DELIVERABLE

Acronym / Number	**WASTE2GRIDS / 826161**
Title	Converting WASTE to offer flexible GRID balancing Services with highly-integrated, efficient solid-oxide plants
Duration	24 months
Start date	01.01.2019

Deliverable Number	D3.3
Deliverable Name	Promising business cases
Lead beneficiary	SOLIDpower SA
Authors (beneficiary)	Ligang Wang (EPFL)
Type (R/DEC/...)	R
Disse. level (PU/CO/CI)	PU
Delivery date expected	31.08.2020 (M20)
Actual delivery date	31.12.2020 (M24)
Comments	

Summary

This deliverable is the last technical and the concluding one of the whole project. The D2.2 and D2.3 define scenarios to create case studies and the plant CAPEX target of each case study, thus identifies the case studies with high plant CAPEX target. However, the economic potential is only valid when the real specific plant CAPEX is below the plant CAPEX target of the case study. Therefore, this deliverable evaluates the plant CAPEX with the information from D2.2: Plant size and design. The obtained Plant CAPEX Real is then compared with the plant CAPEX target, and finally concludes with potential business cases.

Considering the plants deployed in each case study, the plant CAPEX real of the case studies is within 5000–12000 €/ref-stack, thus with a plant CAPEX target of over 20000 €/ref-stack, the two case studies (DK-DK1- FICFB-P1 with the plant deployed in Ostjylland, IT-SUD-FICFB-P1 with the plant deployed in Campania or Calabria) with low capacity factors of below 10% and deploying a plant of around 100 MWth biomass feed are treated as potential business cases, even with additional costs for engineering and contingency apart from the gross Grassroot CAPEX.

Potential business cases can be enabled by the conditions: 5-year payback time, 40 €/MWh energy balancing price, 5-year stack lifetime, 0.8 €/kg SNG selling price, and a capacity factor of below 10% (requiring the stack costs of below 1600 €/kWe SOFC stack). By increasing the capacity factor to around 60%, the stack costs need to be below 200-600 €/kWe SOFC stack to enable more potential business cases.

One conclusion, in short, is that the triple-mode W2G plant concept is proven to be economically potential when the stack costs are reduced to below 2000 €/kWe SOFC, even with the current grid-balancing prices. The key of enabling high economic feasibility is high annual hours of PowGen and PowSto operation (e.g., over 7500 hours), since only these two modes gain profit from the grid-balancing services.

Contents

1 Introduction

This deliverable differs from the description of Task 3.3 due to the tasks performed in D2.2:

- We have introduced the indicator of **Plant CAPEX Target** to fast evaluate the economic potential of case studies without investigating the detailed CAPEX of the specific plants deployed.
- We have performed a sensitivity analysis of several most influential parameters on the **plant CAPEX target** including balancing energy price, payback time, methane sale price, biomass supply chain.
- We have selected several potential case studies with large plant CAPEX target with the zone, the number of W2G plants, the location, size, design and operation of each W2G plant, the optimal biomass supply chain.

Therefore, the task of this deliverable becomes rather straightforward. The selected potential case studies in D2.2 are further investigated in this deliverable with the detailed calculation of CAPEX of each W2G plant given their capacity and design.

The following deliverable is organized as follows: In section 2, the overall methodology to identify promising business cases is further introduced with the highlight of the task of this deliverable. In section 3, the case studies identified in D2.2 are further described and summarized, particularly with the size and design of each plant and plant CAPEX target. In section 4, the unique plants deployed in all case studies are extracted, referring to the size and design of each plant deployed; then, the CAPEX is evaluated in detail for each component and each plant by calculating the total capital investment, with which the plant CAPEX real is calculated for each case study and compared with the plant CAPEX target to highlight potential business cases. In section 5, the conditions to derive high profitable business cases are further identified. The deliverable and the project are finally concluded in section 6.

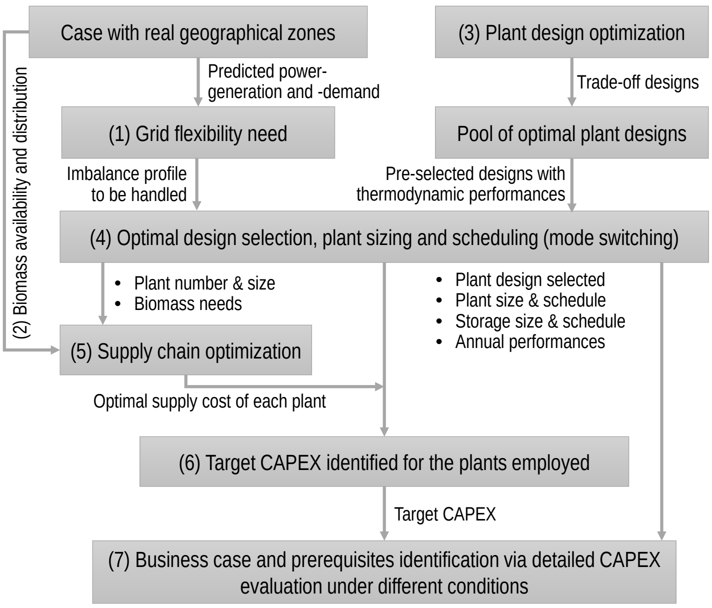


Figure 1 The overall decomposition-based methodology to identify feasible business cases for the grid-balancing plants.

2 The overall methodology to identify promising business cases

The overall target is to identify promising future business cases for the grid-balancing plants from a set of well-defined case studies. A case study must seat on a specific geographical zone to consider realistic (or reasonably predicted) grid-flexibility needs and biomass availability. However, in one single optimization problem, it is difficult to simultaneously consider the nonlinear programming for optimal conceptual plant design and the mixed-integer programming for optimal plant scheduling to cope with a specific imbalance profile, not even to mention the computation-expensive supply chain optimization. Thus, it is necessary to decompose the overall complex optimization problem for high solvability. Although global optimum is not guaranteed, it is believed that the optimal solutions obtained are good enough for practical applications.

We proposed a decomposition-based, sequential approach in Ref. [1] (Figure 1), summarized as follows:

- **Step 1 (D1.1):** Identification of (future) grid flexibility needs. Based on the multi-timescale data-driven method presented in Ref. [2], for the zone considered, hourly time series of the fluctuating discrepancies between variable renewable energy production and electricity consumption are generated for step (4), which have been detailed discussed in D1.1.
- **Step 2 (D1.2):** Identification of (future) biomass availability. In compliance with the classification schemes and methodology applied in the projects like BEE [3], S2Biom [4] and BIOMASS FUTURE [5], the biomass streams in the zones interested are assessed with further available Directives, Regulations and Reports, to build the geodatabase with their weight, characteristics and location coordinates for step (5).
- **Step 3 (D2.1):** Optimization of conceptual plant design. An application-free pool of trade-off designs is generated for each process option and fed to step (4).
- **Step 4 (D2.2):** Optimization of design selection, plant sizing and scheduling to satisfy the flexibility needs. With hourly flexibility needs from step (1) and multiple plant designs from step (3). The number, design, size and scheduling of the plants employed are determined to maximize the gain from grid-balancing services and the cost of oxygen and tank. Note that the capital expenditures (CAPEXs) of the plants are not considered at this step. The input biomass energy needed for each plant is provided to step (5), while the gain is fed to step (6).
- **Step 5 (D2.2):** Optimization of the biomass supply chain. With the biomass geodatabase from step (2) and the biomass energy needed for each plant from step (4), the costs of biomass supply chain and pre-treatment are minimized with the superstructure-based method presented in Refs. [6,7,8] and fed to step (6).
- **Step 6 (D2.2):** Identification of plant CAPEX (capital expenditure) target. Plant CAPEX target with payback time *l* years (€/ref-stack), is defined as the profit from providing grid balancing divided by **the equivalent number of reference stacks (ref-stack, each with 5120 cm^2 active cell area):**

  $$\text{Plant CAPEX Target}_l = \frac{\text{Profit}_l - \text{supply chain cost}_l}{\text{Total number of reference stacks of all plants installed}} \quad (1)$$

  The target plant CAPEX of the grid-balancing plants employed can be further calculated based on the gain from step (4) and the costs related to biomass collection from step (5).
- **Step 7 (D3.3):** Identification of potential business cases. With the plant details from step (4), the CAPEX of each plant is evaluated at different conditions, e.g., different specific investment costs of the stack, to determine the prerequisites for potential business cases.

This deliverable thus focuses on the implementation of Step 7 (D3.3).

2.1 A further explanation of plant CAPEX target

The profit involved in calculating the plant CAPEX target in Eq. (1) is calculated by considering (1) **revenue from providing balancing power $R_{d,i}^{\text{bal}}$, (2) additional revenue (positive) or cost (negative) of oxygen trade with the market $R_{d,i}^{\text{oxy}}$, and (3) the costs of oxygen gas tank R^{tank}**:

$$\text{Profit}_l = \left(\sum_{t=1}^{l} \sum_{d=1}^{TD} \sum_{i=1}^{24} \frac{\alpha_d (R_{d,i}^{\text{bal}} - R_{d,i}^{\text{oxy}})}{(1+r)^t} \right) - R^{\text{tank}}$$

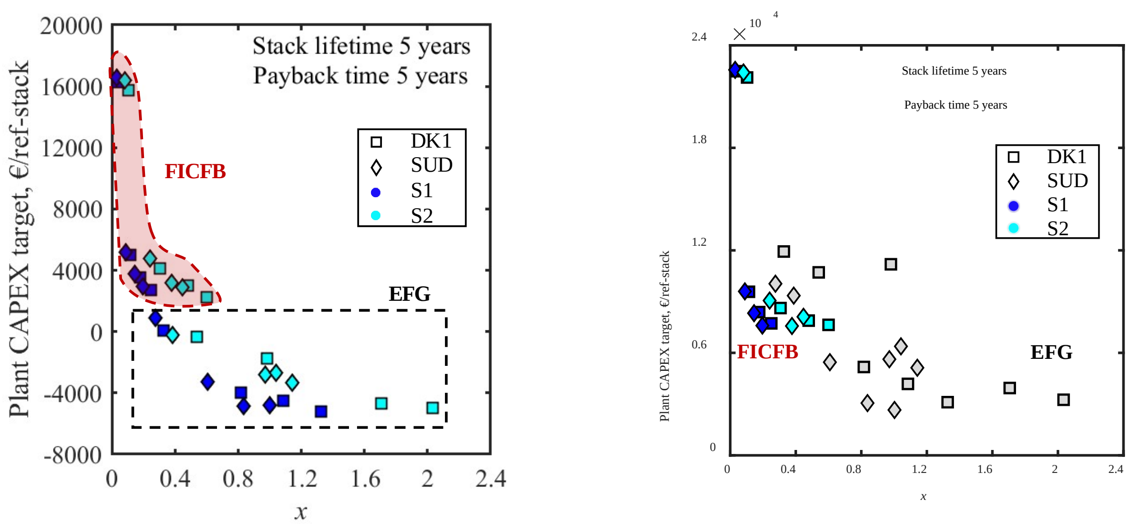
where t is the year that should be lower than the stack lifespan Y, TD is the number of typical days d representing long-term historical data, α_d is the repetition times of each typical day in an entire year, i represents the hours (1–24 h) in each typical day, and r is the discount rate (0.05).

The costs of the biomass supply chain include the **CAPEX, which is invested in the first year**, and **the OPEX, which is considered for each year**. Similarly, **any other investment costs, e.g., the storage tanks of chemicals, are considered to be invested in the first year.**

Note that the revenue from the sale of synthesis natural gas (SNG) has been considered separately, which means for each case study, we provide two values of plant CAPEX targets: one without SNG-sale profit, one with SNG-sale profit.

3 Case studies identified in D2.2

With the profit and the biomass supply chain calculated, the plant CAPEX target has been calculated for different case studies with different numbers of plants involved, see details in D2.2. Below summarizes the major findings and the case studies selected for further investigation.



(a) Without SNG-sale profit (b) With SNG-sale profit

Figure 2 Plant CAPEX target (€/ref-stack) of different case studies (from D2.2): (a) without SNG-sale profit, (b) with SNG-sale profit.

The economic feasibility is preliminarily presented in Figure 2, and all details of the case studies with their plant CAPEX target reaching over 6000 €/ref-stack when considering SNG-sale profit have been listed in the summary section of D2.2 and also the *Appendix – List of case studies*. It has been found that the W2G plants based on fast internal circulating fluidized-bed (FICFB) gasifier with the capacity of 10-100 MWth (biomass input) has shown higher economic feasibility than those based on entrained-flow gasifier (EFG) with the capacity of a single plant ranging within 100-1000 MWth. This is mainly due to (1) the substantial share of biomass supply costs for big plants of around 1000 MWth, and (2) less flexibility for coordinating multiple plants to cope with residual flexibility needs, which results in large capacities operated under PowNeu mode.

4 Plant CAPEX evaluation

According to the *Appendix – List of case studies*, in all case studies, the plants deployed with the biomass feed capacity and plant design are further filtered in section 4.1 and the CAPEX of each plant has been calculated with different cost levels of the stack as well as other uncertainties in section 4.2.

4.1 Unique W2G plants deployed in all case studies

All case studies listed deploy many plants with the same size and design (represented by the mode efficiencies); therefore, to avoid additional work on the evaluation of the same plants, unique plants have been extracted and listed in Table 1. A plant becomes not unique if the plant size or plant design (both the PowGen and PowSto efficiencies) is the same as other plants. Out of all plants deployed in all case studies, there have been, in total, 18 unique FICFB-based plants with a capacity of 70–100 MWth biomass feed and 64 unique EFG-based plants with a capacity of 130–1000 MWth biomass feed. The PowGen / PowSto efficiencies are distributed within 40–60% and 64–77%, respectively. This further proves the importance of the optimal plant deployment with a set of plant designs, since the variety of plant designs employed by the final plants indicates that a single plant design can not help reach such an optimum. The plant designs selected are also not limited to a specific technology combination (TC), but 6 technology combinations are selected. With this variety of plant designs, the FICFB-based plants deployed result in PowGen / PowSto capacities of 34–60 MWe and 70–160 MWe, respectively; while the EFG-based plants deployed result in PowGen / PowSto capacities of 55–550 MWe and 132–1470 MWe, respectively.

Table 1 The unique plants used in all case studies. The plants are considered to be the same only if the plant size and plant design, identified by the efficiencies of PowGen and PowSto efficiencies, are the same.

