DELIVERABLE

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Duration	24 months
Start date	01.01.2019

Deliverable Number	D2.2
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Authors (beneficiary)	Ligang Wang (EPFL) with critical inputs from DTU and ENEA
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Comments	

Summary

This deliverable is one of the key deliverables of the project, in which the overall decomposition-based optimization methodology for evaluating the economic feasibility of the W2G plants is implemented. Based on the D1.1, D1.2 and D2.1, the flexibility needs, waste availability and plant design pool are fed into the optimal plant selection, sizing and scheduling to maximize the profits from the grid-balancing services, and the waste supply chain optimization to evaluate the biomass supply costs and finally the plant CAPEX target.

The results show the FICFB-based W2G plant concept is potentially to be with high economic feasibility with a plant CAPEX target up to 17000 €/ref-stack for a five-year payback time, 5-year stack lifetime and 40 €/MWh balancing energy price. Increasing the balancing energy price and counting the profit from chemical scale, e.g., the profit of grid integration, the plant CAPEX target can even reach 22000 €/ref-stack.

Thus, it is concluded that sound business cases exist for using the W2G concept for grid-balancing services. The cases with the W2G design based on FICFB technology (5-year payback time, 40 €/MWh balancing price and 5-year stack lifetime) will be taken as case studies to be further investigated. These selected case studies will be further investigated in the following two deliverables:

- D2.3: Elaborating the auxiliary requirements to integrate the W2G plants to the grid
- D3.3: Finalizing the economic feasibility study considering the detailed evaluation of the plant CAPEX with the process flow diagram and component sizes of each plant deployed. This will derive specific business cases with the net profits calculated

Contents

1 Introduction

The deliverable has enhanced the original target of Task 2.2, by complete the overall methodology proposed in the proposal and D2.1. The developed sequential methodology has decomposed the complex optimization problem into a step-by-step easy-to-implement optimization problem. Different from the original task description, where the cost and CAPEX are supposed not to be involved in Task 2.2, we have introduced an economic indicator of **Plant CAPEX target** to have a quick evaluation of the economic feasibility of case studies established. Therefore, it has taken over certain responsibility of Task 3.3.

1.1 Background and task description

Sustainable renewable energy sources are urgently required to satisfy rapid growing energy demand and limit greenhouse gas emissions. The penetration of renewables in the global electricity supply has reached a record of 27% in 2019 and is expected to be 49% in 2030 [1]. This rapid growth is largely contributed by wind and solar power [2]. The high penetration of the intermittent renewables challenges the electricity markets in terms of supply-demand balance, transient and frequency stability, thus the Transmission System Operators (TSOs) will require large flexibility needs for grid management. In Denmark, building a 10 GW offshore wind plant, the grid flexibility needs will vary between an 8 GW power shortage to a 20 GW power surplus [3].

There is a portfolio of supply- and demand-side options for advanced TSOs evolving towards high flexibility by means of, e.g., flexible power generators as reserve, demand-side management, cross-region interconnections, and the crucial alternative energy storage [4]. Particularly, when the penetration of renewable power becomes high enough that energy is no longer a limiting factor, while thermal power plants and nuclear power plants will still give a firm supply and not be dispatched frequently, there will be considerable power surplus [3]. The excess electricity could be addressed by energy storage technologies, which store energy when excess and release it as electricity when needed. A storage capacity of average daily energy demand can address a renewable energy penetration up to 50% in Texas, which is 15% higher than only employing flexible power generators as reserve [5].

Various energy storage technologies are available. Currently, physical storage options, including pumped-hydro storage and thermal storage, are dominating, e.g., 50% of the flexibility needs in Belgium [6]; however, they are generally limited by geographical and environmental restrictions, or low energy conversion efficiency [7]. Electrochemical storage options, particularly lithium batteries and flow batteries, have gained large development and reached commercialization. Batteries can participate in primary frequency response and also energy management [8], accounting for 25% of the 2030 flexibility needs in Belgium [6]. However, large-scale, long-term energy management may be better handled by electrolysis-based power-to-hydrogen technologies, which convert excess electricity to hydrogen and its derivatives. The stored chemical energy can be converted back to electricity via fuel-to-power. This energy storage-release cycle is named as power-to-x-to-power (PXP). It has been expected that over 20% of Danish electricity will be converted to hydrogen or hydrogen-based fuels in 2030 for grid down-regulation [3], with generated fuels converted to electricity for grid up-regulation or injected to chemical and transportation sectors.

Economic flexibility of power-to-hydrogen system for down-regulation has been investigated in the literature, which mainly focuses on the systems enabled by proton exchange membrane or alkaline electrolyzers [9,10,11,12,13].The power-to-hydrogen systems can hardly be economically viable due to (1) the low hydrogen production efficiency of 65% (lower heat value, LHV) [9], (2) the high investment cost 3400 €/kW [10, 12], and (3) the expensive hydrogen storage [11]. Those power-to-hydrogen systems for down-regulation can further attach a hydrogen-to-power system for up-regulation via fuel cells. However, using proton exchange membrane fuel cell for Germany secondary control reserve market is also not economically potential [9], because (1) the threshold of hydrogen price is calculated to be 1.1 €/kg, which is far from the current market price (around 5 €/kg [14]); (2) the annual equivalent full-load hours are as low as 150 h, due to the expensive bidding balance service using hydrogen.

The investment costs of PXP are mainly contributed by the FC and EL stacks, which could be largely reduced by employing solid-oxide technology. The same solid-oxide stack can operate “reversibly” by switching between fuel cell mode and electrolysis mode. Thus, the solid-oxide cell can also be called reversible solid-oxide cell (RSOC) and enables a single RSOC-based plant to work for power generation (PowGen) and power storage (PowSto) at different time periods [15]. This reversible operation of the same plant can potentially (1) increase the utilization hours, (2) decrease the total capital expenditure (CAPEX), (3) achieve high round-trip efficiency of 55%–70% (LHV) [15,16,17] and (4) utilize hydrocarbons as fuels directly, such as methane [15] and methanol [18] to avoid expensive hydrogen storage. Additional CO2 sources needed in the PowSto mode can be solved by combining the biomass with RSOC systems.

Using renewable, carbon-neutral, and widely available biomass, RSOC based grid-balancing plants are potential to provide grid-balancing service. In literature, only a few case studies of such a concept were found [19,20,21,22], which focus mainly on the thermodynamic perspective. The authors have recently proposed a concept of triple-mode RSOC-based grid-balancing plant in Ref. [23], which can interact with or be isolated from the electrical grid as capacity reserves, thus are capable of nonstop operation all year round.

This report has been a follow-up of our previous work [23] and aims at evaluating the economic feasibility of such a grid-balancing concept. The analysis is performed for two RES-dominated zones (Italy and Denmark) to support the identification of potential business cases. Three main tasks are considered as follows:

- Evaluation of the imbalance in RES-dominated zones (Denmark and Italy) based on the work on D1.1.
- Design of the triple-mode grid-balancing plants for matching with the imbalance in RES-dominated zones.
- Optimal matching the plants with specific applications to identify potential business cases.

1.2 Deliverable structure

The report is organized as follows: In section 2, the theoretical flexibility needs identified in D1.1 is characterized into typical days to represent the annual imbalance power profiles. In section 3, the optimal conceptual design of the Waste2GridS (W2G) plants identified in D2.1 has been carried out to generate an optimal design pool for matching with the balancing grid. In section 4, the methodology to identify potential business cases will be introduced by optimal matching the plant designs with grid-balancing needs. Section 5 shows the results for Denmark and Italy. Section 6 concludes the deliverable.

2 Concept of the triple-mode grid-balancing plants

Biomass-to-electricity or -chemical via power-to-x are combined in the W2G plant, a triple-mode grid-balancing plant, by integrating biomass gasification via reversible solid-oxide cell stacks. The W2G plant can switch among power generation (PowGen), power storage (PowSto) and power neutral (PowNeu) modes. The generic concept of the triple-mode plant proposed in Ref. [24] is illustrated in Figure 1. The three-mode plant is enabled by the coordination of two RSOC blocks:

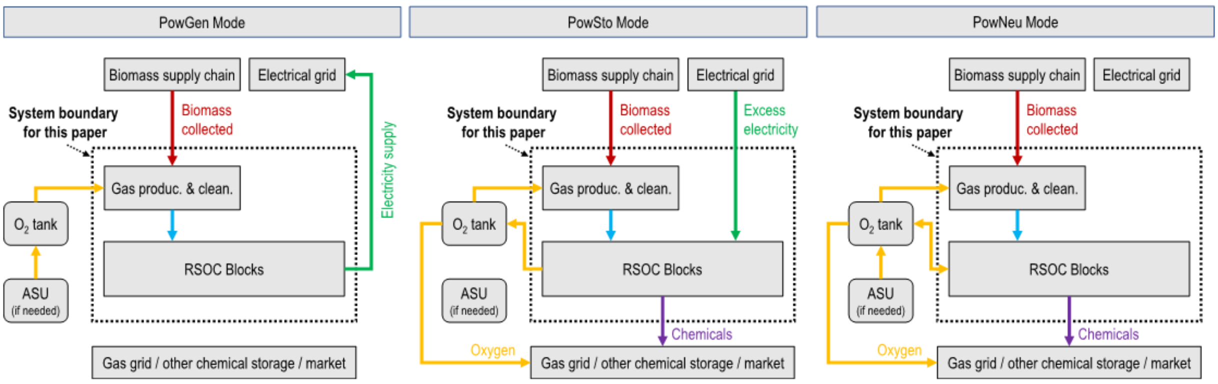


Figure 1 The overall system and system boundary of triple-mode grid-balancing plant.

