot z(t|k_e,k_h). \quad (41)$$

In phase 4, renewable electricity is fed into the grid or curtailed, and only grid-supplied electricity is converted in the PtG facility, leading to the contribution margin:

$$CM_4(t|k_e,k_h) = \left(epex^+(t) + sub \cdot premium(t)\right) \cdot CF(t) \cdot k_e + [CV - p^b(t)] \cdot k_h. \quad (42)$$

Phase 5 equals the PtG operations in phase 1, the same applies for phase 6 and 4.
Therefore: $CM_5(t|k_e,k_h) = CM_1(t|k_e,k_h)$ *and* $CM_6(t|k_e,k_h) = CM_4(t|k_e,k_h)$.

The presented margins of each phase, can then be conveniently aggregated to the optimized contribution margin by using the auxiliary variables $p^{b+}(t)$ and $p^+(t)$ to substitute the values observable in *Table 10*:[109]

$$CM(t|k_e,k_h) = \left(epex^+(t) + sub \cdot premium(t)\right) \cdot CF(t) \cdot k_e + [p^{b+}(t) - p^b(t)] \cdot k_h + [p^+(t) - p^s(t)] \cdot z(t|k_e,k_h).$$

[109] The proof follows the procedure shown in the Appendix of Glenk and Reichelstein (2019b).

A.2 Anomalies of the allocation of the EEG levy

The allocation of the cost associated to the full rate of the EEG levy payable for the non-exempt electricity volume can cause anomalies, when different levy rates apply to the two sources of electricity, the renewable energy system and the public grid.

If the cost of the levy was allocated equally among all units of electricity consumed, the resulting levy for different electricity consumption scenarios would be:

Grid power consumption [MWh]	Power consumption [in MWh] from a RES ≤ 750 kW => EEG levy reduced to 40 % of the full rate									
	200	400	600	800	1000	1200	1400	1600	1800	2000
200	4.55	3.90	3.58	3.38	2.83	2.44	2.15	1.92	1.74	1.59
400	5.20	4.55	4.16	3.48	3.00	2.64	2.36	2.13	1.95	1.79
600	5.53	4.94	4.13	3.56	3.13	2.79	2.52	2.30	2.12	1.96
800	5.72	4.78	4.11	3.61	3.22	2.91	2.65	2.44	2.26	2.11
1000	5.43	4.67	4.10	3.66	3.30	3.01	2.77	2.56	2.39	2.23
1200	4.67	4.10	3.66	3.30	3.01	2.77	2.56	2.39	2.23	2.10
1400	4.10	3.66	3.30	3.01	2.77	2.56	2.39	2.23	2.10	1.98
1600	3.66	3.30	3.01	2.77	2.56	2.39	2.23	2.10	1.98	1.88
1800	3.30	3.01	2.77	2.56	2.39	2.23	2.10	1.98	1.88	1.78
2000	3.01	2.77	2.56	2.39	2.23	2.10	1.98	1.88	1.78	1.70

Figure 14: Equal allocation of the EEG levy to both grid and renewable electricity.

Grid power consumption [MWh]	Power consumption [in MWh] from a RES ≤ 750 kW => EEG levy reduced to 40 % of the full rate									
	200	400	600	800	1000	1200	1400	1600	1800	2000
200	2.60	2.60	2.60	2.60	2.27	2.01	1.81	1.65	1.51	1.40
400	2.60	2.60	2.60	2.32	2.10	1.92	1.77	1.64	1.53	1.43
600	2.60	2.60	2.36	2.17	2.00	1.86	1.74	1.63	1.54	1.46
800	2.60	2.39	2.22	2.06	1.93	1.82	1.72	1.63	1.55	1.48
1000	2.41	2.26	2.12	1.99	1.89	1.79	1.70	1.62	1.55	1.49
1200	2.04	1.93	1.83	1.74	1.66	1.58	1.51	1.45	1.40	1.34
1400	1.77	1.69	1.61	1.54	1.48	1.42	1.36	1.31	1.27	1.23
1600	1.57	1.50	1.44	1.38	1.33	1.28	1.24	1.20	1.16	1.13
1800	1.40	1.35	1.30	1.26	1.21	1.18	1.14	1.10	1.07	1.04
2000	1.27	1.23	1.19	1.15	1.12	1.08	1.05	1.02	1.00	0.97

Figure 15: Ratio-based allocation of the EEG levy payable on renewable electricity.