Index (the same with other tables)	Technology combination of plant designs[c]	Biomass gasifier capacity, MW_{th}^{LHV}	PowGen power capacity[a], MWe	PowSto power capacity[b], MWe	PowSto SNG produced, kg/s	PowNeu SNG produced, kg/s	PowGen efficiency (LHV), %	PowSto efficiency (LHV), %
FICFB-1	TC2	100	57	159	3.67	0.98	56.5	70.8
FICFB-2	TC3	100	58	149	3.36	0.95	58.3	67.2
FICFB-3	TC3	100	58	159	3.75	1.03	57.6	72.5
FICFB-4	TC3	100	52	159	3.88	0.96	51.7	74.8
FICFB-5	TC1	95	41	101	2.54	0.74	43.8	64.6
FICFB-6	TC2	98	55	155	3.60	0.96	56.6	70.8
FICFB-7	TC3	100	59	153	3.59	1.00	58.7	70.9
FICFB-8	TC1	100	44	106	2.67	0.78	43.8	64.6
FICFB-9	TC3	100	52	137	3.06	0.85	51.8	64.4
FICFB-10	TC1	100	43	100	2.69	0.83	43.3	67.0
FICFB-11	TC1	100	49	102	2.73	0.90	49.0	67.5
FICFB-12	TC2	100	52	140	3.27	0.89	51.7	68.1
FICFB-13	TC2	100	57	154	3.90	1.06	57.3	76.5
FICFB-14	TC1	69	34	70	1.89	0.62	49.0	67.5
FICFB-15	TC1	89	39	95	2.38	0.70	43.8	64.6

FICFB-16	TC3	99	58	152	3.55	0.99	58.7	70.9
FICFB-17	TC3	98	51	134	3.00	0.83	51.8	64.4
FICFB-18	TC3	94	55	141	3.16	0.89	58.3	67.2
EFG-1	TC6	995	463	1364	29.36	7.49	46.6	62.2
EFG-2	TC6	613	285	841	18.09	4.62	46.6	62.2
EFG-3	TC4	1000	501	1470	32.10	8.28	50.1	65.0
EFG-4	TC5	595	242	787	17.77	4.20	40.8	64.3
EFG-5	TC5	849	346	1122	25.35	6.00	40.8	64.3
EFG-6	TC6	994	463	1363	29.33	7.48	46.6	62.2
EFG-7	TC6	702	325	938	20.66	5.38	46.3	63.0
EFG-8	TC5	134	55	177	4.00	0.95	40.8	64.3
EFG-9	TC6	310	144	425	9.15	2.33	46.6	62.2
EFG-10	TC6	693	321	926	20.40	5.31	46.3	63.0
EFG-11	TC5	546	254	703	15.97	4.25	46.6	63.9
EFG-12	TC6	982	457	1347	28.98	7.39	46.6	62.2
EFG-13	TC6	881	408	1177	25.93	6.75	46.3	63.0
EFG-14	TC5	558	227	738	16.66	3.94	40.8	64.3
EFG-15	TC5	622	254	823	18.57	4.40	40.8	64.3
EFG-16	TC6	293	137	402	8.65	2.21	46.6	62.2
EFG-17	TC4	339	174	411	10.81	3.26	51.2	72.2
EFG-18	TC5	1000	408	1322	29.86	7.07	40.8	64.3
EFG-19	TC5	505	206	668	15.08	3.57	40.8	64.3
EFG-20	TC6	648	302	889	19.12	4.88	46.6	62.2
EFG-21	TC6	935	433	1249	27.52	7.17	46.3	63.0
EFG-22	TC5	532	217	704	15.89	3.76	40.8	64.3
EFG-23	TC5	230	107	296	6.73	1.79	46.6	63.9
EFG-24	TC5	123	50	162	3.67	0.87	40.8	64.3
EFG-25	TC6	704	328	966	20.78	5.30	46.6	62.2
EFG-26	TC6	407	188	544	11.98	3.12	46.3	63.0
EFG-27	TC5	859	350	1136	25.65	6.07	40.8	64.3
EFG-28	TC5	960	391	1270	28.67	6.78	40.8	64.3
EFG-29	TC6	340	151	443	10.12	2.59	44.4	64.6
EFG-30	TC6	636	296	873	18.77	4.79	46.6	62.2
EFG-31	TC6	598	277	799	17.60	4.58	46.3	63.0
EFG-32	TC4	128	66	155	4.08	1.23	51.2	72.2
EFG-33	TC5	112	49	132	3.33	0.92	44.0	68.2
EFG-34	TC5	236	110	304	6.90	1.84	46.6	63.9
EFG-35	TC6	508	237	697	14.99	3.83	46.6	62.2
EFG-36	TC6	566	262	756	16.66	4.34	46.3	63.0
EFG-37	TC5	630	257	834	18.81	4.45	40.8	64.3
EFG-38	TC5	974	428	1150	28.97	7.98	44.0	68.2
EFG-39	TC5	211	98	271	6.17	1.64	46.6	63.9
EFG-40	TC5	851	347	1125	25.41	6.01	40.8	64.3
EFG-41	TC6	103	46	135	3.06	0.78	44.4	64.6

EFG-42	TC6	999	465	1370	29.48	7.52	46.6	62.2
EFG-43	TC6	495	229	661	14.57	3.79	46.3	63.0
EFG-44	TC5	113	46	149	3.37	0.80	40.8	64.3
EFG-45	TC5	406	178	479	12.08	3.33	44.0	68.2
EFG-46	TC5	425	198	548	12.43	3.31	46.6	63.9
EFG-47	TC5	239	97	316	7.14	1.69	40.8	64.3
EFG-48	TC6	441	196	575	13.12	3.35	44.4	64.6
EFG-49	TC6	700	326	960	20.66	5.27	46.6	62.2
EFG-50	TC6	100	46	134	2.94	0.77	46.3	63.0
EFG-51	TC5	835	340	1104	24.93	5.90	40.8	64.3
EFG-52	TC5	324	151	417	9.48	2.52	46.6	63.9
EFG-53	TC5	707	288	935	21.11	5.00	40.8	64.3
EFG-54	TC5	867	418	995	25.99	7.86	48.3	69.8
EFG-55	TC6	236	105	308	7.02	1.80	44.4	64.6
EFG-56	TC6	794	370	1089	23.43	5.98	46.6	62.2
EFG-57	TC6	359	166	479	10.57	2.75	46.3	63.0
EFG-58	TC5	351	143	465	10.48	2.48	40.8	64.3
EFG-59	TC5	197	87	233	5.86	1.61	44.0	68.2
EFG-60	TC5	122	57	157	3.57	0.95	46.6	63.9
EFG-61	TC5	214	87	283	6.39	1.51	40.8	64.3
EFG-62	TC6	119	53	156	3.54	0.91	44.4	64.6
EFG-63	TC6	377	176	517	11.13	2.84	46.6	62.2
EFG-64	TC6	345	160	461	10.16	2.64	46.3	63.0

[a] The net electricity exported from the plant to the grid.
[b] The total electricity imported from the grid to the plant.
[c] These designs are selected from the publication [1] derived from D2.2 with an updated calculation with the technology combinations:

(1) FICFB-based technology combinations:
TC1: air drying, no pyrolysis, FICFB, *hot cleaning*, *high-temperature stage*, *radiative cooling*, direct heating, *steam electrolysis*
TC2: air drying, no pyrolysis, FICFB, *cold cleaning*, *tar reformer*, direct heating, *steam electrolysis*
TC3: air drying, no pyrolysis, FICFB, *cold cleaning*, *tar reformer*, direct heating, *co-electrolysis*

(2) EFG-based technology combinations:
TC4: air drying, pyrolysis, EFG, *hot cleaning*, direct heating, *steam electrolysis*
TC5: air drying, pyrolysis, EFG, *cold cleaning*, direct heating, *steam electrolysis*
TC6: air drying, pyrolysis, EFG, *cold cleaning*, direct heating, *co-electrolysis*

4.2 CAPEX evaluation for each plant

The CAPEX of each plant listed in Table 1 is further evaluated in detail based on detailed process simulation and component sizing for the given plant capacity. The cost evaluation methods employed are based on Refs. [9,10]. The CAPEX evaluated is the total capital investment (TCI) of each plant, which is **calculated from the purchase equipment costs (PEC)** of each component used in the plant (calculated by **the cost functions given in *Appendix: Cost functions***):

$$C_{\mathrm{BM}} = f_{\mathrm{BM}}\, PEC = f_{\mathrm{M}}\, f_{\mathrm{P}}\, f_{\mathrm{T}}\, PEC$$
$$C_{\mathrm{TM}} = f_{\mathrm{TM}}\, C_{\mathrm{BM}}$$
$$C_{\mathrm{GR}} = C_{\mathrm{TM}} + f_{\mathrm{GR}}\, C_{\mathrm{BM}}$$
$$TCI = f_{\mathrm{TCI}}\, C_{\mathrm{GR}}$$

where the f_{BM} is usually related to the materials used (f_{M}), pressure levels (f_{P}) and temperature levels (f_{T}), which have been well defined for each type of component. **However, the total modular factor and grassroot**

factor have been considered the same for all components for simplification purposes. The plant-wise cost factors have been given in Table 2.

Table 2 Cost factors to estimate the TCI from PEC.

Plant lifetime	20 years
Total modular factor ($\boldsymbol{f}_{\mathbf{TM}}$)	1.18
Grassroot factor ($\boldsymbol{f}_{\mathbf{GR}}$)	0.35
Engineering factor ($\boldsymbol{f}_{\mathbf{ENG}}$)	0
Contingency factor ($\boldsymbol{f}_{\mathbf{CON}}$)	0
Working capital factor ($\boldsymbol{f}_{\mathbf{WC}}$)	0
Total capital investment (TCI) factor	$\mathbf{1} + \boldsymbol{f}_{\mathbf{ENG}} + \boldsymbol{f}_{\mathbf{CON}} + \boldsymbol{f}_{\mathbf{WC}}$

As concluded in D2.2, the stack CAPEX contributed the most to the TCI and it also results in the biggest uncertainty in the CAPEX evaluation, since the CAPEX is based on prediction for the future. There have been different predictions of stack costs from different organizations. For the EU circumstance, we rely on the prediction from CEA (France) obtained in the EU project, ECo, and the prediction from leading industry company, SpA, which is also a part of the W2G consortium. These predictions are all given in Figure 3. It is shown that at a lower annual production of stacks, the prediction of stack CAPEX differs significantly between different sources; however, when the annual production reaching a total cell area of over 10,000–20,000 m^2/year, the results of the two predictions approach each other. To cope with this uncertainty, we have 5 cost levels (CL) for the stack CAPEX evaluations as given in Figure 3:

- CL1: CEA prediction – Lower bound (with the annual productions of 15000 and 50000 m^2/year)
- CL2: CEA prediction – Upper bound (with the annual productions of 15000 and 50000 m^2/year)
- CL3: SpA prediction for 1.5 kW stack production experiences
- CL4: SpA prediction for 10 kW stack production experiences
- CL5: SpA prediction for 40 kW stack production

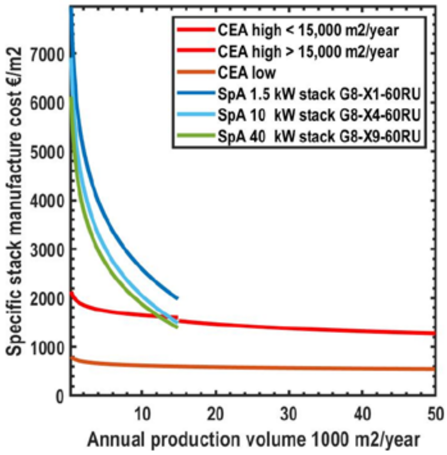


Figure 3 Different CAPEX predictions for the RSOC stack, defining the 5 cost levels (CL): CL1 – CEA lower bound, CL2 – CEA upper bound, CL3 – SpA 1.5 kW, CL4 – SpA 10 kW, CL5 – SpA 40 kW.

Note that the stack lifetime is assumed to be 5-year continuous operation, thus for a plant lifetime of 20 years, there will be a total of $ceil\left(\frac{Plant\ lifetime}{Stack\ lifetime}\right) - 1$ times of stack replacement. For each stack replacement, **we**

account for only the bare module costs of the stacks since it is expected that only the stacks themselves need to be replaced.

With these calculation methods and assumptions, the CAPEX for the capacity of the plants listed in Table 1 is broken down to that of each component or subsystem, including:

- SPOW: Stack power system
- RAUX: Auxiliary components for the reversible system, e.g., steam methane reformer
- HHEX: High-temperature heat exchangers, over 1000 C (Nickel-containing steel)
- MHEX: Medium-temperature heat exchangers, 500–1000 C (Stainless steel)
- LHEX: Lower-temperature heat exchangers, < 500 (Carbon steel)
- METH: Methanation reactor
- SNT: Steam turbine network, including steam turbines and pumps and related components
- GASI: Gasifier subsystem, including onsite biomass pretreatment, gasifier, and syngas cleaning
- RSOC: reversible solid-oxide stacks, only initial CAPEX GR, while the replacement costs the bare modular cost of the stacks used

Note that the costs of the components or subsystems mentioned in SPOW, RAUX, METH, SNT, GASI and RSOC, does not include the costs of heat exchangers needed, which are evaluated separately for those of the whole plants by high-temperature (HHEX), medium-temperature (MHEX) and low-temperature (LHEX) heat exchangers. Particularly, the initial RSOC CAPEX has been evaluated separately with the 5 cost levels defined above. While when calculating the plant CAPEX GR, the stack replacement costs are also included.

In the following, several big tables below provide the following information:

- For the annual production of 15,000 m^2/year **(5 cost levels: CL1–CL5)**
  - Table 3: Breakdown of CAPEX GR for all unique plants
  - Table 4: Plant CAPEX GR and Plant CAPEX Real of **each unique plant**
- For the annual production of 50,000 m^2/year **(2 cost levels: CL1 and CL2)**
  - Table 5: Breakdown of CAPEX GR **for all unique plants**
  - Table 6: Plant CAPEX GR and Plant CAPEX Real **of each unique plant**
- Table 7: Comparison of Plant CAPEX Target and Plant CAPEX Real of **each case study**. Plant CAPEX Real of each case study is calculated by considering the plants deployed in each case study, as listed in Table 4 and Table 6.