- PowGen mode: biomass-to-electricity with both RSOC blocks under the fuel cell mode.
- PowSto mode: biomass-to-chemical with both RSOC blocks under the electrolyzer mode to enable the power-to-x capability powered by excess renewable electricity.
- PowNeu mode: biomass-to-chemical with one RSOC block under the FC mode to power the other block under the EL mode for chemical production. No external electricity is needed.

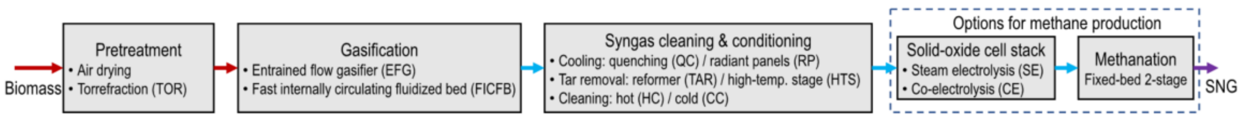


Figure 2 Process options considered in this paper with the stack section showing only the options for methane production.

The oxygen as the gasification agent is managed with buffer tanks, charged by the RSOC blocks under EL mode and a standalone air separation unit (ASU, if needed), and discharged to the market when excess. However, the ASU itself is not considered in the plant design, since its sizing depends on the plant scheduling determined by specific applications. The waste heat utilization, e.g., for district heating, depends highly on local circumstances and thus is not included in the efficiency definition. The final chemical product is assumed to be SNG, which is injected into the gas transmission network. Therefore, the key system boundaries are:

- Biomass: For agricultural residues and forest wood, since the lower heating value on a dry basis (LHVdb) usually varies within 18–20 MJ/kg [25], the properties considered are C 50.81 wt.%, H 5.96 wt.%, O 43.05 wt.%, N 0.18 wt.% with the LHVdb being 19.1 MJ/kg, and humidity of 0.5 kg-H2O/kg-biomass. For the wastes, represented by municipal solid waste, the approximate analysis considered is moisture 20%, fixed carbon 10.23%, volatile matter 75.90% and ash 13.81%, resulting in an LHVdb of 19.4 MJ/kg [26].
- Oxygen storage conditions: 200 bar and 30 °C.

- Grid injection: 80 bar, methane molar fraction > 96%. The variation of injection pressure has a negligible impact on the plant's performance.

There are many technology options available for pre-treatment, gasification, syngas cleaning and conditioning, and syngas-to-SNG, e.g., Fig. 3. Considering the sizes of the gasifiers, two types of gasifiers are involved in this paper: (1) entrained-flow gasifier with direct heating (EFG, 1200–1500 ºC, 30–80 bar) for large-scale applications (100–1000 MW_{th}), (2) twin (dual) fluidized-bed gasifier, e.g., fast internally circulating fluidized-bed (FICFB, 800–1000 ºC, 1–4 bar) for medium-scale applications (10–100 MW_{th}). Plasma gasifier (4000 ºC, 1 bar) for small-scale applications (1–30 MW_{th}) are not considered. The biomass pretreatment considers air drying and torrefaction (only for EFG). Syngas cooling can be done by water/steam quenching (QC) or radiant panel (RP) for steam generation. Tar removal is needed mainly for FICFB due to a low gasification temperature and it can be done by a high-temperature stage (HTS) up to 1300 ºC or catalytic tar reforming (TAR). The syngas-to-SNG can be achieved by two means: (1) steam electrolysis with the produced hydrogen injected to syngas for methanation, and (2) co-electrolysis of H_2O and CO_2 with syngas directly sent into the stack to adjust the composition for methanation.

3 Overall methodology to identify feasible 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.

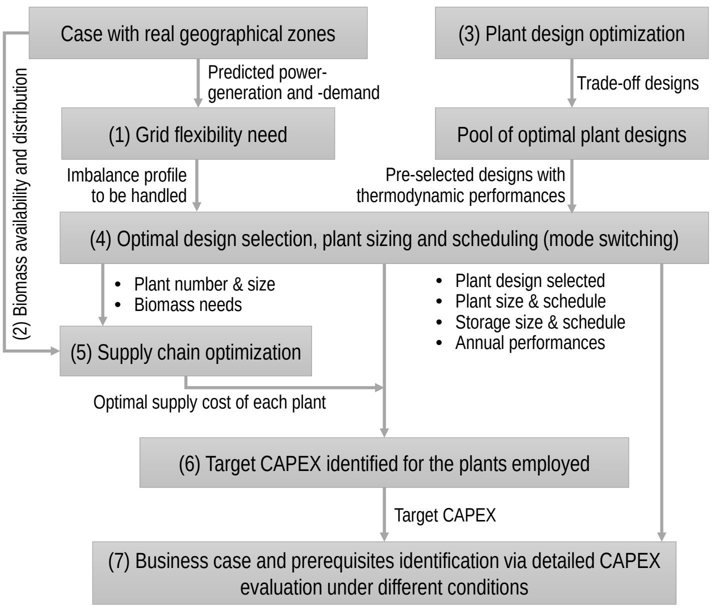


Figure 3 The overall decomposition-based methodology to identify feasible business cases for the grid-balancing plants.

We proposed a decomposition-based, sequential approach in Ref. [24] (Figure 3), summarized as follows:

- **Step 1 (D1.1):** Identification of (future) grid flexibility needs. Based on the multi-timescale data-driven method presented in Ref. [27], for the zone considered, hourly timeseries 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 [28], S2Biom [29] and BIOMASS FUTURE [30], 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). The design pools using different options have been illustrated in section 5.
- **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 methodology will be described below in section 6.2 to determine the number, design, size and scheduling of the plants employed to maximize the gain from grid-balancing services and the cost of oxygen and tank. The methodology will be introduced in section 6.2. 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. [31,32,33] and fed to step (6). The methodology will be introduced in section 7.
- **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 the feasibility of the case study. 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.

4 Summary of the grid flexibility needs identified in D1.1

In Italy, based on the prediction from PNIEC (i.e., Italy's 'Integrated National Energy & Climate Plan') 2030 scenario, it is expected to have a large increase in electricity storage (up to 6 GW electrochemical & pumped-hydro energy storage) in 2030 to counteract the phase-out of conventional dispatchable power plants and the increase in power imbalances. The national imbalance (i.e., power overgeneration) will reach up to 9 GW; however, for more than 96% of the year, it will stay below 3 GW.

In Demark, the government has passed a climate law aimed at cutting Denmark's greenhouse gas emissions by 70% (compared to 1990) by 2030. The reduction target generally has been broadly supported from the Danish parliament and the energy sector. In addition, the Danish government's paper of understanding from summer 2019 states that it will 'explore the possibilities of Denmark building the first energy island to be connected to at least 10 GW (wind turbines) by 2030'. Large-scale power-to-x based electricity storage is required to effectively integrate and utilize large-scale offshore wind.

Six RES-dominated zones have been identified in D1.1. Considering the computational capability and the combinatory nature of zones, technology combination of plant designs and flexibility-need scenarios, we consider two zones for further evaluation:

- Southern Italy (SUD)
- Western Denmark (DK1)

The hourly imbalance profiles of DK1, and Italy (SUD) of 2030 were predicted based on the statistical analysis of historical data and aggregation / disaggregation of available forecast data. It shows that in the 2030 scenario, in Denmark, the UP/DOWN regulation will occur frequently with a larger power capacity. In Italy SUD, a stronger penetration of variable renewable energy sources will cause higher grid flexibility needs, and these will be mostly daily flexibility needs, since the system will have to be able to deal with stronger overgeneration and steeper load ramps.

4.1 Scenarios of flexibility needs handled by the W2G plants

It has been identified by many TSOs that, in 2030, cross-country interconnections will play an important role in coping with the flexibility needs, and the conventional technologies will not be completely replaced by new grid-balancing technologies. **Thus, only part of the theoretical flexibility needs will be coped with by the W2G plants and this is difficult to be predicted due to the complexity of the grid-balancing market.** Therefore, we will rely on the report from TSOs to define several scenarios, which scale the theoretical flexibility needs to that addressed by the W2G plants. We believe it is enough at the stage of evaluating the economic flexibility of the W2G technology.

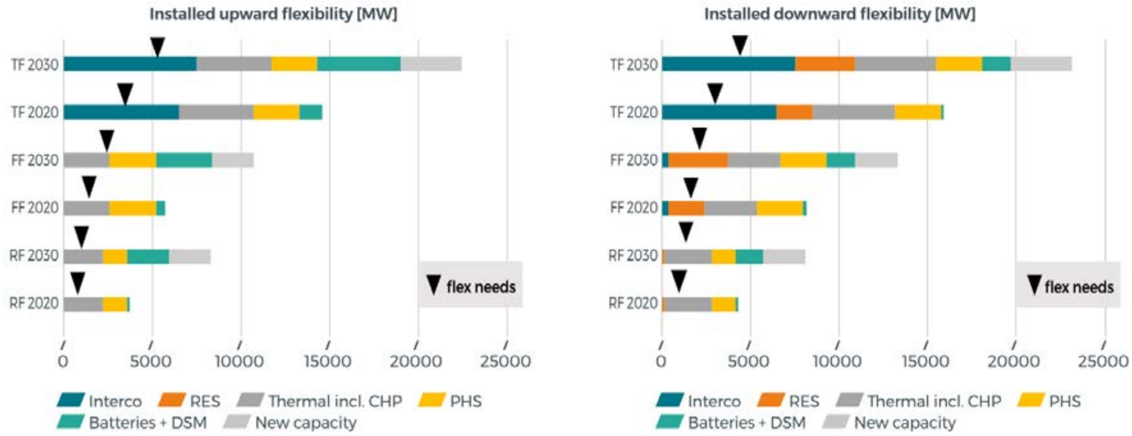


Figure 4 Flexibility technologies for Belgium in 2030 [6].