The scenarios above are based on an EEG levy with a full rate of 6.50 €ct/kWh and the rate reduced to 40% at 2.60 €ct/kWh. *Figure 14* shows the resulting average rates of the EEG levy, if cost was allocated equally. It can be observed that the allocated cost is above the reduced rate of 2.60 €ct/kWh payable for own electricity consumption. *Figure 15* follows the allocation according to the ratio 40:100, where own electricity consumption is weighted at 40% and power consumption from the grid is weighted fully. The resulting allocation is continuous and shows a pattern, which sets the right incentives to reward higher consumption with a lower levy rate. The allocation can be mathematically expressed depending on power consumption (Q^{grid}, Q^{res}):

$$eegLevy^{res}(y|Q^{grid}, Q^{res}) = \frac{totalCost_{eegLevy} \cdot \frac{40\% \cdot Q^{res}}{100\% \cdot Q^{grid} + 40\% \cdot Q^{res}}}{Q^{res}}. \tag{43}$$

$$eegLevy^{grid}(y|Q^{grid}, Q^{res}) = \frac{totalCost_{eegLevy} \cdot \frac{100\% \cdot Q^{grid}}{100\% \cdot Q^{grid} + 40\% \cdot Q^{res}}}{Q^{grid}}. \tag{44}$$

A.3 Maximum value of synergies

In order to determine if an integrated energy system possesses a break-even price, it is necessary to identify the maximum value of synergies attainable through the integration of the renewable energy system and the PtG facility. Based on observations it became evident that the maximum value of synergies in some scenarios – contrary to logic – can decrease at a rising price of hydrogen in a limited range. This development is related to the variable statutory fees which decrease when more electricity is converted, as discussed in section *3.3 Circularity problem,* provided that power consumption is above the legal threshold of 1 GWh. When the fees payable on grid power drop by a higher amount than the fees on renewable power, this lowers the benefit of converting self-produced power instead of grid power and thus shrinks the synergistic value. When considering an undersized renewable energy source, this effect can fully unfold, while for a system with a more balanced capacity ratio the effect is much less pronounced, as becomes visible in *Figure 16*.

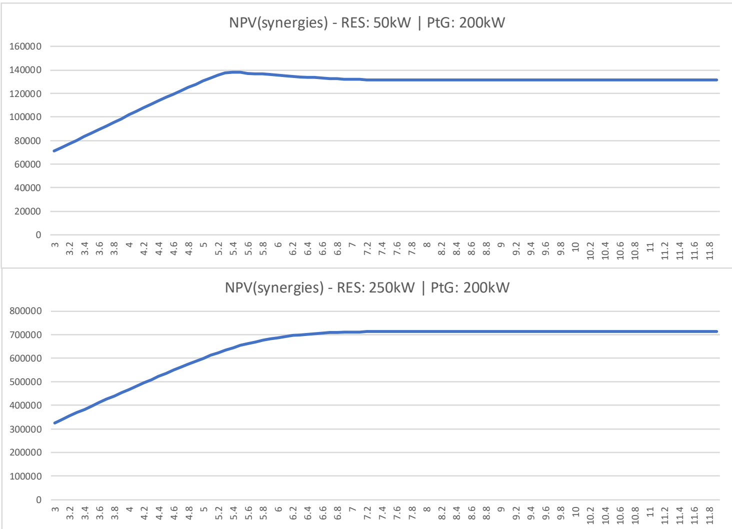


Figure 16: Synergistic value at a variation of the hydrogen price for differently sized systems.

At some point, the PtG facility runs at full load, so no additional power can be converted. That is, when the upper bound of the value of synergies appears. For the mathematical proof of the upper bound refer to *A.4*.