Table 3 **CAPEX GR** of each component or subsystem with **annual cell production of 15000 m^2/year**.

Index (the same with other tables)	SPOW, M€	RAUX, M€	HHEX, M€	MHEX, M€	LHEX, M€	METH, M€	SNT, M€	GASI, M€	**Initial CAPEX,** RSOC, M€				
									CL1	CL2	CL3	CL4	CL5
FICFB-1	24.6	0.17	1.91	3.08	16.7	42.7	0.37	6.94	24.0	61.2	74.1	55.7	52.0
FICFB-2	21.7	0.15	1.84	2.94	25.0	41.7	1.70	6.42	27.7	70.7	85.6	64.4	60.0
FICFB-3	22.9	0.13	2.01	2.83	25.6	33.7	1.70	6.77	39.7	101.4	122.7	92.3	86.1
FICFB-4	23.3	0.10	1.64	2.70	23.6	44.6	2.58	5.92	35.2	89.9	108.8	81.8	76.3
FICFB-5	21.8	0.21	1.36	4.20	9.0	29.0	2.85	10.38	18.4	47.1	57.0	42.8	40.0
FICFB-6	25.2	0.17	1.97	3.17	17.1	43.9	0.38	7.14	24.6	62.8	76.0	57.1	53.3
FICFB-7	22.8	0.07	2.03	3.48	15.5	34.3	1.60	8.52	31.8	81.2	98.2	73.9	68.9
FICFB-8	17.0	0.16	1.06	3.24	6.9	22.4	2.18	8.03	14.4	36.7	44.4	33.4	31.2
FICFB-9	20.9	0.15	1.37	3.71	11.4	34.0	1.71	7.10	17.2	44.0	53.3	40.1	37.4
FICFB-10	16.6	0.10	0.70	3.63	8.4	23.6	0.36	8.97	15.1	38.7	46.8	35.2	32.8
FICFB-11	16.6	0.13	0.86	2.90	9.4	24.6	3.04	8.37	16.0	40.9	49.5	37.2	34.7
FICFB-12	21.2	0.15	1.61	3.84	12.2	35.6	0.33	7.36	19.6	50.1	60.7	45.6	42.6
FICFB-13	23.2	0.14	1.04	2.80	16.5	40.5	0.40	7.60	28.8	73.5	88.9	66.9	62.4
FICFB-14	7.9	0.07	0.42	1.52	4.8	12.4	1.31	4.26	7.6	19.5	23.5	17.7	16.5
FICFB-15	13.2	0.14	0.83	2.58	5.5	17.7	1.78	6.36	11.2	28.5	34.5	25.9	24.2
FICFB-16	22.6	0.07	2.01	3.45	15.4	34.0	1.60	8.45	31.5	80.3	97.2	73.1	68.2
FICFB-17	20.5	0.15	1.35	3.66	11.2	33.4	1.69	6.99	16.9	43.1	52.2	39.2	36.6
FICFB-18	20.4	0.15	1.74	2.81	23.6	39.4	1.64	6.10	26.0	66.5	80.5	60.5	56.4
EFG-1	205	1.15	16.0	15.1	82	295	11.9	70.9	175	446	539	406	378
EFG-2	126	0.71	9.8	9.3	51	182	7.3	43.7	108	275	332	250	233
EFG-3	227	1.13	14.1	19.2	79	241	12.1	83.2	195	499	604	454	423
EFG-4	122	0.72	7.7	14.5	40	172	6.7	38.8	103	263	318	239	223
EFG-5	175	1.03	11.0	20.7	57	246	9.5	55.4	147	375	454	342	319
EFG-6	204	1.15	15.9	15.1	82	295	11.9	70.8	174	445	539	405	378
EFG-7	145	0.81	12.3	13.8	51	195	8.2	53.3	119	303	366	275	257
EFG-8	28	0.16	1.7	3.3	9	39	1.5	8.7	23	59	72	54	50
EFG-9	64	0.36	5.0	4.7	26	92	3.7	22.1	54	139	168	126	118
EFG-10	143	0.80	12.2	13.6	50	192	8.1	52.6	117	299	362	272	254
EFG-11	109	0.65	8.8	7.1	52	176	1.0	38.7	97	247	299	224	209
EFG-12	202	1.13	15.8	14.9	81	292	11.8	69.9	172	440	532	400	374
EFG-13	181	1.02	15.5	17.3	63	244	10.3	66.8	149	380	460	346	322
EFG-14	115	0.68	7.2	13.6	38	161	6.3	36.4	97	247	299	225	209
EFG-15	128	0.76	8.1	15.2	42	180	7.0	40.6	108	275	333	250	233
EFG-16	60	0.34	4.7	4.5	24	87	3.5	20.9	51	131	159	119	111
EFG-17	66	0.24	2.6	3.5	27	70	0.8	26.7	113	288	348	262	244
EFG-18	206	1.21	13.0	24.4	68	289	11.2	65.2	173	442	535	402	375
EFG-19	104	0.61	6.6	12.3	34	146	5.7	32.9	87	223	270	203	190
EFG-20	133	0.75	10.4	9.9	54	192	7.8	46.1	114	290	351	264	246
EFG-21	193	1.08	16.4	18.3	67	259	10.9	70.9	158	403	488	367	342
EFG-22	109	0.65	6.9	13.0	36	154	6.0	34.7	92	235	285	214	200
EFG-23	46	0.27	3.7	3.0	22	74	0.4	16.3	41	104	126	95	88

EFG-24	25	0.15	1.6	3.0	8	36	1.4	8.0	21	54	66	49	46
EFG-25	145	0.81	11.3	10.7	58	209	8.4	50.1	124	315	382	287	268
EFG-26	84	0.47	7.2	8.0	29	113	4.8	30.9	69	175	212	160	149
EFG-27	177	1.04	11.1	21.0	58	248	9.6	56.0	149	380	460	346	322
EFG-28	197	1.17	12.5	23.4	65	278	10.8	62.6	166	424	514	386	360
EFG-29	69	0.35	3.2	4.7	25	92	0.6	23.5	62	158	191	144	134
EFG-30	131	0.73	10.2	9.7	53	189	7.6	45.3	112	285	345	259	242
EFG-31	123	0.69	10.5	11.7	43	166	7.0	45.4	101	258	312	235	219
EFG-32	25	0.09	1.0	1.3	10	26	0.3	10.1	43	109	131	99	92
EFG-33	21	0.07	1.0	2.4	6	26	1.8	7.9	26	65	79	60	56
EFG-34	47	0.28	3.8	3.1	22	76	0.4	16.7	42	107	129	97	91
EFG-35	104	0.59	8.2	7.7	42	151	6.1	36.2	89	228	275	207	193
EFG-36	117	0.65	10.0	11.1	41	157	6.6	42.9	96	244	295	222	207
EFG-37	130	0.77	8.2	15.4	43	182	7.1	41.1	109	279	337	253	237
EFG-38	182	0.65	8.4	21.2	56	226	15.6	68.5	223	569	688	518	483
EFG-39	42	0.25	3.4	2.7	20	68	0.4	15.0	37	95	115	87	81
EFG-40	175	1.03	11.0	20.8	58	246	9.5	55.5	147	376	455	342	319
EFG-41	21	0.11	1.0	1.4	8	28	0.2	7.1	19	48	58	43	41
EFG-42	205	1.15	16.0	15.2	83	297	12.0	71.1	175	448	542	407	380
EFG-43	102	0.57	8.7	9.7	36	137	5.8	37.6	84	213	258	194	181
EFG-44	23	0.14	1.5	2.8	8	33	1.3	7.4	20	50	60	45	42
EFG-45	76	0.27	3.5	8.9	23	94	6.5	28.6	93	237	287	216	201
EFG-46	85	0.51	6.9	5.5	40	137	0.8	30.1	75	192	232	175	163
EFG-47	49	0.29	3.1	5.8	16	69	2.7	15.6	41	106	128	96	90
EFG-48	90	0.45	4.2	6.1	33	119	0.8	30.5	80	205	248	186	174
EFG-49	144	0.81	11.2	10.7	58	208	8.4	49.8	123	314	380	285	266
EFG-50	21	0.12	1.8	2.0	7	28	1.2	7.6	17	43	52	39	37
EFG-51	172	1.01	10.8	20.4	57	241	9.4	54.4	145	369	447	336	313
EFG-52	65	0.39	5.2	4.2	31	104	0.6	23.0	57	146	177	133	124
EFG-53	145	0.86	9.2	17.3	48	204	7.9	46.1	122	313	378	284	265
EFG-54	157	0.45	6.9	9.3	60	193	1.7	58.6	265	676	818	615	574
EFG-55	48	0.24	2.2	3.2	17	64	0.4	16.3	43	109	133	100	93
EFG-56	163	0.92	12.7	12.1	66	236	9.5	56.5	139	356	431	324	302
EFG-57	74	0.41	6.3	7.0	26	100	4.2	27.2	61	155	187	141	131
EFG-58	72	0.43	4.6	8.6	24	101	3.9	22.9	61	155	188	141	132
EFG-59	37	0.13	1.7	4.3	11	46	3.2	13.9	45	115	139	105	98
EFG-60	24	0.15	2.0	1.6	12	39	0.2	8.6	22	55	67	50	47
EFG-61	44	0.26	2.8	5.2	14	62	2.4	14.0	37	95	115	86	80
EFG-62	24	0.12	1.1	1.6	9	32	0.2	8.2	22	55	67	50	47
EFG-63	78	0.43	6.0	5.7	31	112	4.5	26.8	66	169	204	154	143
EFG-64	71	0.40	6.1	6.8	25	96	4.0	26.2	58	149	180	135	126

Table 4 **Plant CAPEX GR** and **Plant CAPEX Real** of **each unique plant** with annual cell production of **15000 m^2/year**.

Index (the same with other tables)	Number of reference stack, -	**Plant CAPEX GR** considering stack replacements, M€					**Plant CAPEX Real**, considering stack replacements, €/ref-stack				
		CL1	CL2	CL3	CL4	CL5	CL1	CL2	CL3	CL4	CL5
FICFB-1	26677	167	278	316	261	250	6278	10411	11840	9800	9386
FICFB-2	30816	183	311	355	292	279	5951	10085	11514	9473	9060
FICFB-3	44185	213	396	459	369	351	4825	8958	10387	8347	7933
FICFB-4	39154	209	370	426	346	330	5326	9460	10889	8848	8434
FICFB-5	20506	133	218	247	206	197	6504	10637	12067	10026	9612
FICFB-6	27348	172	285	324	268	257	6285	10419	11848	9807	9393
FICFB-7	35365	182	329	379	307	292	5157	9291	10720	8679	8265
FICFB-8	15998	104	170	193	160	153	6477	10611	12040	9999	9585
FICFB-9	19178	131	211	238	199	191	6851	10984	12413	10373	9959
FICFB-10	16846	107	177	201	167	160	6364	10498	11927	9886	9472
FICFB-11	17808	113	187	212	176	169	6363	10496	11925	9885	9471
FICFB-12	21839	140	231	262	217	208	6427	10560	11989	9949	9535
FICFB-13	32015	177	310	355	290	277	5538	9672	11101	9060	8646
FICFB-14	8479	55	90	102	85	82	6521	10655	12084	10043	9629
FICFB-15	12418	81	133	150	125	120	6539	10673	12102	10061	9647
FICFB-16	35011	181	325	375	304	289	5160	9294	10723	8682	8268
FICFB-17	18795	129	207	233	195	187	6860	10994	12423	10382	9968
FICFB-18	28967	173	293	334	275	263	5972	10106	11535	9494	9080
EFG-1	194234	1214	2017	2295	1898	1818	6251	10385	11814	9773	9359
EFG-2	119664	748	1243	1414	1169	1120	6251	10385	11814	9773	9359
EFG-3	217284	1254	2153	2463	2020	1930	5773	9907	11336	9295	8881
EFG-4	114633	708	1182	1346	1112	1064	6178	10311	11740	9700	9286
EFG-5	163569	1010	1687	1920	1587	1519	6178	10311	11740	9700	9286
EFG-6	194038	1213	2015	2292	1896	1816	6251	10385	11814	9773	9359
EFG-7	131860	829	1374	1563	1294	1239	6288	10421	11850	9810	9396
EFG-8	25817	159	266	303	250	240	6178	10311	11740	9700	9286
EFG-9	60515	378	628	715	591	566	6251	10385	11814	9773	9359
EFG-10	130169	818	1357	1543	1277	1223	6288	10421	11850	9810	9396
EFG-11	107499	679	1123	1277	1058	1013	6316	10449	11878	9838	9424
EFG-12	191696	1198	1991	2265	1873	1794	6251	10385	11814	9773	9359
EFG-13	165482	1041	1725	1961	1623	1555	6288	10421	11850	9810	9396
EFG-14	107505	664	1109	1262	1043	998	6178	10311	11740	9700	9286
EFG-15	119835	740	1236	1407	1162	1113	6178	10311	11740	9700	9286
EFG-16	57196	358	594	676	559	535	6251	10385	11814	9773	9359
EFG-17	125294	531	1049	1228	972	920	4235	8368	9798	7757	7343
EFG-18	192661	1190	1987	2262	1869	1789	6178	10311	11740	9700	9286
EFG-19	97294	601	1003	1142	944	903	6178	10311	11740	9700	9286
EFG-20	126496	791	1314	1494	1236	1184	6251	10385	11814	9773	9359
EFG-21	175625	1104	1830	2081	1723	1650	6288	10421	11850	9810	9396
EFG-22	102496	633	1057	1203	994	952	6178	10311	11740	9700	9286