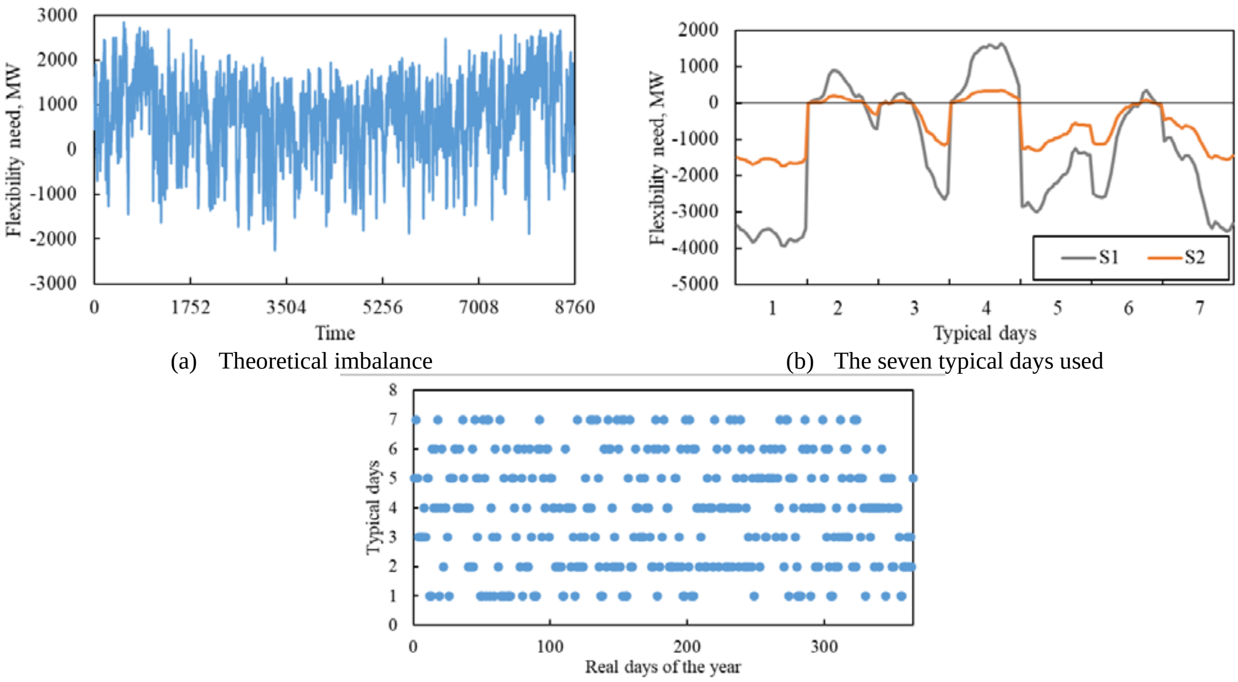
For the zones of DK-DK1 and IT-SUD, Terna (Italian TSO) and Energinet (Denmark) have not been relevant reports released for 2030. In this report, the scaling factors of the theoretical flexibility needs are based on Ref. [6], a comprehensive prediction of the flexibility needs in 2030 of Belgium with two key figures relevant to this project shown in Figure 4. In 2030, 34% of the UP regulation and 32% of the DOWN regulation can be handled by cross-country interconnections. Considering also batteries and classical thermal power plants, only 14% of the UP regulation and 30% of the DOWN regulation may be handled by the W2G plants. Thus, **two scenarios are defined to represent the flexibility needs for W2G technology:**

- ➢ ***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

To reduce the number of data points and hence the computational load of the optimization, a number of typical days are selected to represent the annual imbalance profile (365 days, 8760 time-steps). The k-means developed in Ref. [34] are used to cluster the annual imbalance profile.

4.2 Imbalance power (flexibility need) profile of DK-DK1 and IT-SUD in 2030

In DK-DK1, the hourly residual load becomes more frequently negative (Figure 5a), i.e., more hours with excess renewable power. Seven typical days are clustered to represent the annual imbalance profile (Figure 5b). For the scenario S1 (excluding interconnections between areas), the flexibility needs are between -4 GW–1.6 GW; further excluding balancing service from traditional plants and batteries in the scenario S2, the regulation needs are between -1.7 GW–0.3 GW. The repetition of the typical days over the 365 days in a year is shown in Figure 5c. The proportions of seven typical days in Figure 5b are 12%, 18%, 12%, 20%, 15%, 14%, and 9%.



(a) Theoretical imbalance

(b) The seven typical days used

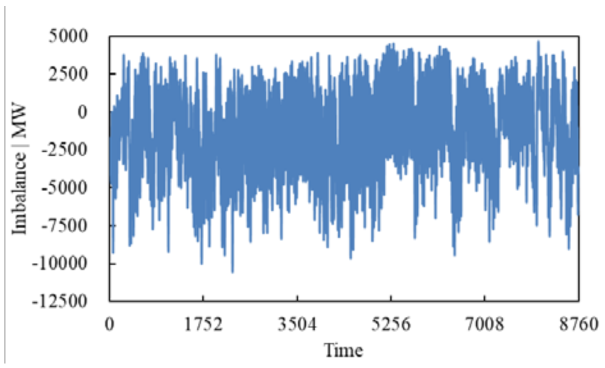
(c) The repetition of seven typical days over the real days of a year

Figure 5 The characterization of theoretical imbalance profiles of DK-DK1.

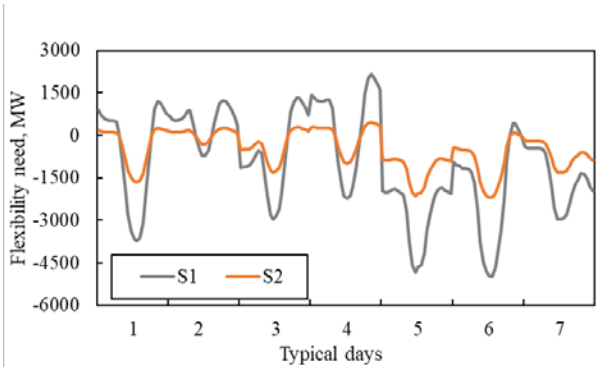
In IT-SUD, the hourly residual load is also more frequently negative, indicating more hours with DOWN regulation needs (Figure 6a). Seven typical days are clustered to represent the annual imbalance profile (Figure 6b). Excluding interconnections between areas (S1), the residual loads are between -5–2 GW; further excluding balancing service from traditional plants and batteries (S2), the regulation need is between -2–0.5 GW. The repetition of the typical days is shown in Figure 6(c). The proportions of each typical day listed in Figure 6b are 14%, 10%, 8%, 25%, 9%, 13%, and 20%.

When employing RSOC-based triple-mode grid-balancing plants to cope with the residual loads, they will be operated as follows:

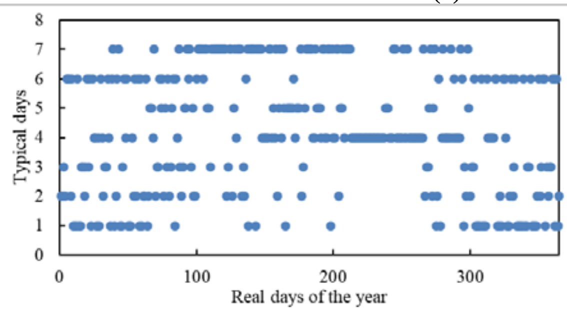
- DOWN regulation (negative values): PowSto mode
- UP regulation (positive values): PowGen mode
- Zero imbalance: PowNeu mode



(a) Theoretical imbalance



(b) The seven typical days identified



(c) The repetition of seven typical days over the real days of a year

Figure 6 The characterization of theoretical imbalance profiles of IT-SUD.

5 Summary of optimal plant design from D2.1 and Ref. [24]

5.1 Method of optimal conceptual plant design

We employed the iterative procedure proposed in Figure 7 to cope with the combinatory nature of technologies, nonlinearity and multiple objective functions. The method first assembles the flowsheets of the three modes based on the specified process option, which are then simulated by professional simulators (e.g., Vali, Aspen Plus) or other means with specific technological specifications (decision variables). The resulting energy and mass flows of all three modes are formatted as the input for multi-time heat and mass integration with utility selection and sizing, formulated as a mixed-integer linear programming (MILP) problem as described in detail in Ref. [35]. The solving of this MILP problem concludes utility sizes, hot-cold and grand composite tables/curves for illustrating the heat cascade utilization, based on which the heat exchanger network area and costs can be further estimated. Practical constraints, key performance indicators and objective functions are then evaluated *a posteriori* with access to all data from the above steps. Queuing multi-objective optimizer as a master program controls the iteration and concludes a set of Pareto plant designs.

Each mode of the plant (PowGen, PowSto and PowNeu) corresponds to a time step in the multi-time MILP formulation, which sizes the two RSOC blocks simply via the electricity balance in the PowNeu mode (no electricity import and export). If a steam turbine network is employed to recover waste heat to electricity, the ratio of the stack number in the fuel cell/electrolyzer blocks will decrease. It is also assumed that the operating points of the FC blocks in the PowGen and PowNeu modes remain the same, so do those of the EL blocks in the PowSto and PowNeu modes. Thus, the total stack number becomes identical for all three modes.