For the purpose of defining if a break-even point exists, based on equation (34), I use the upper bound value of the NPV of synergies as $NPV_{syn}^{\max}$, which is the valid maximum NPV for the entire price range, while the little pronounced peak of NPV_{syn} is only a valid maximum in the respective range. For calculation of the upper bound I compute NPV_{syn} at a very high price of hydrogen. Thus, I obtain the maximum value of synergies by:

$$NPV_{syn}^{max} = NPV_{syn}^{upper} = NPV_{syn}(price = 10000).$$

A.4 Proof of upper bound of the net present value of synergies

Consider the synergistic term:

$$NPV_{syn}(k_e, k_h) = (1-\alpha) \cdot L \cdot (\overline{p^+}_{Tm} - \overline{p^s}_{Tm}) \cdot z_{xy}(k_e, k_h).$$

With: $$z_{xy}(k_e, k_h) = \frac{1}{T \cdot m} \cdot \int_0^{T \cdot m} z(t|k_e, k_h) \cdot \frac{p^+(t) - p^s(t)}{\overline{p^+}_{Tm} - \overline{p^s}_{Tm}} \cdot \frac{xy(t)}{\overline{xy}_{Tm}} dt.$$

With: $$p^+(t) = \max\{ min \ \{p^b(t), CV\}, p^s(t) \}.$$

With: $$CV = [\eta_h \cdot (p_h - w_h)] + CV_o \cdot o2.$$

The synergistic term only depends on the price of hydrogen p_h through the conversion value CV, which affects $p^+(t)$. A rising hydrogen price raises the conversion value. At some point the conversion value is higher than the price of grid electricity $p^b(t)$ for all t. Thus, the formula for $p^+(t)$ loses its dependency on CV, because the minimizer $min\{p^b(t), CV\}$ always evaluates to $p^b(t)$. At that point the synergistic term loses its dependency on the conversion value and remains constant when the hydrogen price is furtherly increased. An upper bound is reached.

A.5 Compensation ratio of a negative NPV of the renewable energy system

The stand-alone NPV of the renewable energy system is defined by:

$$NPV_{RES}(k_e) = (1-\alpha) \cdot L \cdot \left(\Gamma^{ep^+} \cdot \overline{epex^+}_m + sub \cdot premium - LCOE\right) \cdot \overline{CF}_m \cdot k_e.$$

It can be expressed as:

$$NPV_{RES}(k_e) = NPV_{RES}(1) \cdot k_e.$$

This means, that the stand-alone NPV of the renewable source scales proportional to k_e.

The synergistic term is defined by:

$$NPV_{syn}(k_e, k_h) = (1-\alpha) \cdot L \cdot (\overline{p^+}_{Tm} - \overline{p^s}_{Tm}) \cdot z_{xy}(k_e, k_h). \quad (45)$$

With: $$z_{xy}(k_e, k_h) = \frac{1}{T \cdot m} \cdot \int_0^{T \cdot m} z(t|k_e, k_h) \cdot \frac{p^+(t) - p^s(t)}{\overline{p^+}_{Tm} - \overline{p^s}_{Tm}} \cdot \frac{xy(t)}{\overline{xy}_{Tm}} dt. \quad (46)$$

With: $$z(t|k_e, k_h) = \min\{CF(t) \cdot k_e, k_h\}.$$

Combining (45) and (46), the synergistic term evaluates to:

$$NPV_{syn}(k_e, k_h) = (1-\alpha) \cdot L \cdot \frac{1}{T \cdot m} \cdot \int_0^{T \cdot m} z(t|k_e, k_h) \cdot [p^+(t) - p^s(t)] \cdot \frac{xy(t)}{\overline{xy}_{Tm}} dt.$$

During variation of k_e the terms $z(t|k_e, k_h)$ and $[p^+(t) - p^s(t)]$ are affected, the latter indirectly through the value of the variable statutory fees, whose average rate varies depending on the converted electricity volume, provided the non-exempt volume is exceeded.

Suppose, a renewable energy system exhibits a negative stand-alone NPV and is undersized compared to the PtG facility, such that: $k_e \ll k_h$.