EFG-23	45283	286	473	538	445	427	6316	10449	11878	9838	9424
EFG-24	23697	146	244	278	230	220	6178	10311	11740	9700	9286
EFG-25	137428	859	1427	1624	1343	1286	6251	10385	11814	9773	9359
EFG-26	76449	481	797	906	750	718	6288	10421	11850	9810	9396
EFG-27	165496	1022	1706	1943	1605	1537	6178	10311	11740	9700	9286
EFG-28	184955	1143	1907	2171	1794	1717	6178	10311	11740	9700	9286
EFG-29	68727	402	686	784	644	615	5847	9981	11410	9369	8955
EFG-30	124153	776	1289	1467	1213	1162	6251	10385	11814	9773	9359
EFG-31	112325	706	1171	1331	1102	1055	6288	10421	11850	9810	9396
EFG-32	47309	200	396	464	367	347	4235	8368	9798	7757	7343
EFG-33	28501	142	260	301	243	231	4999	9132	10561	8521	8107
EFG-34	46465	293	486	552	457	438	6316	10449	11878	9838	9424
EFG-35	99167	620	1030	1172	969	928	6251	10385	11814	9773	9359
EFG-36	106314	668	1108	1260	1043	999	6288	10421	11850	9810	9396
EFG-37	121376	750	1252	1425	1177	1127	6178	10311	11740	9700	9286
EFG-38	247857	1239	2263	2618	2112	2009	4999	9132	10561	8521	8107
EFG-39	41543	262	434	493	409	391	6316	10449	11878	9838	9424
EFG-40	163954	1013	1691	1925	1590	1522	6178	10311	11740	9700	9286
EFG-41	20820	122	208	238	195	186	5847	9981	11410	9369	8955
EFG-42	195014	1219	2025	2304	1906	1825	6251	10385	11814	9773	9359
EFG-43	92978	585	969	1102	912	874	6288	10421	11850	9810	9396
EFG-44	21771	134	224	256	211	202	6178	10311	11740	9700	9286
EFG-45	103316	516	943	1091	880	838	4999	9132	10561	8521	8107
EFG-46	83676	528	874	994	823	789	6316	10449	11878	9838	9424
EFG-47	46046	284	475	541	447	428	6178	10311	11740	9700	9286
EFG-48	89143	521	890	1017	835	798	5847	9981	11410	9369	8955
EFG-49	136647	854	1419	1614	1335	1279	6251	10385	11814	9773	9359
EFG-50	18783	118	196	223	184	176	6288	10421	11850	9810	9396
EFG-51	160872	994	1659	1889	1560	1494	6178	10311	11740	9700	9286
EFG-52	63790	403	667	758	628	601	6316	10449	11878	9838	9424
EFG-53	136211	841	1404	1599	1321	1265	6178	10311	11740	9700	9286
EFG-54	294575	1271	2488	2909	2308	2186	4313	8447	9876	7835	7421
EFG-55	47705	279	476	544	447	427	5847	9981	11410	9369	8955
EFG-56	154996	969	1610	1831	1515	1451	6251	10385	11814	9773	9359
EFG-57	67433	424	703	799	662	634	6288	10421	11850	9810	9396
EFG-58	67624	418	697	794	656	628	6178	10311	11740	9700	9286
EFG-59	50131	251	458	529	427	406	4999	9132	10561	8521	8107
EFG-60	24020	152	251	285	236	226	6316	10449	11878	9838	9424
EFG-61	41229	255	425	484	400	383	6178	10311	11740	9700	9286
EFG-62	24055	141	240	274	225	215	5847	9981	11410	9369	8955
EFG-63	73594	460	764	869	719	689	6251	10385	11814	9773	9359
EFG-64	64803	407	675	768	636	609	6288	10421	11850	9810	9396

Table 5 **CAPEX GR** of each **component** or **subsystem** with **annual cell production of 50000 m^2/year**. The initial CAPEX of CL3–4 is not given since SpA cost functions are not valid for annual production of 50000 m^2/year.

Index (the same with other tables)	SPOW, M€	RAUX, M€	HHEX, M€	MHEX, M€	LHEX, M€	METH, M€	SNT, M€	GASI, M€	**Initial CAPEX,** RSOC, M€	
									CL1	CL2
FICFB-1	19.7	0.17	1.91	3.08	16.7	42.7	0.37	6.94	21.9	51.0
FICFB-2	17.4	0.15	1.84	2.94	25.0	41.7	1.70	6.42	25.3	58.9
FICFB-3	18.4	0.13	2.01	2.83	25.6	33.7	1.70	6.77	36.3	84.4
FICFB-4	18.7	0.10	1.64	2.70	23.6	44.6	2.58	5.92	32.2	74.8
FICFB-5	17.5	0.21	1.36	4.20	9.0	29.0	2.85	10.38	16.9	39.2
FICFB-6	20.2	0.17	1.97	3.17	17.1	43.9	0.38	7.14	22.5	52.3
FICFB-7	18.3	0.07	2.03	3.48	15.5	34.3	1.60	8.52	29.1	67.6
FICFB-8	13.6	0.16	1.06	3.24	6.9	22.4	2.18	8.03	13.2	30.6
FICFB-9	16.7	0.15	1.37	3.71	11.4	34.0	1.71	7.10	15.8	36.7
FICFB-10	13.3	0.10	0.70	3.63	8.4	23.6	0.36	8.97	13.8	32.2
FICFB-11	13.3	0.13	0.86	2.90	9.4	24.6	3.04	8.37	14.6	34.0
FICFB-12	17.0	0.15	1.61	3.84	12.2	35.6	0.33	7.36	18.0	41.7
FICFB-13	18.6	0.14	1.04	2.80	16.5	40.5	0.40	7.60	26.3	61.2
FICFB-14	6.3	0.07	0.42	1.52	4.8	12.4	1.31	4.26	7.0	16.2
FICFB-15	10.6	0.14	0.83	2.58	5.5	17.7	1.78	6.36	10.2	23.7
FICFB-16	18.1	0.07	2.01	3.45	15.4	34.0	1.60	8.45	28.8	66.9
FICFB-17	16.4	0.15	1.35	3.66	11.2	33.4	1.69	6.99	15.5	35.9
FICFB-18	16.4	0.15	1.74	2.81	23.6	39.4	1.64	6.10	23.8	55.4
EFG-1	164	1.15	16	15.1	82.3	295	11.9	70.9	160	371
EFG-2	101	0.71	10	9.3	50.7	182	7.3	43.7	98	229
EFG-3	182	1.13	14	19.2	78.9	241	12.1	83.2	179	415
EFG-4	98	0.72	8	14.5	40.3	172	6.7	38.8	94	219
EFG-5	140	1.03	11	20.7	57.5	246	9.5	55.4	134	313
EFG-6	164	1.15	16	15.1	82.2	295	11.9	70.8	160	371
EFG-7	116	0.81	12	13.8	50.5	195	8.2	53.3	108	252
EFG-8	22	0.16	2	3.3	9.1	39	1.5	8.7	21	49
EFG-9	51	0.36	5	4.7	25.6	92	3.7	22.1	50	116
EFG-10	114	0.80	12	13.6	49.9	192	8.1	52.6	107	249
EFG-11	88	0.65	9	7.1	51.7	176	1.0	38.7	88	205
EFG-12	162	1.13	16	14.9	81.2	292	11.8	69.9	158	366
EFG-13	145	1.02	15	17.3	63.4	244	10.3	66.8	136	316
EFG-14	92	0.68	7	13.6	37.8	161	6.3	36.4	88	205
EFG-15	102	0.76	8	15.2	42.1	180	7.0	40.6	99	229
EFG-16	48	0.34	5	4.5	24.2	87	3.5	20.9	47	109
EFG-17	53	0.24	3	3.5	27.1	70	0.8	26.7	103	239
EFG-18	165	1.21	13	24.4	67.7	289	11.2	65.2	158	368
EFG-19	83	0.61	7	12.3	34.2	146	5.7	32.9	80	186
EFG-20	107	0.75	10	9.9	53.6	192	7.8	46.1	104	242
EFG-21	154	1.08	16	18.3	67.3	259	10.9	70.9	144	336
EFG-22	88	0.65	7	13.0	36.0	154	6.0	34.7	84	196

EFG-23	37	0.27	4	3.0	21.8	74	0.4	16.3	37	87
EFG-24	20	0.15	2	3.0	8.3	36	1.4	8.0	19	45
EFG-25	116	0.81	11	10.7	58.2	209	8.4	50.1	113	263
EFG-26	67	0.47	7	8.0	29.3	113	4.8	30.9	63	146
EFG-27	141	1.04	11	21.0	58.1	248	9.6	56.0	136	316
EFG-28	158	1.17	12	23.4	65.0	278	10.8	62.6	152	353
EFG-29	56	0.35	3	4.7	25.2	92	0.6	23.5	57	131
EFG-30	105	0.73	10	9.7	52.6	189	7.6	45.3	102	237
EFG-31	99	0.69	11	11.7	43.0	166	7.0	45.4	92	215
EFG-32	20	0.09	1	1.3	10.2	26	0.3	10.1	39	90
EFG-33	17	0.07	1	2.4	6.5	26	1.8	7.9	23	54
EFG-34	38	0.28	4	3.1	22.3	76	0.4	16.7	38	89
EFG-35	84	0.59	8	7.7	42.0	151	6.1	36.2	82	190
EFG-36	93	0.65	10	11.1	40.7	157	6.6	42.9	87	203
EFG-37	104	0.77	8	15.4	42.6	182	7.1	41.1	100	232
EFG-38	146	0.65	8	21.2	56.2	226	15.6	68.5	204	474
EFG-39	34	0.25	3	2.7	20.0	68	0.4	15.0	34	79
EFG-40	140	1.03	11	20.8	57.6	246	9.5	55.5	135	313
EFG-41	17	0.11	1	1.4	7.6	28	0.2	7.1	17	40
EFG-42	164	1.15	16	15.2	82.6	297	12.0	71.1	160	373
EFG-43	82	0.57	9	9.7	35.6	137	5.8	37.6	76	178
EFG-44	19	0.14	1	2.8	7.6	33	1.3	7.4	18	42
EFG-45	61	0.27	3	8.9	23.4	94	6.5	28.6	85	197
EFG-46	68	0.51	7	5.5	40.2	137	0.8	30.1	69	160
EFG-47	39	0.29	3	5.8	16.2	69	2.7	15.6	38	88
EFG-48	72	0.45	4	6.1	32.7	119	0.8	30.5	73	170
EFG-49	115	0.81	11	10.7	57.9	208	8.4	49.8	112	261
EFG-50	16	0.12	2	2.0	7.2	28	1.2	7.6	15	36
EFG-51	138	1.01	11	20.4	56.5	241	9.4	54.4	132	307
EFG-52	52	0.39	5	4.2	30.7	104	0.6	23.0	52	122
EFG-53	116	0.86	9	17.3	47.9	204	7.9	46.1	112	260
EFG-54	126	0.45	7	9.3	60.4	193	1.7	58.6	242	563
EFG-55	39	0.24	2	3.2	17.5	64	0.4	16.3	39	91
EFG-56	131	0.92	13	12.1	65.6	236	9.5	56.5	127	296
EFG-57	59	0.41	6	7.0	25.8	100	4.2	27.2	55	129
EFG-58	58	0.43	5	8.6	23.8	101	3.9	22.9	56	129
EFG-59	30	0.13	2	4.3	11.4	46	3.2	13.9	41	96
EFG-60	20	0.15	2	1.6	11.5	39	0.2	8.6	20	46
EFG-61	35	0.26	3	5.2	14.5	62	2.4	14.0	34	79
EFG-62	19	0.12	1	1.6	8.8	32	0.2	8.2	20	46
EFG-63	62	0.43	6	5.7	31.2	112	4.5	26.8	61	141
EFG-64	57	0.40	6	6.8	24.8	96	4.0	26.2	53	124

Table 6 **Plant CAPEX GR** and **Plant CAPEX Real** of **each unique plant** with annual cell production of 50000 m^2/year. Results of CL3–4 is not given since SpA cost functions are not valid for annual cell production of 50000 m^2/year.

Index (the same with other tables)	Number of reference stack, -	**Plant CAPEX GR** considering stack replacements, M€		**Plant CAPEX Real**, considering stack replacements, €/ref-stack	
		CL1	CL2	CL1	CL2
FICFB-1	26677	157	243	5867	9091
FICFB-2	30816	172	271	5584	8808
FICFB-3	44185	199	341	4494	7719
FICFB-4	39154	195	321	4981	8205
FICFB-5	20506	124	190	6065	9289
FICFB-6	27348	161	249	5875	9099
FICFB-7	35365	170	284	4802	8026
FICFB-8	15998	97	148	6038	9262
FICFB-9	19178	123	185	6407	9631
FICFB-10	16846	100	154	5941	9165
FICFB-11	17808	106	163	5951	9175
FICFB-12	21839	131	202	6007	9231
FICFB-13	32015	165	269	5167	8391
FICFB-14	8479	52	79	6109	9333
FICFB-15	12418	76	116	6100	9324
FICFB-16	35011	168	281	4805	8029
FICFB-17	18795	121	181	6417	9641
FICFB-18	28967	162	256	5605	8829
EFG-1	194234	1129	1756	5815	9039
EFG-2	119664	696	1082	5815	9039
EFG-3	217284	1160	1860	5338	8562
EFG-4	114633	658	1027	5738	8962
EFG-5	163569	939	1466	5738	8962
EFG-6	194038	1128	1754	5815	9039
EFG-7	131860	770	1196	5843	9067
EFG-8	25817	148	231	5738	8962
EFG-9	60515	352	547	5815	9039
EFG-10	130169	761	1180	5843	9067
EFG-11	107499	633	979	5886	9110
EFG-12	191696	1115	1733	5815	9039
EFG-13	165482	967	1500	5843	9067
EFG-14	107505	617	963	5738	8962
EFG-15	119835	688	1074	5738	8962
EFG-16	57196	333	517	5815	9039
EFG-17	125294	489	893	3903	7127
EFG-18	192661	1106	1727	5738	8962
EFG-19	97294	558	872	5738	8962
EFG-20	126496	736	1143	5815	9039

EFG-21	175625	1026	1592	5843	9067
EFG-22	102496	588	919	5738	8962
EFG-23	45283	267	413	5886	9110
EFG-24	23697	136	212	5738	8962
EFG-25	137428	799	1242	5815	9039
EFG-26	76449	447	693	5843	9067
EFG-27	165496	950	1483	5738	8962
EFG-28	184955	1061	1658	5738	8962
EFG-29	68727	372	594	5419	8643
EFG-30	124153	722	1122	5815	9039
EFG-31	112325	656	1018	5843	9067
EFG-32	47309	185	337	3903	7127
EFG-33	28501	132	224	4625	7849
EFG-34	46465	274	423	5886	9110
EFG-35	99167	577	896	5815	9039
EFG-36	106314	621	964	5843	9067
EFG-37	121376	696	1088	5738	8962
EFG-38	247857	1146	1945	4625	7849
EFG-39	41543	245	378	5886	9110
EFG-40	163954	941	1469	5738	8962
EFG-41	20820	113	180	5419	8643
EFG-42	195014	1134	1763	5815	9039
EFG-43	92978	543	843	5843	9067
EFG-44	21771	125	195	5738	8962
EFG-45	103316	478	811	4625	7849
EFG-46	83676	493	762	5886	9110
EFG-47	46046	264	413	5738	8962
EFG-48	89143	483	771	5419	8643
EFG-49	136647	795	1235	5815	9039
EFG-50	18783	110	170	5843	9067
EFG-51	160872	923	1442	5738	8962
EFG-52	63790	375	581	5886	9110
EFG-53	136211	782	1221	5738	8962
EFG-54	294575	1173	2122	3980	7205
EFG-55	47705	259	412	5419	8643
EFG-56	154996	901	1401	5815	9039
EFG-57	67433	394	611	5843	9067
EFG-58	67624	388	606	5738	8962
EFG-59	50131	232	393	4625	7849
EFG-60	24020	141	219	5886	9110
EFG-61	41229	237	370	5738	8962
EFG-62	24055	130	208	5419	8643
EFG-63	73594	428	665	5815	9039
EFG-64	64803	379	588	5843	9067

Table 7 **Plant CAPEX Target** and **Plant CAPEX Real** of the **case studies** listed in *Appendix: List of Case Studies*.