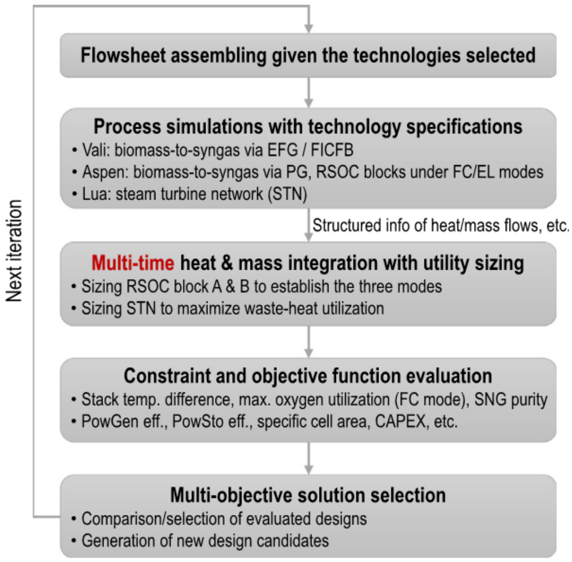


Figure 7 The method for optimal conceptual plant design

The constraints evaluated posteriorly are mainly related to the stack operation, including maximum temperature difference between the stack inlet and outlet, maximum oxygen utilization, carbon deposition (evaluated via cantera [36]), etc. The grid injection of SNG is only constrained here by the purity (96 vol.%) but not the Wobbe index.

The key performance indicators involve the energy efficiencies (based on LHV) of the three modes and the investment costs of the plant:

(1) PowGen efficiency:

$$\eta_{PowGen} = \frac{\dot{E}_{ele,out}}{\dot{E}^{lhv}_{bio,in}} \tag{2}$$

(2) PowSto efficiency:

$$\eta_{PowSto} = \frac{\dot{E}^{lhv}_{sng,out}}{\dot{E}^{lhv}_{bio,in}+\dot{E}_{ele,out}} \tag{3}$$

(3) PowNeu efficiency:

$$\eta_{PowNeu} = \frac{\dot{E}^{lhv}_{sng,out}}{\dot{E}^{lhv}_{bio,in}} \tag{4}$$

(4) Specific cell area needed (m^2/kW-LHVdb):

$$\bar{A} = A_{tot}/\dot{E}^{lhv}_{bio,in} + M\,\dot{m}_{syngas,burnt} \tag{5}$$

In the above formulations, $\dot{E}$ represents the incoming (in) or out-going (out) energy flow of biomass (bio), synthesis natural gas (sng), or electricity (elec) in the energy balance of a specific mode. The energy flows carried by materials are based on the LHV. The specific cell area needed ($\bar{A}$) is evaluated with a penalty term ($M\,\dot{m}_{\mathrm{syngas,burnt}}$ with M being a big number) to suppress the syngas burnt for process heating, thus the minimization of this specific cell area can promote the amount of syngas converted by the RSOC stacks. All indicators are calculated following the procedure described in Figure 7.

5.2 Design pool of the triple-mode grid-balancing plant

The optimal designs considering the trade-offs between the three objectives (PowGen efficiency, PowSto efficiency and specific cell area) for different process combinations are illustrated in Figure 8.

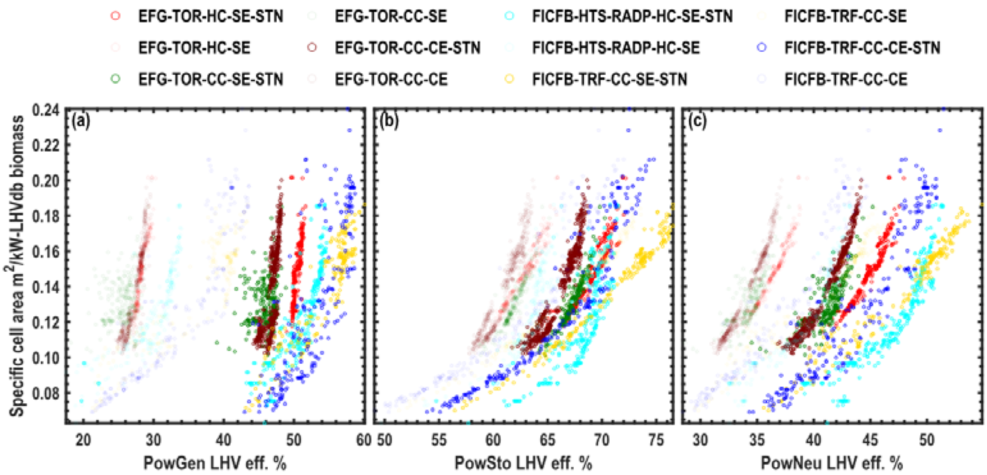


Figure 8 The design pools of different process options illustrating the trade-off between the efficiency and specific cell area needed per kW-LHVdb biomass. The abbreviations have been given in Figure 2.

There is no big difference in the three efficiencies (less than 5% points) among different process options of the same gasifier type. The selection of gas cleaning and conditioning processes has a limited effect on plant performance.

The PowSto efficiency is higher than the PowGen efficiency, due to the efficient power-to-x, efficiency definition and steam turbine network; while the PowNeu efficiency is lower than the PowSto efficiency since the SNG production of the PowSto mode is much higher than the PowNeu mode with a large share of syngas converted to electricity to drive the electrolysis stacks. The difference in efficiency among the EFG (entrained flow gasifier) and FICFB (fast-internal circulating fluidized bed) process options is caused by the performances of stacks and steam turbine. The stack performance is affected largely by the syngas composition, particularly the ratio $(H_2/CO_2)_{eq}$: 1.6 (FICFB) and 1.2 (EFG) for the types of biomass considered. The higher efficiency achieved by the FICFB process options is mainly due to the high $(H_2/CO_2)_{eq}$ ratio, yielding better FC performance for power generation and requiring fewer EL stacks to process the same amount of dry syngas.

The specific cell area, the decisive factor of the investment costs, is within 0.1–0.2 m^2/kW-LHVdb biomass. An increased efficiency tends to require more cell area to process the same amount of biomass.

6 Optimal design selection, plant sizing and scheduling (step 4)

6.1 Pre-selection of designs from design pool

Designs are evenly selected from the Pareto fronts in Figure 8 to reduce the computational efforts of the optimization. Since there is no big difference in the three efficiencies among different process options of the same gasifier type as analyzed in section 5.2, the design pool is only classified by the gasifier types, i.e., fast internally circulating fluidized-bed (FICFB) and entrained-flow gasifier (EFG).

Using an entrained-flow gasifier (EFG), the specific cell area is in 0.08–0.24 m^2/kW-LHV biomass, achieving efficiencies of 43%–59% (PowGen), 53%–76% (PowSto) and 35%–55% (PowNeu), as shown in Figure 9.

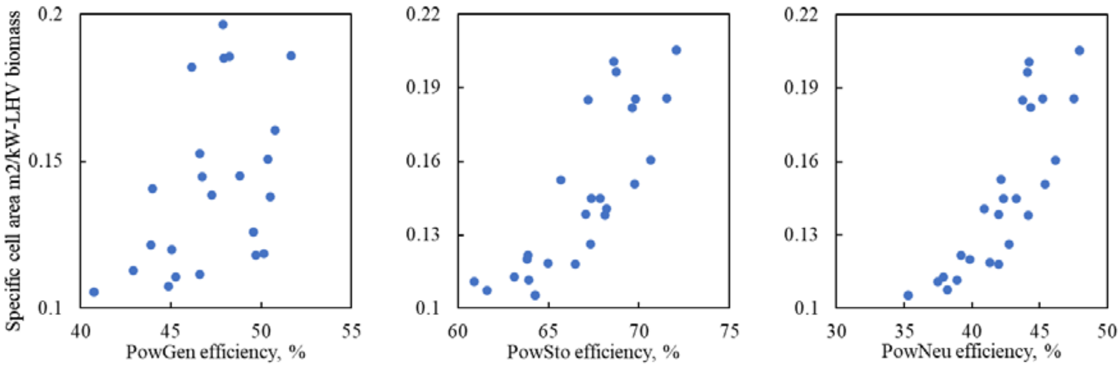


Figure 9 Design pool of plants using EFG. Selected from Figure 8.

The plants using FICFB gasifier realize higher efficiencies of 41%–52% (PowGen), 61%–72% (PowSto) and 35%–48% (PowNeu) as shown in Figure 10. The specific cell area is in 0.11–0.2 m^2/kW-LHV biomass.

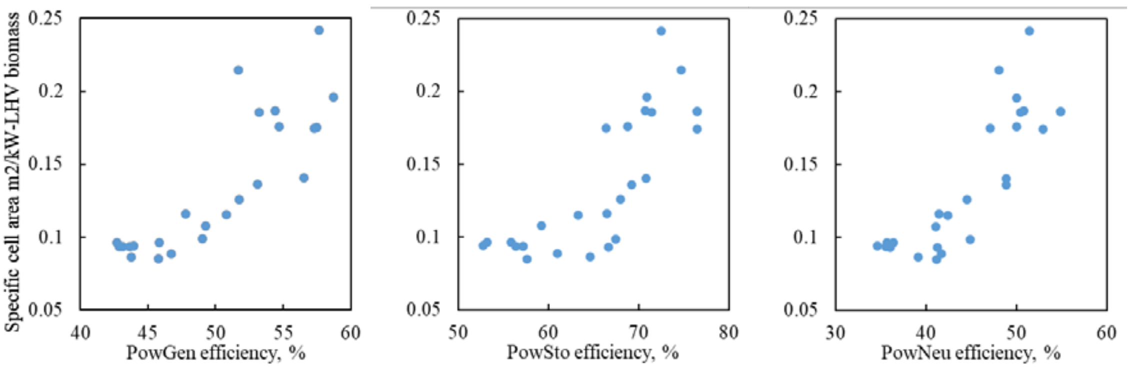


Figure 10 Design pool of plants using FICFB. Selected from Figure 8.

6.2 Optimal design selection, plant sizing and scheduling

The triple-mode grid-balancing plant could (1) provide up-regulation via converting biomass to electricity by PowGen mode, (2) provide down-regulation via using excess power to combine biomass to chemicals in PowSto mode, (3) produce chemicals with the electricity generated internally and thus the plant can be isolated from the electrical grid in PowNeu mode. Thus, the RSOC plants are capable of non-stop operation all over the year.

