DELIVERABLE

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Comments	

Summary

This deliverable investigates the management and operating strategies of the W2G plants of the case studies selected from the 18 case studies with potentially high economic feasibility. The major information of all these case studies has been discussed in D2.2, thus this deliverable will be a relatively short one. The four selected case studies are further studied in terms of mass balance (oxygen, biomass, and SNG), the sizes of the air separation unit (ASU), and the plant operation with the mode switch.

The plants deployed in different case studies are almost all at a capacity of 100 MW_{th} biomass. The mass flows of oxygen, biomass and SNG increase almost linearly with the increase in the total plant capacities deployed (or the plant number). **The ASU size is concluded to be around 5 t/h for a W2G plant with a biomass input of 100 MW_{th}.**

For the operating strategy, it is found that when the timely flexibility need is lower than the total capacities of the plants deployed, the W2G plants have to operate on the PowNeu mode. Employing one single plant (100 MW_{th} biomass input), the annual PowNeu utilization hour is only 887 h, while employing 5 plants (500 MW_{th} biomass input), the annual utilization hours of PowNeu mode is increased to 1400 h on average.

Contents

1 Introduction

The major task of the originally proposed WT2.3 has been combined in the current D2.2 due to the implementation of the overall methodology. **This deliverable, D2.3, was supposed to be removed during the amendment of the project. Considering the length of D2.2 and the contents included there, D2.3 becomes a short one, emphasizing the information to ensure continuous operation of the plants in selected case studies.**

1.1 Background and task description

Renewable energy sources (RESs) like wind and solar energy can provide sustainable power in an environmentally friendly way. However, RESs are usually intermittent and unstable which leads to a great power supply-demand imbalance and create challenges of grid stability. Therefore, there is a need for flexibility to balance the power grids with a suitable power plant [1]. The flexibility needs can be provided by the Waste2GridS (W2G) plants integrating biomass-to-electricity and -chemical via reversible solid-oxide cell stacks (RSOC), which could flexibly switch among power generation (PowGen), power storage (PowSto) and power neutral (PowNeu) modes. Such a W2G concept proposed in [2] allows for enhanced annual full-load operating hours (nonstop operation over the year if no maintenance is needed).

The W2G plants first convert the biomass into syngas via gasification, where the syngas is further converted in the solid-oxide cell stacks. The clean syngas produced is converted to electricity under PowGen mode, or synthesis natural gas under the PowSto and PowNeu modes. Oxygen should be fed into the gasifier as the gasification agent. The oxygen is managed with buffer tanks, charged by the RSOC blocks under PowSto mode and a standalone air separation unit (ASU, if needed), and discharged to the market when excess. The SNG produced is injected into the gas transmission network.

The overall objective of the W2G project is to identify potential business cases of such W2G plants. With the inputs from WP1, two RES-dominated zones, i.e., western Denmark (DK-DK1) and southern Italy (IT-SUD) are selected for case-study evaluation. The critical boundary conditions of grid-flexibility needs and biomass availability have been identified in D1.1 and D1.2. The optimal plant design has been investigated in D2.1 to obtain application-free design pool. A decomposition-based optimization methodology is further proposed and implemented in D2.2 to identify potential case studies considering optimal plant selection, sizing and scheduling, as well as biomass supply chain and costs to maximize the profits from the grid-balancing services. The optimization is performed under different scenarios of grid-flexibility needs and plant capacity factors. Finally, the **plant CAPEX target (€/ref-stack)** with the reference stack having an active cell area of 64*80 cm^2 is calculated in D2.2 as the basic economic indicator for identifying promising case studies. The plant CAPEX target is defined as

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

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}. 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.