Case study	Capacity factor[a]	**Plant CAPEX target**[b], €/ref-stack		**Plant CAPEX Real** for annual cell production of 15000 m^2/year, €/ref-stack					**Plant CAPEX Real** for annual cell production of 50000 m^2/year, €/ref-stack	
		Without SNG sale	With SNG sale[c]	CL1	CL2	CL3	CL4	CL5	CL1	CL2
DK-DK1-S1-FICFB-P1	0.03	16282	22486	6278	10411	11840	9800	9386	5867	9091
DK-DK1-S2-FICFB-P1	0.1	15733	22118	6278	10411	11840	9800	9386	5867	9091
IT-SUD-S1-FICFB-P1	0.03	16556	22564	6278	10411	11840	9800	9386	5867	9091
IT-SUD-S2-FICFB-P1	0.08	16414	22412	6278	10411	11840	9800	9386	5867	9091
DK-DK1-S1-FICFB-P3	0.11	4975	9575	5547	9681	11110	9069	8655	5185	8409
DK-DK1-S2-FICFB-P3	0.31	4130	8622	5356	9489	10918	8878	8464	5000	8224
IT-SUD-S1-FICFB-P3	0.09	5164	9598	5547	9681	11110	9069	8655	5185	8409
IT-SUD-S2-FICFB-P3	0.24	4795	9061	5547	9681	11110	9069	8655	5185	8409
DK-DK1-S1-FICFB-P5	0.18	3558	8386	5589	9722	11151	9111	8697	5218	8442
DK-DK1-S2-FICFB-P5	0.48	3014	7886	5554	9688	11117	9076	8662	5186	8410
IT-SUD-S1-FICFB-P5	0.15	3780	8321	5619	9753	11182	9141	8727	5248	8472
IT-SUD-S2-FICFB-P5	0.38	3189	7572	5554	9688	11117	9076	8662	5186	8410
DK-DK1-S1-FICFB-P7	0.25	2738	7725	5630	9763	11192	9152	8738	5259	8483
DK-DK1-S2-FICFB-P7	0.6	2259	7639	5815	9948	11377	9337	8923	5430	8654
IT-SUD-S1-FICFB-P7	0.2	2955	7596	5674	9807	11236	9196	8782	5297	8521
IT-SUD-S2-FICFB-P7	0.45	2870	8110	6072	10206	11635	9594	9180	5675	8899
DK-DK1-S1-EFG-P1	0.33	48	11931	6251	10385	11814	9773	9359	5815	9039
DK-DK1-S2-EFG-P1	0.54	-341	10711	6251	10385	11814	9773	9359	5815	9039
IT-SUD-S1-EFG-P1	0.28	870	10047	5773	9907	11336	9295	8881	5338	8562
IT-SUD-S2-EFG-P1	0.39	-232	9394	6178	10311	11740	9700	9286	5738	8962
DK-DK1-S1-EFG-P3	0.82	-3964	5173	6237	10370	11799	9759	9345	5797	9021
DK-DK1-S2-EFG-P3	0.98	-1741	11184	6264	10398	11827	9786	9373	5822	9046
IT-SUD-S1-EFG-P3	0.61	-3248	5453	6279	10413	11842	9801	9387	5841	9065
IT-SUD-S2-EFG-P3	0.97	-2825	5626	6192	10326	11755	9714	9301	5754	8978
DK-DK1-S1-EFG-P5	1.08	-4484	4183	5878	10012	11441	9400	8986	5457	8681
DK-DK1-S2-EFG-P5	1.71	-4656	3941	6242	10375	11805	9764	9350	5804	9028
IT-SUD-S1-EFG-P5	0.84	-4848	3059	6176	10309	11738	9698	9284	5737	8961
IT-SUD-S2-EFG-P5	1.04	-2660	6381	5872	10006	11435	9394	8980	5455	8679
DK-DK1-S1-EFG-P7	1.33	-5241	3112	5873	10007	11436	9395	8982	5453	8677
DK-DK1-S2-EFG-P7	2.03	-4959	3254	5922	10056	11485	9444	9030	5501	8725
IT-SUD-S1-EFG-P7	1	-4814	2656	5597	9731	11160	9119	8705	5193	8417
IT-SUD-S2-EFG-P7	1.14	-3313	5128	6030	10163	11592	9552	9138	5601	8825

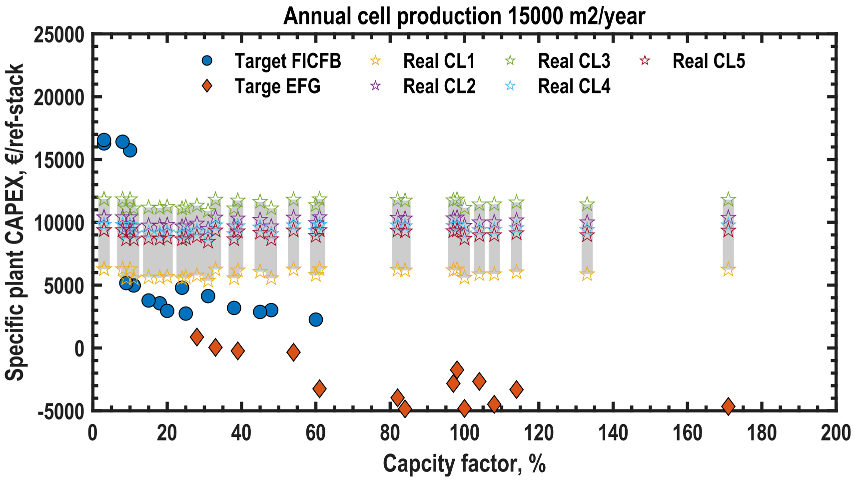
[a] Capacity factor defined in D2.2 represents the contribution of the W2G plants installed to the flexibility needs to be handled by them.

[b] The plant CAPEX target is based on 5-year payback time, 40 €/MWh balancing price and 5-year stack lifetime.

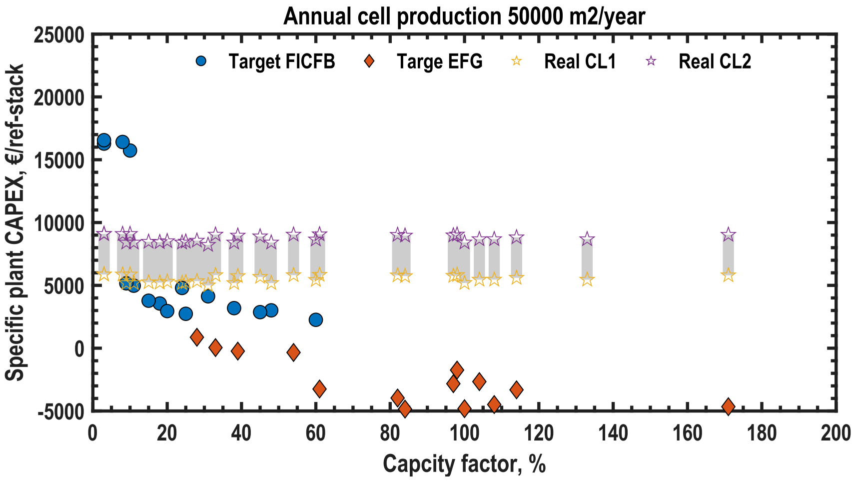
[c] The plant CAPEX target is based on 5-year payback time, 40 €/MWh balancing price, 5-year stack lifetime, and SNG selling price of 0.8 €/kg.

4.3 Plant CAPEX Target versus Plant CAPEX Real of case studies

The Plant CAPEX Target of the case studies needs to be compared with the Plant CAPEX Real of each corresponding case study, to identify the economically viable case studies, whose Plant CAPEX Real should be lower than the Plant CAPEX Target. Both types of specific plant CAPEX have been listed in Table 7 with different predictions of stack costs under different annual production capacity.



(a) For annual cell production of 15000 m^2/year (roughly at an annual production scale of 40–50 MWe SOFC, equivalent to 120–150 MWe SOEC for the state-of-the-art design points).



(b) For annual cell production of 50000 m^2/year (roughly at an annual production scale of 130–150 MWe SOFC, equivalent to 400–500 MWe SOEC for the state-of-the-art design points).

Figure 4 Comparison of **Plant CAPEX Target (with no SNG sale)** and Plant CAPEX Real of the case studies selected.

Table 7 is further illustrated in Figure 4 and Figure 5. As shown in Figure 4, with an annual cell production of 15000 m^2, equivalent to 40–50 MWe SOFC stacks or 120–150 MWe SOEC stacks given the current stack design points, the SpA predictions (CL3–5) give higher costs, while the results of the CEA-CL2, SpA-CL4 and SpA-CL5 are close to each other, further validating the rationality of the cost predictions. The bare modular costs of the stacks are considered in the ranges below:

- CL1 (CEA lower bound): 200–600 €/kWe SOFC
- CL2 (CEA upper bound): 600–1600 €/kWe SOFC
- CL3 (SpA for 1.5 kW): 700–1600 €/kWe SOFC

- CL4 (SpA for 10 kW): 400–1300 €/kWe SOFC
- CL5 (SpA for 40 kW): 400–1300 €/kWe SOFC

For the annual production of 50000 m^2, equivalent to 130–150 MWe SOFC, equivalent to 400–500 MWe SOEC for the state-of-the-art design points, the bare modular costs of the stacks are predicted as follows:

- CL1 (CEA lower bound): 200–600 €/kWe SOFC
- CL2 (CEA upper bound): 400–1400 €/kWe SOFC

These are similar to those of an annual production scale of 15000 m^2, foreseen by the plateau in Figure 3. **With such predictions, the real specific CAPEX of the whole plant is evaluated between 6000-12000 €/ref-stack and 5000-10000 €/ref-stack for the annual production of 15000 and 50000 m^2/year.**

When comparing the plant CAPEX real with the plant CAPEX target calculated without considering the SNG-sale profit (Figure 4), the plant CAPEX real is higher than the plant CAPEX target for the annual cell production of 15000 and 50000 m^2/year, indicating that those case studies can hardly be economical feasible **no matter which prediction methods of stack costs are used**. Only four case studies deploying FICFB-based W2G plants achieve **real economic potential**: **DK-DK1-S1-FICFB-P1, DK-DK1-S2-FICFB-P1, IT-SUD-S1-FICFB-P1, IT-SUD-S2-FICFB-P1**. These four case studies all deploy only one plant with a capacity as high as 100 MWth biomass feed and a small capacity factor of less than 10%. With such small capacity factors, the single plant deployed will operate with very high annual utilization hours of PowGen and PowSto modes, while the PowNeu mode, which does not yield grid-balancing profits, is limited to below 1000 hours per year. These insights have been given in detail in D2.2.

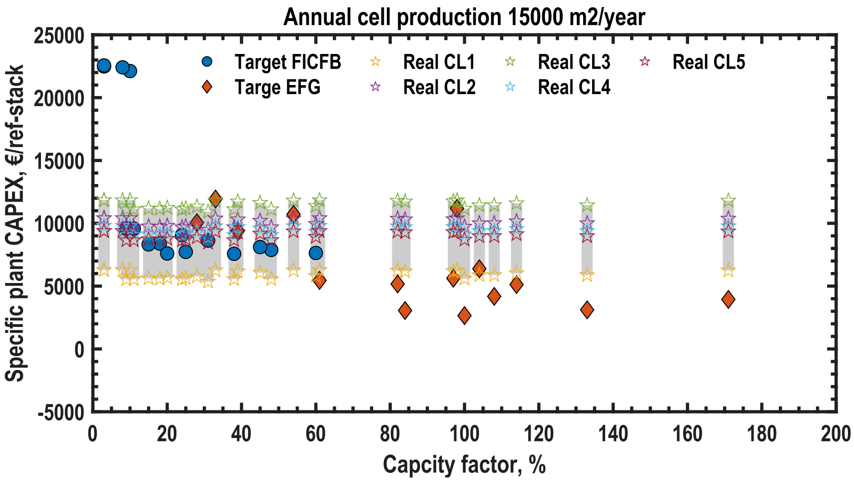
The situation becomes better when considering the profits from the SNG sale, as shown in Figure 5. For the annual production of 15000 m^2/year (Figure 5a), there are more case studies seating within the range of plant CAPEX real, particularly, the case studies with the capacity factor below 60%. If the stack production costs can reach below and around the CEA-CL1 prediction, the cases studies with the capacity factor below 60% can all become economically potential, however, other cost predictions are still higher than the target value.

Similar results are also obtained for the annual production of 50000 m^2/year (Figure 5b), with a further reduction of the specific CAPEX of stack production, there are two more **FICFB-based case studies** reaching the conditions that the plant CAPEX real becomes lower than the plant CAPEX target: **DK-DK1-S1-FICFB-P3 and IT-SUD-S1-FICFB-P3**. While the remaining FICFB case studies achieve a plant CAPEX real close to the plant CAPEX target. Surprisingly, **there are 5 EFG-based case studies becoming economically promising, with one case study even reaching 100% capacity factor**: DK-DK1-S1-EFG-P1, DK-DK1-S2-EFG-P1, IT-SUD-S1-EFG-P1, IT-SUD-S2-EFG-P1, DK-DK1-S2-EFG-P3. Again, if the stack costs could be reduced to the level of CEA-CL1, the case studies with the capacity factor of below 60% are all with high economic potential.