The unit commitment model is employed to optimize the schedule of RSOC plant for coping with grid imbalance towards maximum profit, resulting in:

- optimal design selection from the design pool,
- optimal sizing and scheduling (only mode switching) of the selected designs,
- optimal capacity and scheduling of the oxygen tank.

6.2.1 Objective functions

The profit of RSOC plant in payback time *l* years as given in Eq. (6), is affected by (1) revenue from providing balancing power $R_{d,i}^{\mathrm{bal}}$, (2) additional revenue (positive) or cost (negative) of oxygen trade with market $R_{d,i}^{\mathrm{oxy}}$, (3) cost of oxygen gas tank R^{tank}:

$$Profit_l = \sum_{t=1}^{l} \sum_{d=1}^{TD} \sum_{i=1}^{24} \frac{\alpha_d (R_{d,i}^{\text{bal}} - R_{d,i}^{\text{oxy}})}{(1+r)^t} - R^{\text{tank}} \tag{6}$$

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, r is the discount rate (0.05). The revenue (€) of providing the balancing energy can be calculated as:

$$R_{d,i}^{\text{bal}} = \sum_n \theta_n^{\text{bal}} E_{u,d,i,n} \tag{7}$$

where, θ^{bal} is the price of the settlement of power imbalances (€/MWh); n represents the PowGen or PowGen mode of the plants. $E_{u,d,i,n}$ is the energy generated or consumed by RSOC plant u on an hourly basis in time (d, i). The trade with the gas market can be calculated as:

$$R_{d,i}^{\text{oxy}} = \theta^{\text{oxy,in}} F_{d,i}^{\text{in}} - \theta^{\text{oxy,out}} F_{d,i}^{\text{out}} \tag{8}$$

where, $F_{d,i}^{\text{in}}$ and $F_{d,i}^{\text{out}}$ (kg/h) are the inflow and outflow of oxygen in time step i of typical day d. $\theta^{\text{oxy,in}}$ and $\theta^{\text{oxy,out}}$ are the prices of oxygen purchase and sale (€/kg). The cost of the oxygen tank can be calculated by the tank capacity m (kg) and the tank price θ^{tank} (€/kg):

$$R^{\text{tank}} = \theta^{\text{tank}} m \tag{9}$$

6.2.2 Constraints

(1) Power generation and storage constraint

The grid balancing provided by plants at each time step (d, i) is calculated based on plant mode status and its capacity, and only mode switching is considered without load shifting:

$$P_{u,d,i,n} = Y_u \dot{P}_{u,n} Z_{u,d,i,n} k_u \tag{10}$$

where, the binary variable Y_u represents whether the design u is selected or not, k_u (-) is the sizing factor of plant design u, $\dot{P}_{u,n}$ is the capacity (MW) of design u in mode n with a given size. The sizing factor is limited by the maximum and minimum capacity of the biomass gasifier:

$$k_u^{\text{min}} \leq k_u \leq k_u^{\text{max}} \tag{11}$$

The power generation provided by the RSOC plants should be lower than the upward regulation need of the grid $\hat{P}$:

$$\sum_u P_{u,d,i,n} \leq \hat{P}_{d,i,n} \tag{12}$$

(2) Plant number constraint

The coordination among different RSOC plants is considered by employing multiple plants (U):

$$\sum_u Y_u = U \tag{13}$$

The status of an RSOC plant is unique in a time step (d, i):

$$\sum_{n'} Z_{n',u,d,i} \leq 1 \tag{14}$$

where, n' represents the PowGen, PowNeu or PowSto mode of plant u, $n \in n'$.

(3) Storage-related constraints

The oxygen storage level $\overline{m}_{d,i}$ (kg) in the gas tank is limited by the tank capacity m (kg):

$$0 \leq \overline{m}_{d,i} \leq m \tag{15}$$

where $\overline{m}_{d,i}$ (kg) is related to the level in the previous hour $(d, i-1)$ and the oxygen generated/consumed by plants ($F_{d,i}^{\text{gen}}$, $F_{d,i}^{\text{con}}$, kg/h), and the trade with the market ($F_{d,i}^{\text{in}}$, $F_{d,i}^{\text{out}}$, kg/h):

$$\overline{m}_{d,i} = \overline{m}_{d,i-1} + F_{d,i}^{\text{gen}} - F_{d,i}^{\text{con}} + F_{d,i}^{\text{in}} - F_{d,i}^{\text{out}} \tag{16}$$

$$F_{d,i}^{\text{gen}} = \sum_{u,n} \dot{m}_{u,n}^{\text{gen}} Y_u Z_{u,d,i,n} k_u \tag{17}$$

$$F_{d,i}^{\text{con}} = \sum_{u,n} \dot{m}_{u,n}^{\text{con}} Y_u Z_{u,d,i,n} k_u \tag{18}$$

where $\dot{m}_{u,n}^{\text{gen}}$ and $\dot{m}_{u,n}^{\text{con}}$ are the oxygen produced or consumed by plant design u, kg/h.

Table 1 Set description.

Set	Description	Set	Description
d	Typical days	t	Year
i	Time step in typical day	u	W2G plant design
n	Plant mode		

Table 2 Model parameters.

Name	Description	Units
Y	Lifespan of RSOC plants	-
TD	Typical days	-
α_d	Typical days repetition times	-
θ^{bal}	Balancing power price	€/MWh
$\theta^{\text{oxy,out}}$	Oxygen sale price	€/kg
$\theta^{\text{oxy,in}}$	Oxygen buy price	€/kg
U	Plant number	-
l	Payback year	-
k^{min}	Minimum sizing factor	-
k^{max}	Maximum sizing factor	-
$\hat{P}$	Regulation demand	MW
P	Design power capacity	MW
$\dot{m}$	Oxygen generated/consumed by plants	kg

Table 3 Model variables.

Name	Description	Units
$Profit$	Profit	€
R	Revenue	€
P	Power	MW
F	Oxygen flow	kg/h
Y	W2G plant selection, binary variable	-
Z	Plant status, binary variable	-
k	Size factor of W2G plant design	-
$\overline{m}$	Tank storage level	kg
m	Tank capacity	kg

7 Biomass supply chain optimization (Step 5)

The biomass supply chain plays a crucial role in the deployment of centralized biomass utilization since it influences the economic potential and is usually limited to a certain size for collection, namely biomass supply radius. Therefore, it is necessary to count the minimum biomass supply costs of each W2G plant determined from step (4), considering the biomass geodatabase from step (2). The costs of the biomass supply chain considering biomass collection and pre-treatment are minimized with the superstructure-based method presented in Ref [31,32,33].

Long-term available organic waste streams have been identified in D1.2 with the methodology and tools developed by the projects like EUROPRUNING8, EUWOOD, BIOMASS FUTURE9, together with the EUROSTAT statistics and existing waste inventories and databases for the countries of study. The original bio-waste data are used as sources to set up a new dedicated low-grade waste (MSW, pruning, straw and others) GIS geodatabase for the Waste2GridS project, which spatially covers the RES-dominated zones, i.e., DK-DK1 and IT-SUD. This GIS geodatabase serves for the design of biomass supply chain to evaluate the economic feasibility of the W2G plants, especially for large scales of over hundreds of MWe.

Waste supply design and optimization are formulated by mixed-integer linear programming. The use of a biomass superstructure eases the decision-making task regarding waste collection and pre-treatment before conversion in the W2G plants. The strategic and tactical decisions to be made comprise the configuration and planning of the supply chain, including the biomass used, the locations of pre-treatment plants, and locations of the RSOC power plants. The biomass supply costs for a given plant size are associated with

- the biomass purchase,
- distributed pre-treatment,
- transportation and storage of the biomass

The aim is to obtain, using Universal Transverse Mercator (UTM) coordinates, a number of potential locations in a specific zone (for instance, a European country-specific context), where either a pre-processing site (biomass pre-treatment), a W2G plant, or all together, can be placed. Possible locations for biomass pre-treatment and W2G plants will be, for instance, different points next to the natural gas distribution network. Unless otherwise stated, it is assumed that the W2G plants can always be connected to the electricity grid in the selected zone.

Biomass can be made available at different times (seasonal biomass) and with different characteristics (lower heating value – LHV and moisture content). The material flow between any pair of locations appears if such flow improves the performance or efficiency of the overall supply chain. Input data consist of process and economic data, e.g., moisture content, bulk density, and LHV changes for biomass characteristics in the different supply chain echelons; pre-treatment efficiencies; investments, fixed and variable operating costs for the different supply chain activities.

Specifically, the modeled supply chain activities will be

- biomass transport,
- biomass storage,
- biomass pre-treatment,
- pre-treated biomass storage.

Biomass demands corresponding to the obtained plant size is an input of the optimization problem. The supply-chain optimization determines: (i) the biomass network structure (location, number, and capacity of pre-treatment units, biomass transported volume, biomass storage sites and connections among them), and (ii) the biomass utilization schedule and inventories per month.

Biomass as a source of carbon and energy, in comparison with fossil fuels, has a lower calorific value as well as intrinsic characteristics that are derived from technological limitations. Thus, **typically, 100% biomass to energy projects employ smaller scale conversion systems with an SoA collection and transportation diameter of 50 km. Moreover, they tend to be placed close to the biomass generation sources as well as/or close to the biomass demand points, to avoid high logistic and network infrastructure constraints. Large gasification systems are from 10MW$_{th}$, and small gasification systems cover the range from 100 kW$_{th}$ to a few MW$_{th}$. These ranges lead to significant differences in terms of land use for the plant infrastructure, operation and maintenances costs and, plant dimensions.**

Mathematical programming is an appropriate tool to assist in the quantitative evaluation of biomass-based systems, where biomass generation locations may be far from consumption or demand points. Locally available biomass may not match the biomass demand, and different generation/pre-treatment technologies may be available. The biomass supply chain problem may be addressed using a wide range of decision-maker outlooks: economic, environmental, both, or even social. Biomass-based supply chains should be developed according to the context of each country/project.