Considering the difficulty in predicting future grid flexibility needs, two scenarios have been identified Wby scaling the theoretical flexibility needs to evaluate the impact of uncertainty in power-generation-and-production imbalance profiles:

- ***S1: Excluding interconnections:***
  - 66% of theoretical UP regulation needs
  - 68% of theoretical DOWN regulation needs
- ***S2: Excluding interconnections, batteries, classic plants:***
  - 14% of theoretical UP regulation needs
  - 30% of theoretical DOWN regulation needs

With these two scenarios, the economic feasibility is evaluated in D2.2 for different zones and capacities of plants deployed. The contribution of the W2G plants to cope with the targeted flexibility needs, named as a **capacity factor**, is defined as follows:

$$x = \frac{\sum_{u,n} k_u P_{u,n}}{Max\ (\sum_n \hat{P}_{d,i,n})} \tag{2}$$

where the k_u is the sizing factor of the plant design u, and $P_{u,n}$ is the capacity of electricity interacted with the electrical grid at different operating modes n (PowGen, PowSto). The $\hat{P}_{d,i,n}$ is the regulation needs at different time step (day d, hour i) at different modes n (PowGen, PowSto).

D2.2 shows that FICFB-based W2G plant concept is potentially for business cases with plant CAPEX target even up to 17000 €/ref-stack for a five-year payback time, 5-year stack lifetime and 40 €/MWh balancing energy price. There have been 18 case studies identified in the summary section to be further evaluated in D3.2 with their CAPEX calculated in detail.

Here in D2.3, we select four case studies out of the 18 concluded: DK-DK1-S1-FICFB-P1, IT-SUD-S1-FICFB-P3, DK-DK1-S1-FICFB-P5 and DK-DK1-S2-FICFB-P7 (refer to the summary section of D2.2 for detailed information of these case studies). The mass balance of all plants, the sizes of auxiliaries as well as the operating strategy of each plant, which are critical for a continuous operation of all W2G plants, are illustrated to conclude the requirement of grid integration.

The three main tasks of this deliverable are listed as following:

(1) Investigation of the mass flows of the W2G plants, including:
  - OXYGEN, as the gasification agent and managed by tanks. Optimal capacity and management of the tanks depend on the production and consumption by the RSOC blocks. If there is a lack of oxygen, the tanks will be filled by a standalone air separation unit (ASU), while if the tanks are full, the excess oxygen produced will be discharged to the market.
  - BIOMASS, which is consumed for producing syngas.
  - SYNTHESIS NATURAL GAS, which is generated by W2G plants on PowSto and PowNeu mode.

(2) Investigation of the capacities of the ASU and oxygen storage tank needed

(3) Investigation of the operating strategy of the plants employed.

1.2 Deliverable structure

The report is organized as follows: in section 2, the selected cases are introduced. In section 3, the mass flows of oxygen, biomass and SNG are investigated. In section 4, the capacity of the air separation unit is studied. Section 5 shows the operating strategy of the plants employed. Section 6 concludes the deliverable.

2 The case studies selected

Four case studies using FICFB-based W2G plants are selected as shown in Table 1 (taken from Summary of D2.2). These case studies are further elaborated below:

- Case1, DK-DK1-S1-FICFB-P1: Single W2G plant (P1) provides flexibility for the zone DK-DK1 under the flexibility-need scenario S1. The maximum plant CAPEX target can be up to 16282 €/ref-stack, with the optimal plant capacities of 57 and 159 MWe for the PowGen and PowSto modes, respectively. The plant covers only 3% of the maximum flexibility need, i.e., a capacity factor of 3%.
- Case2, IT-SUD-S1-FICFB-P3: Three W2G plants (P3) are supposed to be employed for the flexibility need for IT-SUD under the scenario S2. The plants can achieve a plant CAPEX target of 5164 €/ref-stack. The overall capacity factor of the three plants has reached 9%.
- Case3, DK-DK1-S1-FICFB-P5: Five W2G plants (P5) provide the flexibility needs of DK-DK1 under scenario S1. Compared with Case1 and Case2, more plant capacities are employed to address more flexibility needs, reaching a capacity factor of 18%. However, the economic feasibility is reduced with the plant CAPEX target decreasing to 3558 €/ref-stack.
- Case4, DK-DK1-S2-FICFB-P7: The plant capacity is further increased by deploying 7 plants in DK-DK1 under scenario S2. The W2G plants contribute to 60% of the maximum flexibility needs, resulting in a plant CAPEX target of 2259 €/ref-stack.

Table 1 Information on the selected case studies. The plant CAPEX target is based on 5-year payback time, 40 €/MWh balancing price and 5-year stack lifetime. The reference stack is defined as an anode-supported stack with an active cell area of 64*80 cm^2.