As a result, the capacity of the PtG facility will never determine the value of the minimizer $\min\{CF(t) \cdot k_e, k_h\}$ of the expression $z(t|k_e, k_h)$.

Therefore:

$$z(t|k_e, k_h) = CF(t) \cdot k_e.$$

When disregarding the effect of the variable statutory fees, present in the term $[p^+(t) - p^s(t)]$, the synergistic term can be simplified to:

$$NPV_{syn}(k_e) = NPV_{syn}(1) \cdot k_e. \tag{47}$$

Thus, for under-sized renewable energy systems the NPV of synergies also scales proportional to k_e, when the effect from variable statutory fees is disregarded.

The analysis of the second term $[p^+(t) - p^s(t)]$ has shown, that there exist various scenarios regarding the applied statutory fees on electricity, which can affect the development of the term differently. In some scenarios the resulting term value develops positively, in others the term decreases in its value.

Therefore, the term $[p^+(t) - p^s(t)]$ can either have an increasing or decreasing effect on the development of $NPV_{syn}(k_e)$ and can lead to an increase above factor k_e, in some cases.

However, as soon as the point is reached, where not only k_e determines the value of $z(t|k_e, k_h)$, but $CF(t) \cdot k_e$ evaluates to an amount exceeding k_h, the term $z(t|k_e, k_h)$ starts scaling with a decreasing factor until NPV_{syn} reaches a constant value.

In a nutshell, when the increase of the renewable energy system capacity results in a growth of $NPV_{syn}(k_e)$ above factor k_e, the compensation ratio $\frac{NPV_{syn}}{|NPV_{RES}|}$ grows, since NPV_{RES} always scales with the factor k_e. This would only occur for under-sized renewable energy systems.

As soon as the renewable source is scaled sufficiently large, compared to the PtG facility, further scaling of RES will not entirely benefit the synergistic value, since a full load of the electrolyzer based on renewable power is reached increasingly. Hence, $NPV_{syn}(k_e)$ will decrease with a factor below k_e resulting in a falling compensation ratio.

A.6 Selected screenshots of the implemented scenario simulator tool

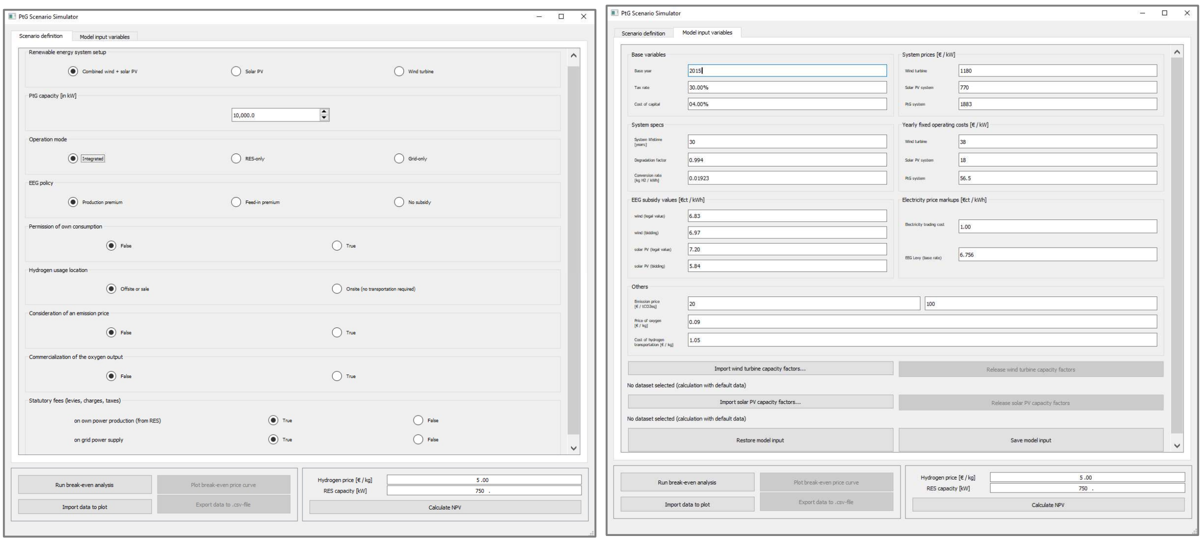


Figure 17: Graphical user interface of the simulator tool for selection of the model input.