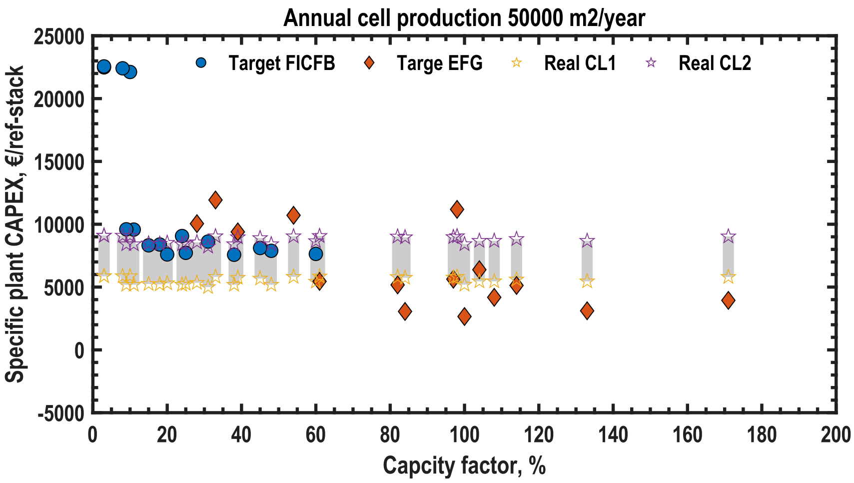
It is noted that in all case studies, the capacity of a single plant deployed might be already larger than the number of stacks produced represented by the annual production scale of 15000 or 50000 m^2/year. This will not change the conclusions of the results, since if a case study is economically potential under the annual production of 15000 or 50000 m^2/year, it will be even more profitable for a further increased production capacity reaching the single-plant capacity.

Therefore, the above analysis can be summarized as:

- **The real specific plant CAPEX (plant CAPEX real) is within the range of 6000-12000 €/ref-stack and 5000-10000 €/ref-stack for the annual production of 15000 and 50000 m²/year, respectively.**
- **The four FICFB-based case studies with a capacity factor of below 10% are with very high economic potential no matter whether SNG sale profit is considered or not.**
- **If the stack bare modular costs could reach the level of CEA-CL1 (200–600 €/kWe stack costs evaluated as SOFC), most of the case studies below 60% capacity factor, including four EFG-based case studies, can be economically potential.**



(a) For annual cell production of 15000 m²/year



(b) For annual cell production of 50000 m²/year

Figure 5 Comparison of **Plant CAPEX Target (with SNG sale)** and Plant CAPEX Real of the case studies selected.

5 Conditions identified and promising business cases finally concluded

As discussed above, the case studies are economically potential with the following assumptions

- For the plant capacity of 100 MWth biomass feed (corresponding to around 60 MWe PowGen capacity / 160 MWe PowSto capacity), the conditions to reach high economic feasibility are:
  - Payback time: > 5 years
  - Energy balancing price: > 40 €/MWh
  - Stack lifetime: > 5 years
  - SNG selling price: > 0.8 €/kg

- Capacity factor: < 10% corresponding to PowNeu operation of below 1000 hours
- Stack costs: < 1600 €/kWe SOFC stack

When the capacity factor of below 10%, there are always case studies with high economically potentials at a plant capacity of **around 100 MWth biomass feed (corresponding to around 60 MWe PowGen capacity / 160 MWe PowSto capacity)**, even with the highest stack production costs predicted, 1600 €/ref-stack. For these case studies, even **considering further engineering factor, contingency factor and working capital factor, they can still be profitable**.

- For the plant capacity of reaching 1000 MWth biomass feed (corresponding to around 500 MWe PowGen capacity / 1500 MWe PowSto capacity), the conditions to reach economical potential:
  - Payback time: > 5 years
  - Energy balancing price: > 40 €/MWh
  - Stack lifetime: > 5 years
  - SNG selling price: > 0.8 €/kg
  - Capacity factor: < 60%
  - Stack costs: < 200–600 €/kWe SOFC stack

It should be also noted that even with the above conditions, the final economic potential is reduced by additional investment related to engineering, contingency and working capital.

Therefore, considering all of the above analysis, we conclude the four FICFB-based case studies with the highest plant CAPEX target as potential business cases, with all the information listed in Table 8. These four case studies can be reduced to two, due to the small effects of the grid-balancing scenarios S1 and S2: DK-DK1- FICFB-P1 with the plant deployed in Ostjylland, IT-SUD-FICFB-P1 with the plant deployed in Campania or Calabria.

Table 8 Potential business cases identified for the conditions of 5-year payback time, 40 €/MWh balancing price, 5-year stack lifetime, and SNG selling price of 0.8 €/kg, and stack costs of 200-1600 €/kWe SOFC.

Case study	Plant CAPEX target, €/ref-stack	Plant CAPEX real, €/ref-stack	Plant location	Plant capacity, MWth biomass input	PowGen capacity, MWe	PowSto capacity, MWe	PowGen efficiency (LHV), %	PowSto efficiency (LHV), %
DK-DK1-S1-FICFB-P1	22486	6000-12000	Ostjylland	100	56.5	158.5	56.5	70.8
DK-DK1-S2-FICFB-P1	22118	6000-12000	Ostjylland	100	56.5	158.5	56.5	70.8
IT-SUD-S1-FICFB-P1	22564	6000-12000	Campania	100	56.5	158.5	56.5	70.8
IT-SUD-S2-FICFB-P1	22412	6000-12000	Calabria	100	56.5	158.5	56.5	70.8

6 Conclusions

Following the D2.2 and D2.3, which evaluated the plant CAPEX target of many case studies under different grid-balancing scenarios and plant capacities, the plant CAPEX target with plant design, size, and location, as well as biomass supply chain is given for all case studies evaluated. This deliverable further evaluates the real specific CAPEX, i.e., plant CAPEX real, to compare with the plant CAPEX target. Those case studies whose plant CAPEX real is below their plant CAPEX target, are identified as potential business cases. Considering the assumptions evaluated, the conditions which can yield potential business cases, are highlighted. The major conclusions are:

- When the annual cell production reaches above 15000 m^2 (40–50 MWe SOFC stacks / 120–150 MWe SOEC stacks), the cost predictions from CEA and SpA become close to each other, around 200–1600 €/kWe SOFC stacks. Further increasing the cell production to 50000 m^2/year (130–150 MWe SOFC / 400–500 MWe SOEC), the stack costs could be reduced to 200–1400 €/kWe SOFC stacks.
- The plant CAPEX real of the W2G plants evaluated with different sizes and designs reaches within 4200–13000 €/ref-stack for annual cell production of 15000 m^2, and reduces to 3900–9600 €/ref-stack for annual cell production of 50000 m^2.
- Considering the plants deployed in each case study, the plant CAPEX real of the case studies is within 5000–12000 €/ref-stack, thus with a plant CAPEX target of over 20000 €/ref-stack, the two case studies (DK-DK1- FICFB-P1 with the plant deployed in Ostjylland, IT-SUD-FICFB-P1 with the plant deployed in Campania or Calabria) with low capacity factors of below 10% and deploying a plant of around 100 MWth biomass feed are treated as potential business cases, even with additional costs for engineering and contingency apart from the gross Grassroot CAPEX. The low capacity factor is a key since a low capacity factor allows the W2G plants to operate under high hours of PowGen and PowSto modes, which is crucial to benefit from offering grid-balancing services.
- Potential business cases can be enabled by the conditions: 5-year payback time, 40 €/MWh energy balancing price, 5-year stack lifetime, 0.8 €/kg SNG selling price, and a capacity factor of below 10% (requiring the stack costs of below 1600 €/kWe SOFC stack). By increasing the capacity factor to around 60%, the stack costs need to be below 200-600 €/kWe SOFC stack to enable more potential business cases.

All in all, this deliverable is a concluding one for the whole W2G project. **One conclusion, in short, is that the triple-mode W2G plant concept is proven to be economically potential when the stack costs are reduced to below 2000 €/kWe SOFC, even with the current grid-balancing prices. The key of enabling high economic feasibility is high annual hours of PowGen and PowSto operation (e.g., over 7500 hours), since only these two modes gain profit from the grid-balancing services.**

Appendix: List of case studies

The table below lists all potentially promising case studies considering SNG sale profit, which is evaluated based on the assumptions: 5-year payback time, 40 €/MWh balancing price and 5-year stack lifetime.

Case study	Plant CAPEX target[a], €/ref-stack		Capacity factor x	Plant number	Plant location	Plant capacity, MWth biomass input	Number of reference stacks of each plant	PowGen capacity, MWe	PowSto capacity, MWe	PowGen efficiency (LHV), %	PowSto efficiency (LHV), %
	Without SNG sale	With SNG sale[b]									
DK-DK1-S1-FICFB-P1	16282	22486	0.03	1	Ostjylland	100	26956	56.50	158.50	56.50	70.80
DK-DK1-S2-FICFB-P1	15733	22118	0.10	1	Ostjylland	100	26956	56.50	158.50	56.50	70.80
IT-SUD-S1-FICFB-P1	16556	22564	0.03	1	Campania	100	26956	56.50	158.50	56.50	70.80
IT-SUD-S2-FICFB-P1	16414	22412	0.08	1	Calabria	100	26956	56.50	158.50	56.50	70.80
DK-DK1-S1-FICFB-P3	4975	9575	0.11	3	Vestjylland	100	26956	56.55	158.50	56.55	70.83
					Sydjylland	100	32776	58.30	149.43	58.30	67.22
					Ostjylland	100	46934	57.64	158.66	57.64	72.52
DK-DK1-S2-FICFB-P3	4130	8622	0.31	3	Vestjylland	100	26846	56.32	157.85	56.55	70.83
					Ostjylland	100	41377	51.71	159.12	51.71	74.77
					Nordjylland	100	46850	57.54	158.38	57.64	72.52
IT-SUD-S1-FICFB-P3	5164	9598	0.09	3	Puglia	100	26956	56.55	158.50	56.55	70.83
					Puglia	100	32776	58.30	149.43	58.30	67.22
					Puglia	100	46934	57.64	158.66	57.64	72.52
IT-SUD-S2-FICFB-P3	4795	9061	0.24	3	Puglia	100	26956	56.55	158.50	56.55	70.83
					Puglia	100	32776	58.30	149.43	58.30	67.22
					Puglia	100	46934	57.64	158.66	57.64	72.52
DK-DK1-S1-	3558	8386	0.18	5	Sydjylland	95	26956	41.42	100.57	43.80	64.61
					Nordjylland	98	37615	55.44	155.40	56.55	70.83

FICFB-P5					Nordjylland	100	20399	58.70	153.37	58.70	70.90
					Sydjylland	100	32776	58.30	149.43	58.30	67.22
					Ostjylland	100	46934	57.41	158.02	57.64	72.52
DK-DK1-S2-FICFB-P5	3014	7886	0.48	5	Nordjylland	100	16675	43.80	106.35	43.80	64.61
					Sydjylland	100	26832	56.29	157.77	56.55	70.83
					Nordjylland	100	37615	58.70	153.37	58.70	70.90
					Vestjylland	100	32776	58.30	149.43	58.30	67.22
					Ostjylland	100	46875	57.57	158.46	57.64	72.52
IT-SUD-S1-FICFB-P5	3780	8321	0.15	5	Puglia	100	26956	56.55	158.50	56.55	70.83
					Puglia	100	37615	58.70	153.37	58.70	70.90
					Calabria	100	20399	51.84	137.29	51.84	64.39
					Puglia	100	32776	58.30	149.43	58.30	67.22
					Calabria	100	46934	57.64	158.66	57.64	72.52
IT-SUD-S2-FICFB-P5	3189	7572	0.38	5	Puglia	100	16675	43.80	106.35	43.80	64.61
					Puglia	100	26956	56.55	158.50	56.55	70.83
					Puglia	100	37615	58.70	153.37	58.70	70.90
					Calabria	100	32776	58.30	149.43	58.30	67.22
					Calabria	100	46934	57.64	158.66	57.64	72.52
DK-DK1-S1-FICFB-P7	2738	7725	0.25	7	Ostjylland	100	14754	43.80	106.35	43.80	64.61
					Nordjylland	100	34052	56.55	158.50	56.55	70.83
					Fyn	100	26956	58.66	153.28	58.70	70.90
					Nordjylland	100	37615	51.84	137.29	51.84	64.39
					Sydjylland	100	20399	51.71	159.12	51.71	74.77
					Sydjylland	100	32776	58.30	149.43	58.30	67.22
					Vestjylland	100	46934	57.64	158.66	57.64	72.52
DK-DK1-S2-FICFB-P7	2259	7639	0.60	7	Fyn	100	17918	43.28	100.45	43.28	67.02
					Sydjylland	100	18942	49.01	102.15	49.01	67.48
					Sydjylland	100	16675	43.80	106.35	43.80	64.61

					Nordjylland	100	23229	51.72	140.12	51.72	68.05
					Fyn	100	20399	51.84	137.29	51.84	64.39
					Vestjylland	100	41377	51.71	159.12	51.71	74.77
					Nordjylland	100	46934	57.64	158.66	57.64	72.52
IT-SUD-S1-FICFB-P7	2955	7596	0.20	7	Campania	100	16675	43.80	106.35	43.80	64.61
					Calabria	100	34052	57.31	154.46	57.31	76.54
					Calabria	100	26956	56.55	158.50	56.55	70.83
					Campania	100	37615	58.70	153.37	58.70	70.90
					Puglia	100	20399	51.84	137.29	51.84	64.39
					Puglia	100	32776	58.30	149.43	58.30	67.22
					Puglia	100	46934	57.64	158.66	57.64	72.52
IT-SUD-S2-FICFB-P7	2870	8110	0.45	7	Calabria	100	17918	43.28	100.45	43.28	67.02
					Puglia	69	13069	33.82	70.48	49.01	67.48
					Puglia	89	14891	39.11	94.97	43.80	64.61
					Campania	100	26956	56.55	158.50	56.55	70.83
					Puglia	99	37210	58.06	151.72	58.70	70.90
					Puglia	98	19942	50.68	134.22	51.84	64.39
					Calabria	94	30933	55.03	141.02	58.30	67.22
DK-DK1-S1-EFG-P1	48	11931	0.33	1	Nordjylland	995	206634	463	1364	46.57	62.22
DK-DK1-S2-EFG-P1	-341	10711	0.54	1	Nordjylland	613	127463	285	841	46.57	62.22
IT-SUD-S1-EFG-P1	870	10047	0.28	1	Altamura	1000	231105	501	1470	50.14	64.97
IT-SUD-S2-EFG-P1	-232	9394	0.39	1	Puglia	595	121987	242	787	40.76	64.29