	Case	Plant CAPEX target, €/ref-stack	Capacity factor, -	Biomass gasifier capacity, MW_{th}	Annual operating hours, h			Plant capacity, MWe	
					PowGen	PowSto	PowNeu	PowGen	PowSto
Case1	DK-DK1-S1-FICFB-P1	16282	0.03	100	3231	4618	887	57	159
Case2	IT-SUD-S1-FICFB-P3	5164	0.09	100	3630	4628	502	57	159
				100	3854	4491	415	58	149
				100	3785	4535	440	58	159
Case3	DK-DK1-S1-FICFB-P5	3558	0.18	95	2487	4348	1901	41	101
				98	2507	4618	1611	55	155
				100	2919	4298	1519	59	153
				100	3186	4453	1097	58	149
				100	2759	4408	1569	57	158
Case4	DK-DK1-S2-FICFB-P7	2259	0.6	100	1155	4261	3320	43	100
				100	1851	3855	3030	49	102
				100	1394	4026	3316	44	106
				100	1217	3837	3682	52	140
				100	1419	3632	3685	52	137
				100	850	3834	4052	52	159
				100	1138	3194	4404	58	159

3 Mass balance

3.1 Oxygen

The oxygen is the gasification agent and is managed by a storage tank. The tank management depends on oxygen production and consumption from the W2G plants. Moreover, it can be filled with a standalone air separation unit (ASU) if there is an oxygen shortage. While if the tanks are full, the oxygen can be sold to the market. The capacity of storage tanks is determined by considering the tradeoff between the benefit of oxygen storage and tank cost. In this report, **the optimal oxygen tank is zero** based on the assumptions listed in Table 2. Thus, all the oxygen production will be sold to the market (outflow), and all the oxygen shortage will be supplied by ASU (inflow).

Table 2 Economic assumptions of the oxygen sale, purchase and storage.

Assumption	Unit	Value	Ref.
Oxygen sale price	€/kg	0.06	[3]
Oxygen purchase price	€/kg	0.1	[3]
Oxygen tank price	€/kg	8	[4]

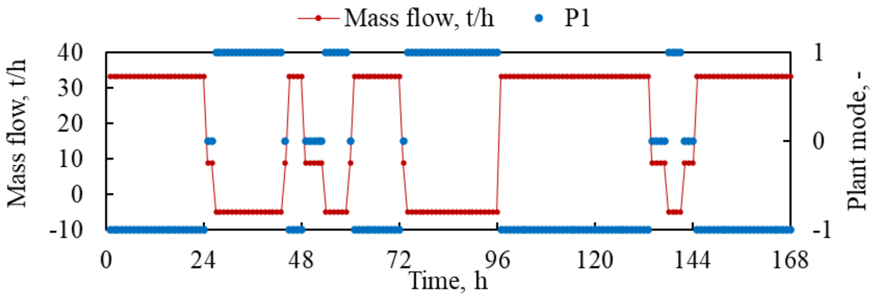
The mass flow of oxygen and the operating mode of the W2G plants are shown in Figure 1 for all the selected case studies. The positive and negative mass flow represents oxygen outflow and inflow, respectively. The plant mode 1, 0 and -1 represents the PowGen, PowNeu, and PowSto mode, respectively.

For Case1 (Figure 1 (a)), the single 100 MW_{th} W2G plant generates 33 t/h oxygen under PowSto mode and the oxygen will be sold to market. Under PowGen mode, the W2G plant needs 5 t/h oxygen, which should be fed by the ASU. On PowNeu mode, the W2G plant generates 9 t/h oxygen.