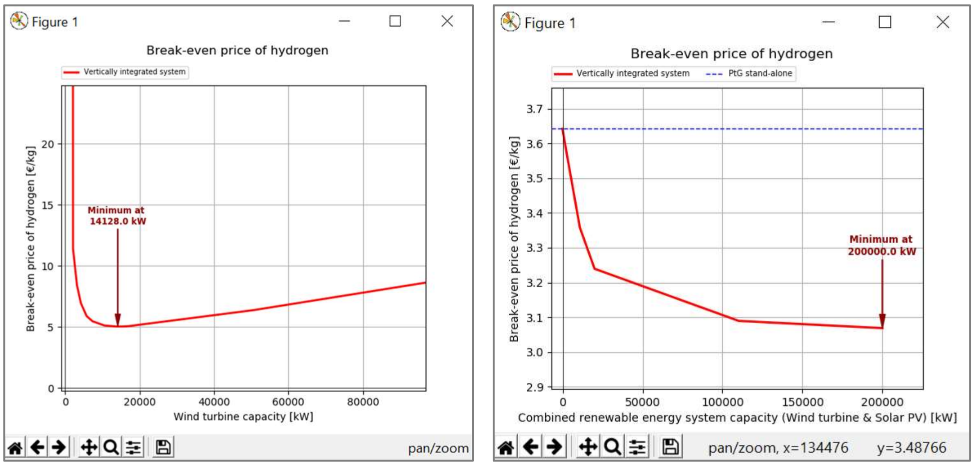
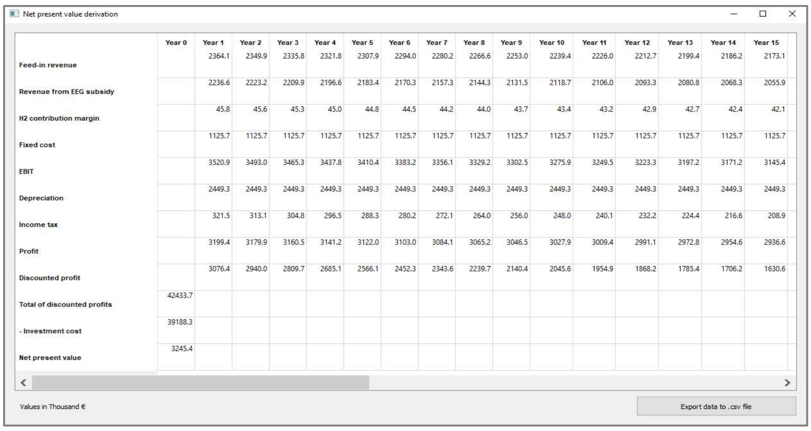


Figure 18: Graphical outputs of the break-even curve from the optimization algorithm.



Net present value derivation

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Feed-in revenue		2364.1	2349.9	2335.8	2321.8	2307.9	2294.0	2280.2	2266.6	2253.0	2239.4	2226.0	2212.7	2199.4	2186.2	2173.1
Revenue from EEG subsidy		2236.6	2223.2	2209.9	2196.6	2183.4	2170.3	2157.3	2144.3	2131.5	2118.7	2106.0	2093.3	2080.8	2068.3	2055.9
H2 contribution margin		45.8	45.6	45.3	45.0	44.8	44.5	44.2	44.0	43.7	43.4	43.2	42.9	42.7	42.4	42.1
Fixed cost		1125.7	1125.7	1125.7	1125.7	1125.7	1125.7	1125.7	1125.7	1125.7	1125.7	1125.7	1125.7	1125.7	1125.7	1125.7
EBIT		3520.9	3493.0	3465.3	3437.8	3410.4	3383.2	3356.1	3329.2	3302.5	3275.9	3249.5	3223.3	3197.2	3171.2	3145.4
Depreciation		2449.3	2449.3	2449.3	2449.3	2449.3	2449.3	2449.3	2449.3	2449.3	2449.3	2449.3	2449.3	2449.3	2449.3	2449.3
Income tax		321.5	313.1	304.8	296.5	288.3	280.2	272.1	264.0	256.0	248.0	240.1	232.2	224.4	216.6	208.9
Profit		3199.4	3179.9	3160.5	3141.2	3122.0	3103.0	3084.1	3065.2	3046.5	3027.9	3009.4	2991.1	2972.8	2954.6	2936.6
Discounted profit		3076.4	2940.0	2809.7	2685.1	2566.1	2452.3	2343.6	2239.7	2140.4	2045.6	1954.9	1868.2	1785.4	1706.2	1630.6
Total of discounted profits	42433.7															
- Investment cost	39188.3															
Net present value	3245.4															