7.1 Problem statement

The Biomass-based supply chain configuration and operation should be tailor-made for a specific practical country/project. The method described in this project is designed for the triple-mode grid balancing plant. The biomass-based supply chain utilizes fixed located sites for waste collection from the dedicated low-grade waste (MSW, pruning, straw, and others) GIS database, as well as with established points for demand, the W2G plants derived from Step 4 ***(Optimal Plant Sizing and Scheduling for Grid Integration)*** that requires a specific amount of inlet energy supplied by the wastes. A list of potential locations for pre-processing sites (waste pre-treatment) and the W2G plants, and distribution centers or storage is proposed taking into account the highest biomass waste production sites. Pre-processing and power plant sites are limited by minimum and maximum capacities. They can be supplied by more than one raw matter producer. Investment costs consider economies of scale. Distribution centers and transportation activities are modeled by considering upper and lower bounds based on their biomass handling capacity. Distribution centers can be supplied from more than one biomass producing site or pre-treatment plant. A material flow between facilities may appear if selecting such flow improves the performance of the supply chain. The treated biomass demand for the W2G plants can be supplied by more than one pre-treatment site.

Inputs for biomass supply chain optimization:

- Process data include
  - amount of available raw biomass waste, and waste characteristics and seasonality,
  - supply chain echelons and inlet biomass properties required, i.e., LHV, humidity and density, for the specified activities,
  - a set of pre-treatment technologies, types of storage and means of transportation; the activities (pre-treatment, storage, and transportation) efficiencies and performances, to determine the outlet waste characteristics in terms of moisture content, bulk density, dry matter, and low heat value; the consumption and life-time of utilities needed for each one of the activities,

- a set of waste states that quantifies moisture content, bulk density, dry matter, and low heat value for each flow of mass between activities,
  - a set of biomass demand, i.e., amounts of seasonal energy required by the W2G plants,
  - a set of locations of the providers, intermediates and consumers,
  - time period, planning horizon, project lifetime, and average working hours for a specific interval of time.
- Economic data including
  - investment, fixed and variable costs associated with all the technological options involved, i.e., pre-treatment and storage devices,
  - unit transportation costs per km and volume of raw/treated biomass to move,
  - base scale and the associated economies of scale for technologies capacity,
  - price of raw biomass, utilities, consumables, and electricity,
  - interest rate.

Outputs for biomass supply chain optimization:

- the network structure that shows the optimal level of centralization/de-centralization: selected pre-processing units with their capacities and locations; types of transportation, storage sites and dimensions, processing unit locations, and connections among sites,
- feedback utilization and schedule, i.e. suppliers operation per month,
- flows of biomass among sites at each time period,
- inventory level at each time period,
- breakdown of costs and investment per echelon or equipment,
- economic criteria values for the whole time horizon.

The optimization objective is the overall life cycle cost of the whole supply chain, considering initial and lifetime investment of equipment and operational costs.

7.2 Mathematical model

The mathematical model of the biomass supply chain considers different decision variables: (i) activation of supply chain nodes and links among them (a node can be represented by processing or distribution activities); (ii) the capacity to carry out each period; (iii) their capacity utilization levels; (iv) selection of the most appropriate pre-treatment technologies; (v) transportation links; and (vi) the amount of matter moved along different supply chain nodes. The performance indicator considered is the overall costs associated with the whole supply chain.

The resulting model is solved using a MILP (mixed-integer linear programming) approach, which aims at minimizing the overall costs. The variables and constraints of the model are classified into two groups: process operations constraints given by the supply chain topology (the so-called design-planning model) and the economic metric formulation, which are described in the following paragraph.

The biomass-based supply chain model comprises sourcing, pre-treatment, intermediate biomass distribution, and final W2G plant. The supply chain is defined as a number of potential locations where pre-processing sites, W2G plants, or distribution centers, or both of them can be installed. Suppliers are at fixed locations where biomass is available. The biomass can be processed at several sites. The properties of raw biomass may be modified/ improved by means of the pre-treatment units so as to allow intermediate to meet the characteristics required by subsequent steps in the supply chain. Pre-treatments may be also convenient to induce savings in storage and transportation costs.

7.3 Design-planning model

The design-planning model selected to handle the biomass supply chain network is adapted from Refs. [37,38,39]. This model translates the State-Task-Network (STN) formulation, which is widely known for scheduling to the supply chain context. The main advantage of this formulation is that it collects all the supply chain nodes activities information through a single variable set. This feature eases the economic metrics formulation and it facilitates the consideration of the different pre-treatment and their possible combination to obtain the required outputs. The supply chain material balances can be modeled using a single equation set for all materials and facilities. This is possible since the processing nodes and distribution centers, as well as final products, raw material and intermediates are handled indistinctively.

The most relevant variable of the model is $P_{ijff't}$ [kg], which represents the magnitude of particular task *i*, performed using technology *j* during period *t*, whose origin is location *f* and destination is *f'*. In the case of production activities, they must receive and deliver material within the same site (P_{ijft}). In contrast, in a distribution activity, facilities *f* and *f'* must be different. This mathematical formulation assumes that an activity consumes and produces certain materials with determined properties and can be performed in different equipment. By using the activities as the core of the formulation rather than products-materials, it results in a flexible formulation that can easily incorporate new technologies/processes. The key constraints are given below:

Firstly, **the mass balance must be satisfied at each node of the network**. The expression for the mass balance for each type of materials (i.e., raw material and pretreated biomass) processed at each potential site *f* in every time period *t* is presented in Eq. **(19)**.

$$\boldsymbol{S_{sft} - S_{sft-1} = \sum_{f'} \sum_{i \in T_s} \sum_{j \in (J_i \cap \tilde{J}_{f'})} \alpha_{sij} P_{ijf'ft} - \sum_{f'} \sum_{i \in \bar{T}_s} \sum_{j \in (J_i \cap \tilde{J}_{f'})} \bar{\alpha}_{sij} P_{ijff't}, \quad \forall s, f, t} \tag{19}$$

where α_{sij} [dimensionless] is the mass fraction of material *s* that is produced by task *i* using technologies *j*. T_s is a set that refers to tasks that produce *s*, while $\bar{\alpha}_{sij}$ and $\bar{T}_s$ are associated with tasks that consume *s*. The change in inventory of material *s* for consecutive planning periods and for each location is given by the difference between the amount of material produced by those tasks belong to set T_s and the amount consumed by those tasks included in set $\bar{T}_s$. The model assumes that process parameters such as conversions, separation factors or temperatures, are fixed for each activity to enforce the linearity of the problem. In this sense, parameters α_{sij} and $\bar{\alpha}_{sij}$ provide the 'recipe' for a specific activity.
Considering the storage process, it is capable of changing biomass properties (e.g. bulk density, moisture content, low heat value). To do so, storage must be considered as an actual activity. Subsets J_{stor} and S_{stor} will represent the storage equipment and those materials that when kept in storage change their properties, respectively. Notice that the mass balance has been decomposed in this case to deal with the one period delay necessary for the properties change to occur. As expressed by Eq. (20) and (21), a storage activity places inventory in the current period *t* and takes inventory from the previous period *t-1*.

$$S_{sft} = \sum_{f'} \sum_{i \in T_s} \sum_{j \in (J_i \cap \tilde{J}_{f'} \cap J_{stor})} \alpha_{sij} P_{ijf'ft}, \quad \forall s \in S_{stor}, f, t \tag{20}$$

$$S_{sft-1} = \sum_{f'} \sum_{i \in \bar{T}_s} \sum_{j \in (J_i \cap \tilde{J}_{f'} \cap J_{stor})} \bar{\alpha}_{sij} P_{ijff't}, \quad \forall s \in S_{stor}, f, t \tag{21}$$

To keep the model linear, Eq. (**20**) and (**21**) are limited to combine different materials in proportions which are defined by the optimization just for the activities right before the energy generation. The states feeding any other activity and their corresponding proportions and properties (e.g. moisture content, bulk density, dry matter, low heat value) must be defined a prior.

Eqs. (22) and (23) represent the temporal change in the equipment technology installed in a potential facility location. We will consider economies of scale by using as piecewise linear approximation in *k* different intervals and a so-called SOS2 variable type ξ_{jfkt}. Such variables are positive and at most two consecutive variables are non-zero. FE_{jfk}^{limit} [h] is the limit of capacity for interval *k*, V_{jfk} is a binary variable indicating whether or not the capacity of technology *j* is expanded at site *f* in period *t*. This formulation will be recalled in the economic performance metric section for computing the investments associated with capacity expansions. Eq. (24) is used for the total capacity F_{jft} [h] bookkeeping taking into account the capacity expansion during the planning period *t* (FE_{jfk} [h]) for equipment technology *j* in facility *f*. This equation considers the case of the initial design of a supply chain ($FE_{jf0} = 0$) as well as a supply chain retrofit scenario ($FE_{jf0} \neq 0$).

$$\sum_k \xi_{jfkt} FE_{jfk}^{limit} = FE_{jfk}, \quad \forall f, j \in \tilde{J}_f, t \tag{22}$$

$$\sum_k \xi_{jfkt} = V_{jfk}, \quad \forall f, j \in \tilde{J}_f, t \tag{23}$$

$$F_{jft} = F_{jft-1} + FE_{jfk}, \quad \forall f, j \in \tilde{J}_f, t \tag{24}$$

Eq. (25) is used to ensure a utilization greater than or equal to a minimum value established by the decision-maker and that the utilized capacity is lower than or equal to the available one. Parameter β_{jf} [dimensionless] defines a minimum utilization level of technology *j* in site f as a proportion of the total available capacity. Parameter $\theta_{ijff'}$ [h/kg] represents the resource utilization factor. This is the capacity utilization level, in terms of capacity units (e.g. machine-hours), of technology *j* by task *i* whose origin is location f and destination location f'.

$$\beta_{jf} F_{jft-1} \leq \sum_{f'} \sum_{i \in I_j} \theta_{ijff'} P_{ijff't} \leq F_{jft-1} \tag{25}$$

The capacity is expressed as equipment *j* available time during one planning period, then $\theta_{ijff'}$ represents the time required to perform task *i* in equipment *j* per unit of produced material. Thus, once operation times are determined, this parameter can be readily approximated.