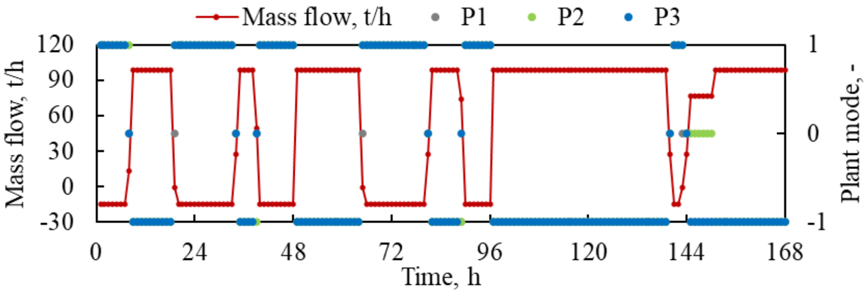
For Case2 (Figure 1 (b)), three W2G plants are employed with a capacity of 100 MW_{th} for each, respectively. The total oxygen outflow of the PowSto mode is increased to 100 t/h due to the increased plant capacities. The oxygen consumption of the PowGen mode is also increased to about 15 t/h. When some plants are scheduled to operate under PowNeu mode, oxygen mass flow ranges between 15 t/h inlow to 100 t/h outflow.

For Case3 (Figure 1 (c)), five W2G plants are employed which can supply more flexibility compared with Case1 (single plant) and Case2 (three plants). The two other plants deployed are at the capacity of 97 and 95 MW_{th}, respectively. The maximum total oxygen outflow is increased to 150 t/h when all plants operated under PowSto mode, and the maximum total oxygen inflow is raised to 24 t/h. When the flexibility need is low, some plants have to operate on PowNeu mode, the oxygen mass flow varies from 24 t/h inflow to 150 t/h outflow.

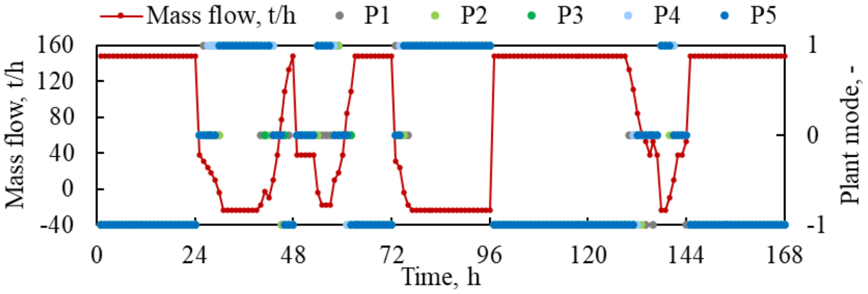
For Case4 (Figure 1 (d)), the seven W2G plants can generate maximum 183 t/h oxygen, when all plants operate under the PowSto mode during the high need of DOWN regulation. Under the highest UP regulation need, the seven W2G plants are operated under PowGen mode, requiring the oxygen inflow up to 34 t/h. While such high oxygen inflow is rarely required because W2G plants have to operate frequently on PowNeu mode.



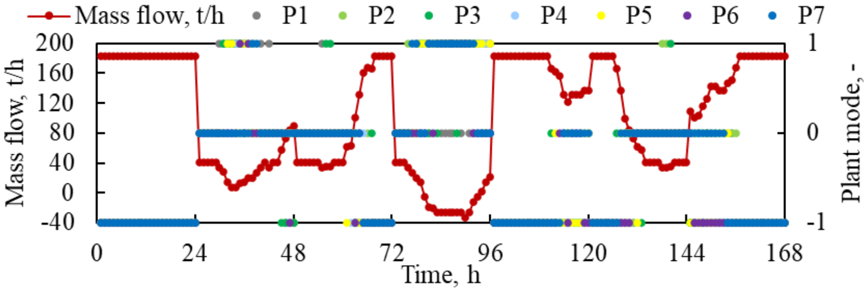
(a) Case 1: DK-DK1-S1-FICFB-P1.



(b) Case2: IT-SUD-S1-FICFB-P3.



(c) Case3: DK-DK1-S1-FICFB-P5.



(d) Case4: DK-DK1-S2-FICFB-P7.

Figure 1 Oxygen mass flows of the four case studies in **the typical days**. The plant mode 1, 0 and -1 represents plant on PowGen, PowNeu, and PowSto mode.

The annual net oxygen outflows listed in Table 3 result in 150, 400, 650, 800 kt for the cases DK-DK1-S1-FICFB-P1, IT-SUD-S1-FICFB-P3, DK-DK1-S1-FICFB-P5 and DK-DK1-S2-FICFB-P7. The oxygen outflow is increased as increasing the W2G plant number.