Values in Thousand €

Export data to .csv file

Figure 19: Case-dependent output of the NPV derivation.

A.7 Results of the sensitivity analysis

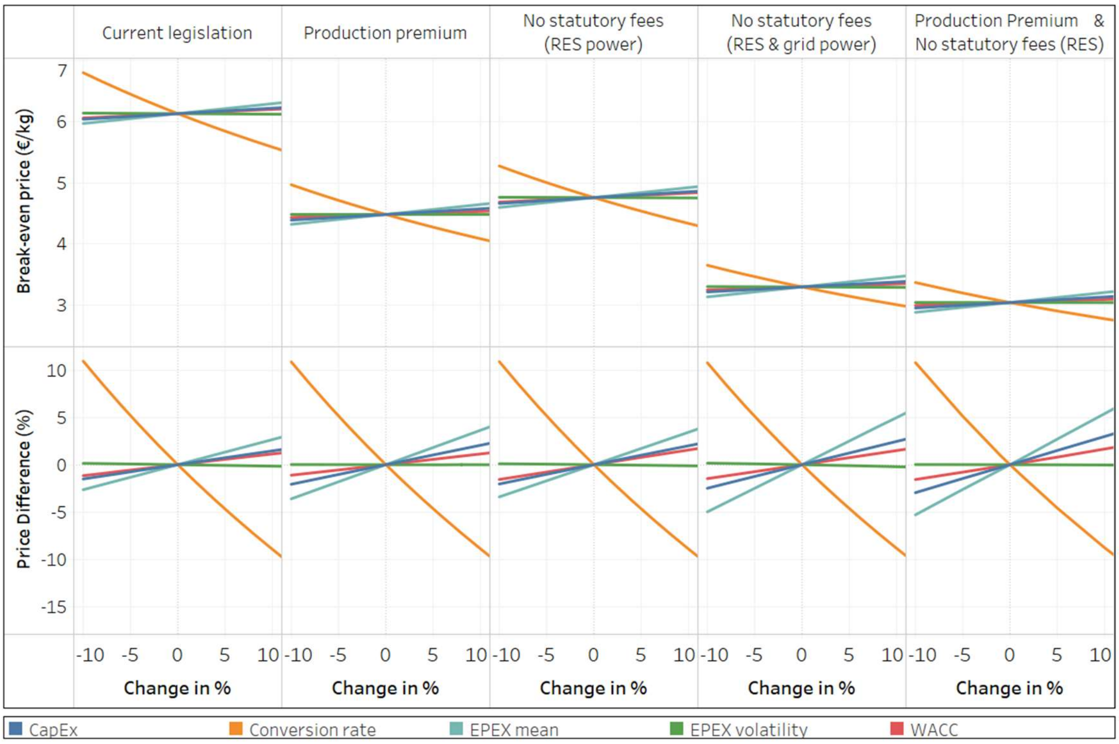


Figure 20: Case-dependent sensitivities of a small-scale vertically integrated system.[110]

Figure 21: Case-dependent sensitivities of a large-scale vertically integrated system.[111]

[110] Own figure. Wind turbine = 750 kW | Solar PV = 750 kW | PtG = 100 kW.
[111] Own figure. Wind turbine = 10 MW | Solar PV = 10 MW | PtG = 1 MW.