DK-DK1-S1-EFG-P3	-3964	5173	0.82	3	Vestjylland	849	173929	346	1122	40.76	64.29
					Fyn	994	206380	463	1363	46.57	62.22
					Sydjylland	702	140287	325	938	46.28	63
DK-DK1-S2-EFG-P3	-1741	11184	0.98	3	Vestjylland	134	27460	55	177	40.76	64.29
					Sydjylland	310	64308	144	425	46.57	62.22
					Ostjylland	693	138462	321	926	46.28	63
IT-SUD-S1-EFG-P3	-3248	5453	0.61	3	Puglia	546	114270	254	703	46.60	63.92
					Vibo Valentia	982	203848	457	1347	46.57	62.22
					Avellino	881	175994	408	1177	46.28	63
IT-SUD-S2-EFG-P3	-2825	5626	0.97	3	Campania	558	114311	227	738	40.76	64.29
					Puglia	622	127552	254	823	40.76	64.29
					Calabria	293	60862	137	402	46.57	62.22
DK-DK1-S1-EFG-P5	-4484	4183	1.08	5	Nordjylland	339	133452	174	411	51.22	72.18
					Fyn	1000	204916	408	1322	40.76	64.29
					Vestjylland	505	103504	206	668	40.76	64.29
					Sydjylland	648	134567	302	889	46.57	62.22
					Fyn	935	186736	433	1249	46.28	63
DK-DK1-S2-EFG-P5	-4656	3941	1.71	5	Nordjylland	532	109058	217	704	40.76	64.29
					Nordjylland	230	48077	107	296	46.60	63.92
					Ostjylland	123	25177	50	162	40.76	64.29
					Vestjylland	704	146186	328	966	46.57	62.22
					Fyn	407	81350	188	544	46.28	63
IT-SUD-S1-EFG-P5	-4848	3059	0.84	5	Campania	859	176087	350	1136	40.76	64.29
					Cosenza	960	196768	391	1270	40.76	64.29
					Basilicata	340	72994	151	443	44.37	64.58
					Puglia	636	132110	296	873	46.57	62.22
					Gioia Tauro	598	119494	277	799	46.28	63
	-2660	6381	1.04	5	Puglia	128	50406	66	155	51.22	72.18

IT-SUD-S2-EFG-P5					Puglia	112	30322	49	132	44	68.19
					Bari	236	49492	110	304	46.60	63.92
					Lamezia Terme	508	105500	237	697	46.57	62.22
					Avellino	566	112992	262	756	46.28	63
DK-DK1-S1-EFG-P7	-5241	3112	1.33	7	Nordjylland	630	129179	257	834	40.76	64.29
					Fyn	974	263513	428	1150	44	68.19
					Vestjylland	211	44083	98	271	46.60	63.92
					Sydjylland	851	174422	347	1125	40.76	64.29
					Ostjylland	103	22173	46	135	44.37	64.58
					Fyn	999	207334	465	1370	46.57	62.22
					Fyn	495	98795	229	661	46.28	63
DK-DK1-S2-EFG-P7	-4959	3254	2.03	7	Fyn	113	23098	46	149	40.76	64.29
					Sydjylland	406	109771	178	479	44	68.19
					Ostjylland	425	89036	198	548	46.60	63.92
					Fyn	239	49008	97	316	40.76	64.29
					Nordjylland	441	94809	196	575	44.37	64.58
					Nordjylland	700	145272	326	960	46.57	62.22
					Nordjylland	100	19978	46	134	46.28	63
IT-SUD-S1-EFG-P7	-4814	2656	1.00	7	Avellino	835	171030	340	1104	40.76	64.29
					Vibo Valentia	324	67752	151	417	46.60	63.92
					Catanzaro	707	144843	288	935	40.76	64.29
					Bitonto	867	313399	418	995	48.25	69.80
					Abruzzo	236	50784	105	308	44.37	64.58
					Cosenza	794	164808	370	1089	46.57	62.22
					Reggio Di Calabria	359	71671	166	479	46.28	63
IT-SUD-S2-	-3313	5128	1.14	7	Basilicata	351	72024	143	465	40.76	64.29
					Puglia	197	53392	87	233	44	68.19

EFG-P7					Casoria	122	25498	57	157	46.60	63.92
					Abruzzo	214	43921	87	283	40.76	64.29
					Puglia	119	25634	53	156	44.37	64.58
					Campania	377	78328	176	517	46.57	62.22
					Calabria	345	68863	160	461	46.28	63

[a] The plant CAPEX target is based on 5-year payback time, 40 €/MWh balancing price and 5-year stack lifetime.

[b] The plant CAPEX target is based on 5-year payback time, 40 €/MWh balancing price, 5-year stack lifetime, and SNG selling price of 0.8 €/kg.

Appendix: Cost functions

The cost functions are mainly from classical chemical engineering handbooks including Ref. [9,10]. The CAPEX evaluation considers the investment costs related to biomass onsite pretreatment unit, gasifier, syngas cleaning, RSOC stack, methanation reactor, heat exchanger network, steam turbine network, compressors/fans and pressure vessels, e.g., water condenser and separator. They are further described in detail below.

(1) Biomass processing

The cost of the torrefraction and drying is estimated based on the dryer volume, which is calculated based on the mass flow rate of biomass to be handled and the assumptions of biomass density of 300 kg/m^3, the void fraction of 0.9, the residence time of 90 min:

$$C_{\mathrm{dryer}} = f_{\mathrm{install}}\, N_{\mathrm{units}} * 17370 * V^{0.74}\ \$,$$

with f_{install} being 1.5 and N_{units} calculated considering a maximum diameter of 4 m and a height-diameter ratio of 2. The convery cost is estimated by the bucket convery cost function:

$$C_{\mathrm{convey}} = f_{\mathrm{BM}}\, 10^{2.5812 + 1.3219 * \log_{10} H} \left(\frac{\mathrm{CEPCI}_{2019}}{\mathrm{CEPCI}_{1982}}\right)\ \$,$$

(2) FICFB Gasifier

The investment is estimated for both the gasifier chamber and combustion chamber, using the same method to calculate the volume of the reactor:

$$D = 2\sqrt{v/(\pi\, \overline{U})},\, H = c_1\, v^{c_2},\, V = H\, \frac{\pi}{4}\, D^2,$$

where the D, H, V are the diameter, height, and volume of the reactor, v is the volumetric flow of the exiting gas, $\overline{U}$ is the mean gas velocity. The coefficients c_1 are set as 8.47 and 4.07 for the combustor and gasifier, while the coefficient c_2 is 0.188. The bare module cost is estimated by the fluid bed with the above parameters:

$$C_{\mathrm{FB}} = f_{\mathrm{M}}\, f_{\mathrm{P}}\, 10^{k_1 + k_2\, \log_{10} V + k_3\, (\log_{10} V)^2} \left(\frac{\mathrm{CEPCI}_{2019}}{\mathrm{CEPCI}_{1996}}\right)\ [\mathrm{USD}],$$

with f_{M} and f_{P} being the material (2.7 for carbon steel, 6.0 for stainless steel, 10.0 for nikel steel) and pressure (1 for atmospheric FICFB) factors. The coefficients k_1, k_2, k_3 are set as 4.105, 4.449e-1 and 3.224e-2, respectively.

(3) Syngas cleaning

The cost function for cold cleaning considers a cyclone, a bag filter, a scrubber, guard beds with ZnO, which can be evaluated in detail via the volume of the vessels used. However, in Ref. [11], a simple cost function scaling from a reference cold-cleaning unit results in similar results, thus it is employed in this project:

$$C_{\mathrm{cgc}} = 25.8\mathrm{e}6 * (v/74.1)\ €,$$

where v is the volumetric flow rate (m^3/s) of the syngas processed.

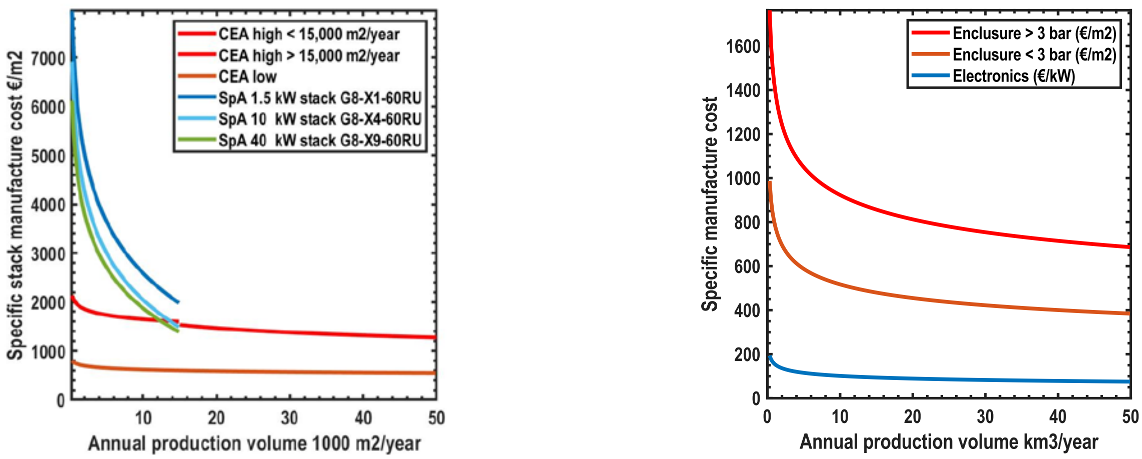
The cost function for hot cleaning can also be scaled from a reference unit available in the literature:

$$C_{\mathrm{hgc}} = 14.3\mathrm{e}6 * (H/(1000 * 400))\ €,$$

where H is the flow enthalpy of the syngas (kW).

(4) Stack

The manufacturing cost of the stacks has been evaluated by many researchers and industry. The specific manufacturing cost of the stack depends highly on the annual production volume of the cell area. In the EU H2020 ECo project, where EPFL has been involved, the partner CEA has summarized all the cost data available in the literature and, together with their internal experience and knowledge on the manufacturing of stacks, proposed cost functions for solid-oxide stacks. Meanwhile, especially for the SpA stack and stack module, the company has done an internal evaluation of the manufacturing cost and has reported these data in D3.1. In Figure 6a, the cost functions from CEA and SpA have been compared. It shows that based on the current production platform of SpA, the manufacturing cost is much higher than those proposed in the literature and by CEA. For a reasonable prediction of the future market with an annual production volume of 15,000 m^2 cells, the cost numbers from both sides become close. Therefore, in the cost evaluation of this project, the annual production volume is set to be 15,000 m^2 and more. Besides, in Figure 6b, the cost of **power electronics** is also related to the annual production volume, resulting in **a manufacturing cost of around 100 €/kW**. The enclosures have been also an important cost element in the CEA's estimation, particularly when under high pressure. **However, with further communication with SpA, the stack is supposed to operate under close-to-atmospheric pressure and the enclosure costs can be neglected, comparing with the stack costs.**



(a) (b)

Figure 6 Specific manufacturing cost of the solid-oxide stack (a) and power electronics (b).

Referring to Figure 6a, we have defined two levels for specific stack costs (€/m^2 cell area), HIGH and LOW, which define an upper-bound and lower-bound of the stack costs:

$$SpecificStackCost \begin{cases} CostLevel = HIGH \begin{cases} 1600 * 0.95^{\frac{\ln\left(V_{\mathrm{ref}} * J_{\mathrm{ref}} * AnnualProductionVolume * \frac{\frac{10000}{1000000}}{200}\right)}{\ln 2}} & AnnualProductionVolume < 15000\ \mathrm{m}^2/\mathrm{year} \\ 1200 * 0.90^{\frac{\ln\left(V_{\mathrm{ref}} * J_{\mathrm{ref}} * AnnualProductionVolume * \frac{\frac{10000}{1000000}}{1000}\right)}{\ln 2}} & AnnualProductionVolume > 15000\ \mathrm{m}^2/\mathrm{year} \end{cases} \\ CostLevel = LOW \begin{cases} 600 * 0.95^{\frac{\ln\left(V_{\mathrm{ref}} * J_{\mathrm{ref}} * AnnualProductionVolume * \frac{\frac{10000}{1000000}}{200}\right)}{\ln 2}} \end{cases} \end{cases}$$

where V_{ref} and J_{ref} are the reference voltage and current density considered (1.34 V and 1 A/cm^2), respectively. The *AnnualProductionVolume* refers to the annual cell production volume (m^2/year). With the specific stack costs calculated, the bare module cost of the stack (€) becomes

$$StackCost = SpecificStackCost * TotalCellArea$$

$$BareModule\_Cost = StackCost * f_{installation}$$

where the $f_{installation}$ is set to be 1.8, according to (DOE/NETL Analysis of Natural Gas Fuel Cell Plant Configurations, 2011).

(5) Methanator subsystem

The cost of a reactor depends on the reactor type, pressure level, material type and actual inlet volumetric flowrate. The number and size of the reactors are defined by the total volumetric flow, the superficial gas velocity and the gas hourly space velocity.