Table 3 Annual net oxygen outflow, kt

Case	Annual net oxygen outflow, kt
Case1: DK-DK1-S1-FICFB-P1	150
Case2: IT-SUD-S1-FICFB-P3	400
Case3: DK-DK1-S1-FICFB-P5	650
Case4: DK-DK1-S2-FICFB-P7	800

3.2 Biomass

The biomass input is considered to be the same for three modes, since the gasification part is assumed to operate without load shifting. The annual biomass needs for all four cases DK-DK1-S1-FICFB-P1, IT-SUD-S1-FICFB-P3, DK-DK1-S1-FICFB-P5, DK-DK1-S2-FICFB-P7 are listed in Table 4, which are 0.88, 2.63, 4.31 and 6.13 TWh_{th}, respectively. The annual biomass needs to increase almost linearly as increasing plant capacities deployed.

Table 4 Annual biomass need, TWh_{th}

Case	Plant number	Annual biomass need, TWh_{th}
Case1: DK-DK1-S1-FICFB-P1	1	0.88
Case2: IT-SUD-S1-FICFB-P3	3	2.63
Case3: DK-DK1-S1-FICFB-P5	5	4.31
Case4: DK-DK1-S2-FICFB-P7	7	6.13

3.3 Chemical product (SNG)

The W2G plants generate SNG under PowSto and PowNeu modes. For Case1, the single plant can generate a maximum, 13 t/h SNG, under PowSto mode, and slightly lower, 3.5 t/h SNG, under the PowNeu mode. For Case2, three plants can generate a maximum 39 t/h SNG when all plants are in PowSto mode. With some plants on PowNeu mode, the SNG production will be decreased. If all plants are on the PowGen mode, there will be no SNG production. For Case3 and Case4, the plant number is increased to five and seven with the total plant capacities increased, the maximum SNG production reaches up to 61 and 80 t/h, achieving by all plants operating on PowSto mode.

Annual SNG production is listed in Table 5, which are 64, 180, 300, 380 kt of the four cases, respectively. Increasing plant number (plant capacity), the annual SNG production is not able to increase linearly because the plants have to operate more frequently under the PowNeu mode as shown in Figure 1.

Table 5 Annual SNG production, kt

Case	Annual SNG production, kt
Case1: DK-DK1-S1-FICFB-P1	64
Case2: IT-SUD-S1-FICFB-P3	180
Case3: DK-DK1-S1-FICFB-P5	300
Case4: DK-DK1-S2-FICFB-P7	380

4 Auxiliary requirement

Air separation unit (ASU) supplies oxygen to W2G plants, which is important auxiliary component to ensure W2G plants operation. The capacities of the ASUs depend on the requirement of the maximum oxygen inflow as shown in Figure 1, which are listed in Table 6.

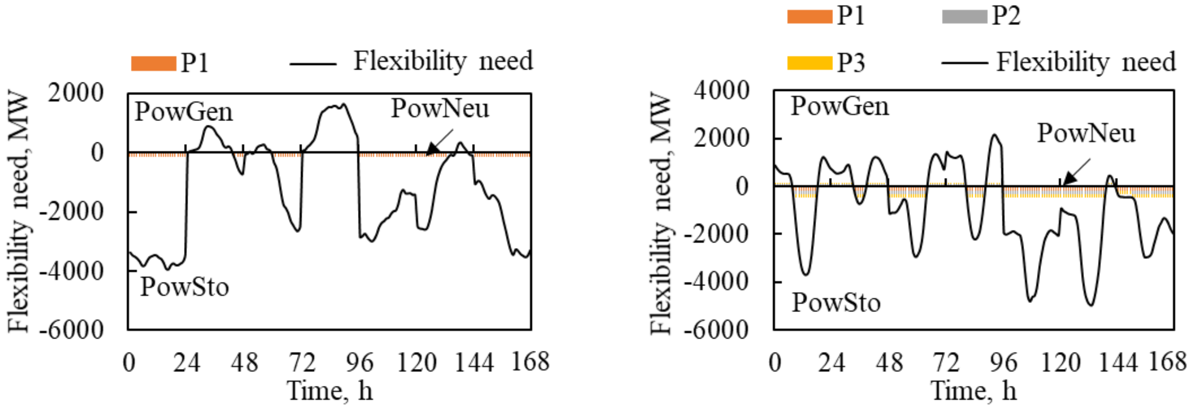
Table 6 Air separation unit capacity in the four cases, t/h