Eq. (26) guarantees that the amount of raw biomass *s* purchased from site *f* at each time period *t* is lower than an upper bound given by suppliers availability A_{sft} [kg] (e.g. seasonality, residues availability in a specific region).

$$\sum_{f'} \sum_{i \in \overline{T}_s} \sum_{j \in J_i} P_{ijff't} \leq A_{sft}, \quad \forall s \in RM, f \in Sup, t \tag{26}$$

$$Adaft_f^L \leq Adaft_f \leq Adaft_f^U \tag{27}$$

$$Sales_{sf'ft} = \eta_f^{plant} HV_s \left(\sum_{i \in (T_s \cap Tr)} \sum_{j \in (J_i \cap \hat{J}_f)} P_{ijf'ft} \right), \quad \forall s \in FP, f \in Mkt, f' \in \overline{Mkt}, t \tag{28}$$

$$\sum_{s \in FP} \sum_{f' \in \overline{Mkt}} Sales_{sf'ft} \leq Adaft_f, \quad \forall f \in Mkt, t \tag{29}$$

$$\sum_{f' \in \overline{Mkt}} Sales_{sf'ft} \geq Dem_{sft}, \quad \forall s \in FP, f \in Mkt, t \tag{30}$$

Adaft$_f$ is a variable that represents the capacity of a W2G plant to process biomass fuels, while η_f^{plant} is the efficiency of plant *f*. Eq. (27) expresses the feasible limits for the modification of a W2G plant to process biomass fuels. Eq. (29) expresses that inlet energy flows must be lower than the available capacity at the W2G plant *f* to process biomass fuels. Eq. (28) estimates the sales of final product $s \in FP$ carried out from facility location f' to market $f \in Mkt$. Eq. (30) is used to express that the flexibility demand are totally satisfied by biomass fuels: the sales of the product *s* carried out in market *f* during the time period *t* could be larger than or equal to the demand.

It is important to emphasize that for this sort of network the final product is the energy delivered to the different regions (Mkt) [the pre-treated biomass delivered to the W2G plant locations (Mkt)]. Thus, for those tasks that carry out the energy generation, their corresponding parameter α_{sij} is a function of the heating value of the input materials and the efficiency of the equipment.

7.4 Objective formulation

The overall costs comprise the operation costs and the total capital investment. The operating costs include fixed and variable costs: Eq. (31) describes the total fixed costs of operating the supply chain network. $FCFJ_{jft}$ [€/h] is the fixed unit capacity cost of using technology *j* at site *f*.

$$\mathrm{FCost_t} = \sum_{\mathrm{f}\in(\overline{\mathrm{Mkt}\cup\mathrm{Sup}})} \sum_{\mathrm{j}\in\tilde{\mathrm{J}}_\mathrm{f}} \mathrm{FCFJ_{jft}F_{jft}}, \quad \forall \mathrm{t} \tag{31}$$

In turn, as variable costs, the cost of purchases from supplier *e*, includes raw material procurement, transportation and production resources, as shown in Eq. (32). The purchases of raw materials ($Purch_{et}^{rm}$ [€]) made to suppliers *e* are evaluated in Eq. (33). We will assume a different supplier for each component of the variable costs. This assumption can be easily relaxed to account for the specific characteristics of the problem being dealt with. The variable x_{est} [€/kg] represents the cost associated with raw material *s* purchased to supplier *e*. Transportation and production variable costs are determined by Eqs. (34) and (35), respectively. The $\rho_{eff't}^{tr}$ [€/kg] denotes the *e* provider unit transportation cost associated with material distribution from location f to f' during the period *t*. The τ_{ijfet}^{ut1} [€/kg] represents the unit production cost associated with performing task *i* using technology *j*, whereas τ_{sfet}^{ut2} [€/kg] represents the unit inventory costs of material *s* storage at the site *f*. The parameter τ_{ijfet}^{ut1} entails similar assumptions to the ones considered for α_{sij} and $\bar{\alpha}_{sij}$, namely, the amount of utilities and labor required by an activity are proportional to the amount of material processed.

$$\mathrm{EPurch_{et}} = \mathrm{Purch_{et}^{rm}} + \mathrm{Purch_{et}^{tr}} + \mathrm{Purch_{et}^{prod}}, \quad \forall \mathrm{e,t} \tag{32}$$

$$\mathrm{Purch_{et}^{rm}} = \sum_{\mathrm{s}\in\mathrm{RM}} \sum_{\mathrm{f}\in\mathrm{F_e}} \sum_{\mathrm{i}\in\overline{\mathrm{T}}_\mathrm{s}} \sum_{\mathrm{j}\in\mathrm{J_i}} \mathrm{P_{ijfft}x_{est}}, \quad \forall \mathrm{e}\in\mathrm{E_{rm}},\mathrm{t} \tag{33}$$

$$\mathrm{Purch_{et}^{tr}} = \sum_{\mathrm{i}\in\mathrm{Tr}} \sum_{\mathrm{j}\in\mathrm{J_i}\cap\bar{\mathrm{J}}_\mathrm{e}} \sum_\mathrm{f} \sum_{\mathrm{f'}} \mathrm{P_{ijff't}\rho_{eff't}^{tr}}, \quad \forall \mathrm{e}\in\overline{\mathrm{E}}_\mathrm{tr},\mathrm{t} \tag{34}$$

$$\mathrm{Purch_{et}^{prod}} = \sum_\mathrm{f} \sum_{\mathrm{i}\in\overline{\mathrm{Tr}}} \sum_{\mathrm{j}\in\mathrm{J_i}\cap\hat{\mathrm{J}}_\mathrm{f}} \mathrm{P_{ijfft}\tau_{ijfet}^{ut1}} + \sum_\mathrm{s} \sum_{\mathrm{f}\in(\overline{\mathrm{Sup}\cup\mathrm{Mkt}})} \mathrm{S_{sft}\tau_{sfet}^{ut2}}, \quad \forall \mathrm{e}\in\widetilde{\mathrm{E}}_\mathrm{prod},\mathrm{t} \tag{35}$$

The total capital investment on fixed assets is calculated using Eq. (36). These equations include the investment made to expand the technology's capacity *j* in facility site *f* in period *t*. Recall that economy of scale for technologies capacity is considered using a piecewise linear approximation in *k* intervals. Here, the $Price_{jfk}^{limit}$ [€] is the investment for a capacity expansion equal to the limit of interval *k* (FE_{jfk}^{limit} [h]).

$$\mathrm{FAsset_t} = \sum_f \sum_j \sum_k \mathrm{Price}_{jfk}^{limit} \xi_{jfkt}, \quad \forall t \tag{36}$$

Eq. (37) calculates the overall cost of the whole biomass-based supply chain in l years. We take into account the planning period related to the biomass supply chain.

$$\text{supply chain cost}_l = \sum_t^l \sum_t \left(\frac{\mathrm{FCost_t} + \mathrm{EPurch_{et}} + \mathrm{FAsset_t}}{(1+i_r)^t}\right) \tag{37}$$

8 Results and discussion

The optimal plant sizing and scheduling consider the indices of algebraic representations listed in Table 1, parameters in Table 2, and key variables given in Table 3. The parameters specified in the economic optimization are listed in Table 4.

Table 4 Parameters specifications

Parameter	Description	Unit	specification
Y	Lifespan of RSOC stacks	Year	5
$\theta^{balance}$	Balancing service price	€/MWh	40
$\theta_{O_2}^{out}$	Oxygen sale price	€/kg	0.06
$\theta_{O_2}^{in}$	Oxygen purchase price	€/kg	0.1
$StoLevelInitial$	Initial storage level	kg	0
r	Interest rate	-	0.05

As aforementioned, **the plant CAPEX target considers both (1) the net profit from providing the grid balancing service minus the operating costs related to chemical trade and auxiliaries, and (2) the biomass supply costs.**

The scenarios S1 and S2 defined in section 4.1 are at different imbalance scales and will result in the deployment of W2G plants at different scales. Considering the economy of scale, a capacity factor x is introduced to set a basis for the comparison of the results from S1 and S2. The factor x somehow represents the contribution of the W2G plants installed to the flexibility needs to be handled by them:

$$x = \frac{\sum_{u,n} k_u P_{u,n}}{Max\,(\sum_n \hat{P}_{d,i,n})} \tag{38}$$

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).