The reactor diameter is determined similarly to that of the vessels but by the superficial gas velocity:

$$n_{\mathrm{reactor}} = \mathrm{ceil}\left(\frac{2\sqrt{\frac{\dot{V}_{\mathrm{tot}}}{\pi\,\bar{v}}}}{D_{\max}}\right)^2$$

$$D_{\mathrm{single}} = 2\sqrt{\frac{\dot{V}_{\mathrm{single}}}{\alpha\,\pi\,\bar{v}}}$$

where the values of the parameter α are 1 for fixed-bed catalytic methanation reactor and MeOH-to-DME reactors, 0.92 (fixed-bed) and 0.49 (slurry-bed) for MeOH- and DME-to-gasoline reactors. The reactor volume is calculated by the gas hourly space velocity (in h^{-1}) based on the volumetric flowrate at standard conditions (15 C and 1 bar):

$$V_{\mathrm{tot}} = 3600\frac{\dot{V}_{\mathrm{tot}}\frac{p}{p_{\mathrm{std}}}\frac{T_{\mathrm{std}}}{T}}{\mathrm{GHSV}}$$

$$V_{\mathrm{single}} = \frac{V_{\mathrm{tot}}}{n_{\mathrm{reactor}}}$$

The determination of the reactor diameter differs from the reactor type:

$$H_{\mathrm{single}} = \begin{cases} \frac{4\,V_{\mathrm{single}}}{\pi\,D_{\mathrm{single}}^2} + 0.914 & \text{type 1} \\ \beta\,D_{\mathrm{single}} & \text{type 2} \end{cases}$$

where type 1 is for the fixed-bed catalytic methanation reactor, and type 2 is for MeOH- and DME-to-gasoline reactors with the parameter β equal to 1.62 for fixed bed and 3.15 for slurry bed, and MeOH-to-DME reactor with the parameter β equal to 1.62.

With the updated diameter, the volume of a single reactor is corrected as

$$V_{\mathrm{single}} = H_{\mathrm{single}}\frac{\pi\,D_{\mathrm{single}}^2}{4},$$

with the calculated n_{reactor}, D_{single}, H_{single} and V_{single}, the reactor cost without catalyst fill is

$$C_{\mathrm{reactor}}^{\mathrm{BM}} = \begin{cases} n_{\mathrm{reactor}}\,C_{\mathrm{vv}}^{\mathrm{BM}} & \text{for adiabatic reactor with } C_{\mathrm{vv}}^{\mathrm{BM}} \text{ calculated above} \\ n_{\mathrm{reactor}}\,C_{\mathrm{jr}}^{\mathrm{BM}} & \text{for isothermal reactor with } C_{\mathrm{jr}}^{\mathrm{BM}} \text{ given below} \end{cases}$$

The isothermal reactor is treated as a jacketed reactor for costing:

$$C_{\mathrm{jr}}^{\mathrm{BM}} = 10^{k_1 + k_2 \log(V) + k_3 (\log(V))^2} F_{\mathrm{p}}\, F_{\mathrm{m}} \left(\frac{\mathrm{CEPCI}_{2019}}{\mathrm{CEPCI}_{2004}}\right)$$

where the reactor volume is calculated as mentioned above, while the coefficient k equals {3.765965, 0.230014, 0.118244}. The material factor F_{m} is 3.0 for carbon steel and 7.6 for stainless steel, while the pressure factor F_{p} is 1.0 ($p \leq 6$), 1.4 ($p \leq 11$), 1.6 ($p \leq 16$), 2.0 ($p \leq 21$), 3.0 ($p \leq 4.1$), 4.3 ($p \leq 81$), 6.5 ($p \leq 161$), 13 ($p \leq 321$).

For the reactors involved, the superficial gas velocity is collected and validated: 0.5 m/s for fixed-bed methanation reactor, 0.317 m/s for fixed-bed MeOH reactor, 0.135 m/s for slurry-bed MeOH reactor, 0.2 m/s for MeOH-to-DME reactor, 0.2136 m/s for DME-to-gasoline reactor. The gas hourly space velocity for the isothermal methanation reactor is set as 2400 h^{-1}.

(6) Heat exchanger network

The area and cost of the heat exchanger network are estimated by a classical vertical heat transfer based on the composite curve. A detailed description of this estimation procedure can be found elsewhere, e.g., chapter 15 of Ref. [**Error! Bookmark not defined.**]. An example has been given in Figure 7. The estimation procedure w orks as follows:

- Identify the temperature intervals (v_i), the involved heat streams and the corresponding heat loads from the composite curve
- Estimate the average heat exchange coefficient ($\overline{U}_{v_i}$) of each vertical heat exchanger (v_i)
  - o Average heat transfer coefficients of hot/cold composite flows ($\overline{U}_{\mathrm{h},v\_i}$ and $\overline{U}_{\mathrm{c},v\_i}$)

$$\overline{U}_{\mathrm{h},v_i} = \frac{\dot{Q}_{\mathrm{tot},v_i}}{\sum_{j\in\mathbb{H}_{v_i}} \frac{\dot{Q}_{j,v_i}}{U_j}}, \qquad \overline{U}_{\mathrm{c},v_i} = \frac{\dot{Q}_{\mathrm{tot},v_i}}{\sum_{j\in\mathbb{C}_{v_i}} \frac{\dot{Q}_{j,v_i}}{U_j}},$$

    where $\dot{Q}_{\mathrm{tot},v_i}$ is the total heat transferred of the temperature interval v_i, $\mathbb{H}_{v_i}$ ($\mathbb{C}_{v_i}$) represent a set of all hot (cold) streams involved in the temperature interval v_i, $\dot{Q}_{j,v_i}$ stands for the amount of heat transferred by stream j in the temperature interval v_i, and U_j indicates the heat transfer coefficient of stream j.

  - o Overall heat transfer coefficient

$$\overline{U}_{v_i} = \frac{1}{\frac{1}{\overline{U}_{\mathrm{h},v_i}} + \frac{1}{\overline{U}_{\mathrm{c},v_i}}}$$

- Calculate the heat exchanger area of each temperature interval (A_{v_i}) and the total (A_{tot})

$$A_{v_i} = \frac{\dot{Q}_{\mathrm{tot},v_i}}{\overline{U}_{v_i}\, \Delta T_{\log}} \qquad A_{\mathrm{tot}} = \sum A_{v_i}$$

  where $\Delta T_{\log}$ is the log temperature difference of the temperature interval v_i.

- Calculate the minimum number of heat exchangers $N_{\min}$ and the average heat exchanger area ($\bar{A}$)

$$N_{\min} = (N_{\mathrm{str}} - 1) + (N_{\mathrm{pstr}} - 1), \qquad \bar{A} = \frac{A_{\mathrm{tot}}}{N_{\min}}$$

  where N_{str} is the total number of heat streams, and N_{pstr} is the number of pinch streams.

- Calculate the bare module cost of the heat exchanger network (in $)

$$C_{\mathrm{hen}}^{\mathrm{BM}} = (1\mathrm{E}4 + 800\ N_{\min}\overline{\mathrm{A}}^{0.8})\ F_{\mathrm{p}}\ F_{\mathrm{m}}$$

where F_{p} and F_{m} are the pressure and material factors. It is assumed that the material used for all heat exchangers is stainless steel with $F_{\mathrm{m}} = 3$, while F_{p} is determined based on the actual operating pressure of the system by the formulation given in Fig.5.37 of Ref. [**Error! Bookmark not defined.**].

Figure 7 An example of using composite curves from heat cascade calculation for heat exchanger area and costs.

To better estimate the heat exchangers cost, the area within different temperature ranges are counted separately to consider the material factors: For the area working below 500 °C, carbon steel is used with a material factor of 1; For the area working within 500 and 1000 °C, stainless steel is used with a material factor of 3.0; For the area working over 1000 °C, nickel steel is used with a factor of 3.8.

(7) Steam turbine network

The cost of the steam cycle mainly comes from the heat exchangers (including the steam generator) and steam turbines. The heat exchanger costs have been readily considered with the estimation method described in section **Error! Reference source not found.**. The investment of each steam turbine can be calculated based on the power output W (kW):

$$C_{\mathrm{st}} = 379.6 * \left(\frac{W}{1e3}\right)^{-0.183} * W * \left(\frac{\mathrm{CEPCI}_{2019}}{\mathrm{CEPCI}_{2008}}\right)\ \$$$

(8) Compressors and pumps

All compressors for different gases involved, e.g., sweep air, hydrogen, syngas, and methane, are modeled by multi-stage isentropic compression with inter-cooling. The maximum pressure ratio per stage (γ_{stage}) is specified as 3. The stage number is determined by an equal distribution of the desired pressure ratio over total pressure ratio:

$$n_{\text{stage}} = \frac{\log(\gamma_{\text{tot}})}{\log(\gamma_{\text{stage}})}$$

Then, the total power required and outlet temperature can be calculated by isentropic compression. The minimum number of compressors in operation ($n_{\text{comp}}^{\text{operation}}$) is then computed with respect to maximum fluid power for a single compressor ($\dot{W}_{\text{single}}^{\max} = 8000$ kW). The costing of centrifugal compressors is considered (Fig.5.30 of (Ulrich,2004)):

$$C_{\text{comp}}^{\text{BM}} = n_{\text{comp}}^{\text{operation}} 10^{k_1 + k_2 \log(\dot{W}_{\text{single}}) + k_3 (\log(\dot{W}_{\text{single}}))^2 + k_4 (\log(\dot{W}_{\text{single}}))^3} F_{\text{m}} F_{\text{bkp}} \left(\frac{\text{CEPCI}_{2019}}{\text{CEPCI}_{2004}}\right)$$

where the coefficient $\boldsymbol{k}$ equals {3.80816, 6.49782E-02, 3.25227E-01, -3.91622E-02}. The material factor, F_{m}, is taken as 2.5 for carbon steel and 6.3 for stainless steel, while the backup factor, F_{bkp}, for considering spare compressors purchase is set as 2.5.

The costing of pumps is treated similarly to that of the compressors, which is formulated as follows (Turton, 2008):

$$C_{\text{pump}}^{\text{BM}} = n_{\text{pump}}^{\text{operation}} 10^{k_1 + k_2 \log(\dot{W}_{\text{single}}) + k_3 (\log(\dot{W}_{\text{single}}))^2} F_{\text{bkp}} (a_1 + a_2 F_{\text{p}} F_{\text{m}}) \left(\frac{\text{CEPCI}_{2017}}{\text{CEPCI}_{1996}}\right)$$

where the coefficient $\boldsymbol{k}$ equals {3.5793, 0.3208, 0.02850}, while the coefficients a_1 and a_2 are 1.8 and 1.51, respectively. The backup factor, F_{bkp}, is specified as 3.21. The material factor F_{m} is 1.8 for carbon steel and 2.4 for stainless steel, while the pressure factor F_{p} is calculated as below:

$$F_{\text{p}} = \begin{cases} 1 & p \leq 11 \text{ bar} \\ b_1 + b_2 \log(\text{p} - 1) + b_3 (\log(\text{p} - 1))^2 & p > 11 \text{ bar} \end{cases}$$

where the coefficient $\boldsymbol{b}$ is {0.1682, 0.3477, 0.4841}, respectively.

(9) Pressure vessels (reactor/flash drum/column)

The drums, reactors, and columns are basically pressure vessels, usually vertical pressure vessels. The vessel volume can be reasonably determined by the actual inlet volumetric flow $\dot{V}$ and the superficial speed $\bar{v}$ (or the residence time τ, or the gas hourly space velocity GHSV). The selection of superficial speed and residence time is usually based on the existing unit operation or experimental setup and may vary largely among the types of equipment.

- Flash drum, the gas-liquid separator

For a flash drum, the residence time is usually selected as 300s. The volumetric flows (m^3/s) of gas and liquid in the drum are assumed to be the same. Thus, the number of drums required can be first determined as follows

$$n_{\text{drum}} = \text{ceil}\left(\frac{(2\,\dot{V}_{\text{tot}}\,\tau/\pi)^{\frac{1}{3}}}{D_{\max}}\right)^3$$

where the maximum diameter allowed $D_{\max}$ is 4 m. The volumetric flowrate of a single vessel is expressed

$$\dot{V}_{\text{single}} = \dot{V}_{\text{tot}}\, n_{\text{vv}}$$

Then, the dimension of a single vessel (D_{single} and H_{single}) is determined:

$$D_{\mathrm{single}} = \left(\frac{2\,\dot{V}_{\mathrm{single}}\,\tau}{\pi}\right)^{\frac{1}{3}}$$

$$H_{\mathrm{single}} = \begin{cases} 3\,D_{\mathrm{single}} & \mathrm{p}-1 \leq 19\ \mathrm{bar} \\ 4\,D_{\mathrm{single}} & \mathrm{p}-1 \leq 34\ \mathrm{bar} \\ 5\,D_{\mathrm{single}} & \mathrm{p}-1 > 34\ \mathrm{bar} \end{cases}$$

With the dimension and bare module cost of a single vessel obtained, the total bare module cost of all drums equipped is given as

$$C_{\mathrm{drum}}^{\mathrm{BM}} = n_{\mathrm{drum}}\,C_{\mathrm{single}}^{\mathrm{BM}}$$

References:

[1] Wang, L.; Zhang, Y.; Li, C.; Pérez-Fortes, M.; Lin, T.-E.; Maréchal, F.; herle , J. V. & Yang, Y. Triple-mode grid-balancing plants via biomass gasification and reversible solid-oxide cell stack: Concept and thermodynamic performance, Applied Energy, 280 (2020) 115987

[2] K. P. Olsen, Y. Zong, S. You, H. Bindner, M. Koivisto, J. Gea-Bermúdez, Multi-timescale data-driven method identifying flexibility requirements for scenarios with high penetration of renewables, Applied Energy 264 (2020) 114702.

[3] Biomass Energy Europe: http://www.eu-bee.eu/.

[4] S2Biom Delivery of sustainable supply of non-food biomass to support a resource-efficient Bioeconomy in Europe: https://www.s2biom.eu/en/.

[5] Biomass Future: https://ec.europa.eu/energy/intelligent/projects/en/projects/biomass-futures.

[6] Puigjaner L. Syngas from waste: Emerging technologies. Springer; 2011.

[7] Laínez JM, Pérez-Fortes M, Bojarski AD, Puigjaner L. Raw materials supply. In: Syngas from waste. Springer; 2011, p. 23–54.

[8] Pérez-Fortes M, Laínez-Aguirre JM, Bojarski AD, Puigjaner L. Optimization of pre-treatment selection for the use of woody waste in co-combustion plants. Chem Eng Res Des 2014;92(8):1539–62.

[9] R. Turton, R. C. Bailie, W. B. Whiting, J. A. Shaeiwitz. (2008). Analysis, synthesis and design of chemical processes, Pearson Education.

[10] G. D. Ulrich, P. T. Vasudevan. (2004). Chemical engineering: process design and economics; a practical guide, Process Publ.

[11] Peduzzi, P., 2014. Biomass To Liquids: Thermo-Economic Analysis and Multi-Objective Optimisation, Doctoral thesis, EPFL.

Acknowledgment

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No (826161). This Joint Undertaking receives support from the European Union’s Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe research.