Case	Plant number	ASU capacity, t/h
Case1: DK-DK1-S1-FICFB-P1	1	5
Case2: IT-SUD-S1-FICFB-P3	3	15
Case3: DK-DK1-S1-FICFB-P5	5	24
Case4: DK-DK1-S2-FICFB-P7	7	34

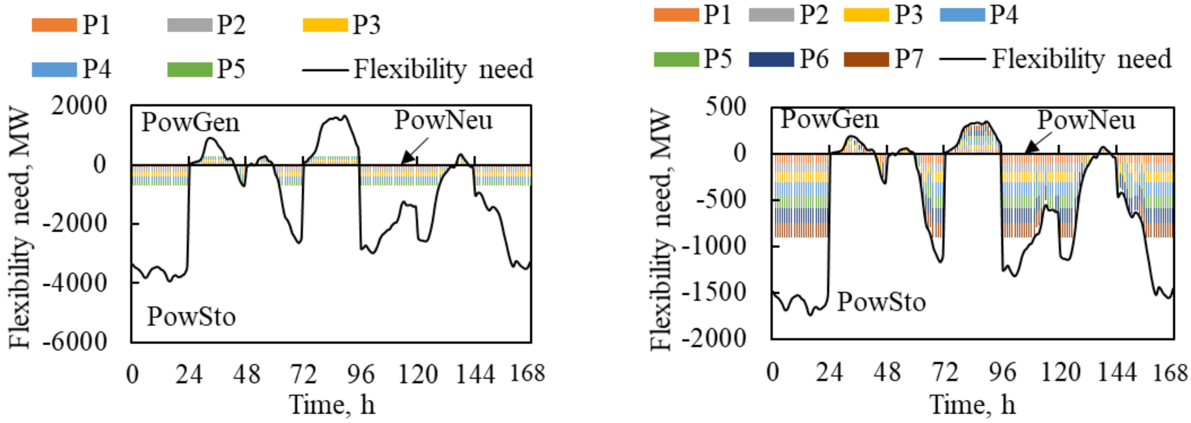
The capacity of the ASU increases almost linearly as increasing the W2G plant number (capacities), which is 5, 15, 24, 34 t/h for 100, 300, 493, 700 MW_{th} W2G plants. The capacity of the W2G plants employed is all close to 100 MW_{th}, as shown in Table 1. However, the ASU will be less operated, when employing more plant capacities because the plants will operate under PowNeu mode more frequently as illustrated in Figure 1.

5 Operating strategy

The operation of the plants employed in the four cases is illustrated in Figure 2. The plant capacities are limited to 100 MW_{th} biomass input due to the FICFB gasifier option as shown in Table 1. For Case1, the maximum flexibility needs are 1650 MWe for UP regulation and 4000 MWe for DOWN regulation as shown in Figure 2 (a). While, the optimal PowGen and PowSto capacity of the single plant is only 57 MWe and 159 MWe, which is only 3% of the maximum grid-flexibility needs. The annual operating hours of the PowGen, PowSto and PowNeu modes are 3231 h, 4618 h, and 887 h, respectively, as listed in Table 1, meaning that the plant employed is operated frequently under PowGen and PowSto modes and rarely under PowNeu mode.



(a) Case1: DK-DK1-S1-FICFB-P1. (b) Case2: IT-SUD-S1-FICFB-P3.



(c) Case3: DK-DK1-S1-FICFB-P5. (d) Case4: DK-DK1-S2-FICFB-P7.

Figure 2 The operation of the W2G plants under the four cases.

For Case2, the maximum flexibility needs of IT-SUD under S1 scenario are 2050 MWe for UP regulation and 5000 MWe for DOWN regulation as shown in Figure 2 (b). The plant capacities are also limited to 100 MW_{th} biomass input due to the FICFB gasifier option as shown in Table 1, with capacities of the three W2G plants about 57, 58, 58 MWe on PowGen mode, and 159, 149, 159 MWe on PowSto mode, accounting for only 9% of the maximum flexibility needs. The annual utilization hours of PowNeu mode of the three W2G plants are 502, 415, 440 h as listed in Table 1. Thus, the plants mostly operate on PowGen and PowSto mode and rarely on PowNeu mode.

For Case3, five W2G plants are employed, which can cover more flexibility needs as shown in Figure 2 (c), compared with Case1 which employs only one single W2G plant (Figure 2 (a)). The capacities of the five plants in total are 271, 717 MWe on PowGen and PowSto mode, reaching 18% of the maximum grid-flexibility needs. The coordination of the five plants also increases the annual utilization hours of the PowNeu mode, reaching 1901, 1611, 1519, 1097, 1569 and 3320 h as shown in Table 1.

For Case4, the maximum flexibility needs of DK1 under S2 scenario are 330 MWe for UP regulation and 1700 MWe for DOWN regulation as shown in Figure 2 (d). Employing seven W2G plants, the capacity of the W2G plants can be 6% of the maximum flexibility needs. More flexibility needs can be covered by the W2G plants compared with other cases as illustrated in Figure 2 (a), (b), and (c). Over 90% of the UP regulation can be covered by the coordination of the seven W2G plants. While, when the flexibility need is lower than the plant capacity, the plant will be put under PowNeu mode, since the plant is set to operate full load under all modes. Thus, the plants have to operate more frequently on PowNeu mode, with the annual utilization hours of PowNeu over 3000 h and even up to 4500 h.

6 Conclusions

This deliverable is the follow-up of D2.2, in which 18 case studies are concluded. This deliverable further investigates 4 case studies out of these 18 case studies in terms of oxygen mass flow, biomass and chemical product (SNG), ASU capacity, and the operating strategy of the W2G plants. The four cases are DK-DK1-S1-FICFB-P1, IT-SUD-S1-FICFB-P3, DK-DK1-S1-FICFB-P5 and DK-DK1-S2-FICFB-P7. The capacity of the plants employed in 4 case studies is limited to 100 MW_{th} biomass input, due to the FICFB gasifier option. The key conclusions are

- The maximum oxygen outflow of the W2G plants is achieved when all plants are operated under the PowSto mode, and the maximum oxygen inflow is required when all plants are under PowGen mode. The oxygen outflow and inflow for one W2G plant are around 33 and 5 t/h, and the maximum oxygen inflow and outflow increase almost linearly as increasing plant number (capacity), reaching 183 and 34 t/h when employing 7 plants (equivalent to 700 MW_{th}). While, such high oxygen inflow is rarely required because some W2G plants have to frequently operate on PowNeu mode. The annual net oxygen outflows to market are 150, 400, 650, 800 kt for the four cases, respectively.
- The annual biomass need increases almost linearly as increasing plant number (capacity), which is 0.88 TWh_{th} for one W2G plant (100 MW_{th} biomass input), and is increased to 6.13 TWh_{th} for seven W2G plants (700 MW_{th}) since the gasification and syngas cleaning section is supposed to be operated without load shifting if no maintenance occurs.
- The W2G plants, generating SNG during the PowSto and PowNeu modes, can supply 64, 180, 300, 380 kt SNG to the gas market/grid under the cases, respectively. Increasing the plant number (capacity), the annual SNG production is not able to increase linearly because plants have to operate more frequently on PowNeu mode to cope with the remaining flexibility needs.
- The capacity of the ASU increases almost linearly as increasing the W2G plant number (capacity), which is 5, 15, 24, 34 t/h for 1, 3, 5, 7 W2G plants with 100 MW_{th} biomass input for each plant.
- Increasing W2G plant number (capacity), the W2G plants can cover higher flexibility needs by the cooperation between different plants and their operating modes. The capacity factors of the four cases employing 1, 3, 5 and 7 plants (100 MW_{th}, 300 MW_{th}, 500 MW_{th}, 700 MW_{th}) are 3%, 9%, 18%, and 60%, respectively. When the timely flexibility need is lower than the total capacities of the plants deployed, the W2G plants have to operate on the PowNeu mode. Employing one single plant (DK-DK1-S1-FICFB-P1), the annual PowNeu utilization hour is only 887 h, while employing five plants (DK-DK1-S1-FICFB-P1), the annual utilization hours of PowNeu mode is increased to 1400 h on average.

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