8.1 Plant CAPEX target

The **Plant CAPEX Targets** (€/ref-stack, Eq. (1)) of scenarios S1 and S2, as well as different technology combinations, are illustrated in Figure 11 versus the capacity factor x (the contribution of W2G plants to the flexibility needs to be handled by them). **The key observations are:**

- **FICFB gasifier option achieves plant CAPEX targets (2000–17000 €/ref-stack) significantly higher than the EFG option (-5000–1000 €/ref-stack).**
- **The plant CAPEX target decreases with the increase in the capacity factor *x*, i.e., an increase in the plant capacities for a given imbalance to be handled.**
- **For the same gasification technology, there is no big difference in plant CAPEX target among different zones (DK-DK1 or IT-SUD) and the magnitudes of the flexibility needs (S1 and S2).**

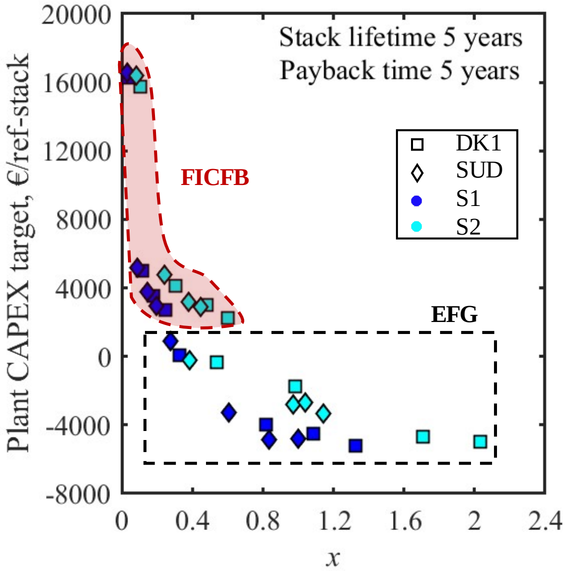


Figure 11 Plant CAPEX target (€/ref-stack) under different scenarios, technology combinations, and geographical zones. Each point is obtained by installing different plants at different sizes to maximize the profit from grid balancing.

According to Eq. (1) and (6), the plant CAPEX target is related to (1) the plant sizes, representing the total number of reference stacks employed in all plants deployed, (2) the lifetime income, (3) the investment costs of the storage tanks, and (4) the biomass supply chain cost. The four points are further discussed below to elaborate on the plant CAPEX targets given in Figure 11.

8.2 Profit

The maximum profits of the W2G plants obtained by 1 MWh_{th} biomass under different scenarios are shown in Figure 12. **Increasing the total plant capacities x by increasing the plant number, the maximum profit obtained by 1 MWh_{th} biomass will be decreased**.

For the FICFB option, the profits of the W2G plants obtained by 1 MWh_{th} biomass is similar for scenarios S1 and S2: (1) 40 €/MWh_{th} (x=0.25 for DK-DK1, x=0.2 for IT-SUD) to 130 €/MWh_{th} (x=0.03 for both DK-DK1 and IT-SUD), and (2) 30 €/MWh_{th} (x=0.6 for DK-DK1, x=0.45 for IT-SUD) to 120 €/MWh_{th} (x=0.1 for DK-DK1, x=0.08 for IT-SUD). For the EFG option, the profits vary in a smaller range 6–21 €/MWh_{th}: (1) under scenario S1, 10–20 €/MWh_{th} for DK-DK1 and 11–21 €/MWh_{th} for IT-SUD; (2) under scenario S2, 6–14 €/MWh_{th} for DK-DK1 and 9–14 €/MWh_{th} for IT-SUD.

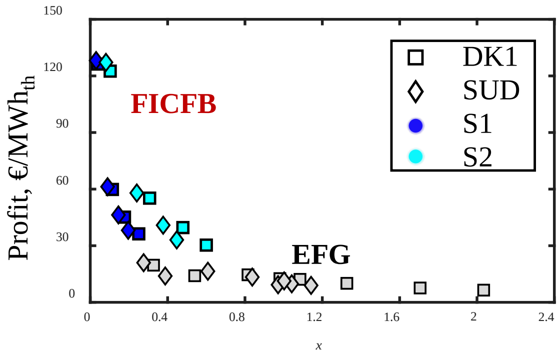


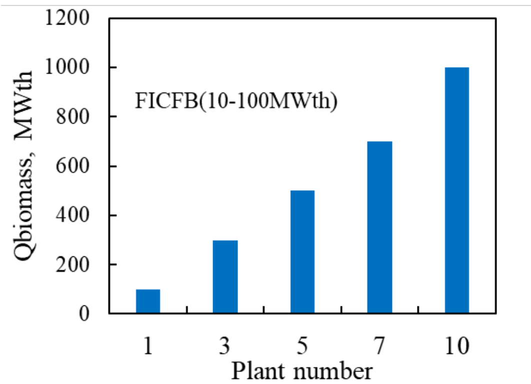
Figure 12 Maximum profit of W2G plants obtained by 1 MWh_{th} biomass under different scenarios. The colored symbols are for the FICFB option, while the gray symbols are for the EFG option.

8.3 Plant deployment

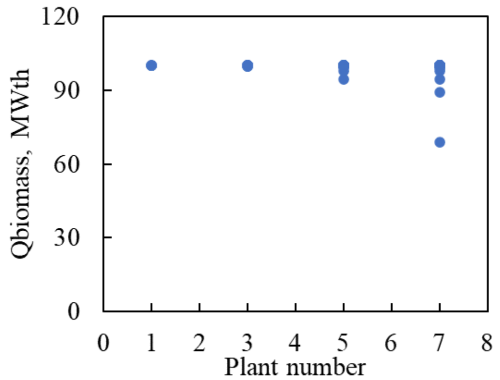
8.3.1 Deployment of the plants with FICFB gasifier (10–100 MW_{th})

The capacity factor is increased by increasing numbers of plants installed. The **maximum plant capacities of all plants installed** represented by the input biomass energy are given in Figure 13a among **four cases (S1-DK1, S2-DK1, S1-SUD, S2-SUD)**. The total capacity increases from 100 to 1000 MW_{th} when increasing the plant number from 1 to 10. Increasing the number of W2G plants, more flexibility needs can be addressed by the newly installed capacities and the coordination with existing capacities. With 10 W2G plants, the total capacities reach 1000 MW_{th}, indicating that each plant is at the maximum size for an individual plant set at 100 MW_{th} for the FICFB option.

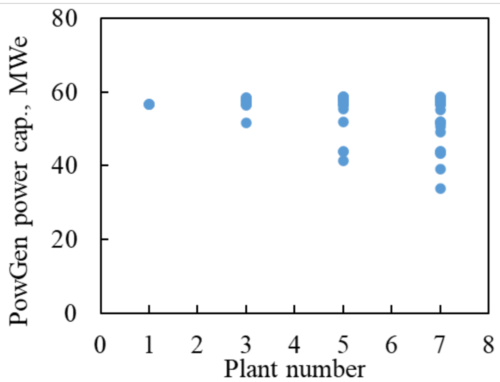
Biomass capacities in all scenarios under different numbers of plants are shown in Figure 13b. Employing less than three RSOC plants, the biomass capacities deployed are all at maximum capacity, 100 MW_{th}. Increasing the number of plants to 5, the economically optimal plant capacities become lower than 100 MW_{th}, and even decrease down to 90 MW_{th}. Further increasing the number of the plant to 7 and 10, the smallest plant capacities are decreased to 70 and 45 MW_{th}, respectively. Employing more than three plants, some W2G plants are not at maximum capacity (100 MW_{th}) but smaller. The major flexibility needs have been coped with by the first three W2G plants installed and the coordination among them, further plant capacities installed are used to address the remaining, **discrete and reduced hours of imbalances**; thus, the further installed plant capacities will be operated more hours under PowNeu operation, which is not favored economically.



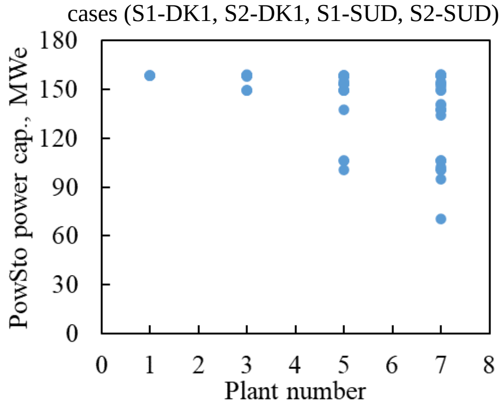
(a) Maximum total $Q_{biomass}$ among the four cases, which is S1-SUD



(b) Distribution of $Q_{biomass}$ of all plants deployed in all four cases (S1-DK1, S2-DK1, S1-SUD, S2-SUD)



(c) Distribution of PowGen capacity of all plants deployed in all four cases (S1-DK1, S2-DK1, S1-SUD, S2-SUD)



(d) Distribution of PowSto capacity of all plants deployed in all four cases (S1-DK1, S2-DK1, S1-SUD, S2-SUD)

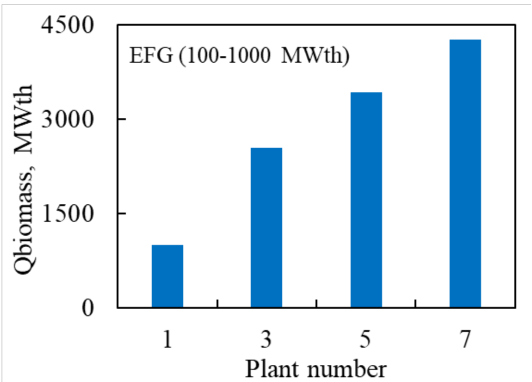
Figure 13 The statistics of the deployment of different numbers of W2G plants in all four cases. The plant capacity is represented by the input biomass energy, MW_{th}.

The PowGen capacities of the W2G plants employed in all four cases are illustrated in Figure 13c, showing a similar trend as the $Q_{biomass}$ (MW_{th}) for each plant in Figure 13b: (1) employing one single W2G plant, its PowGen power capacity reaches its maximum of 60 MWe (converted from the input biomass energy multiplying the PowGen efficiency); (2) increasing the number of plants deployed, the PowGen power capacities decrease to cope with the reduced imbalance. The PowGen power capacities are decreased to 50, 40, 30 and 20 MW_e for 3, 5, 7 and 10 plants, respectively.

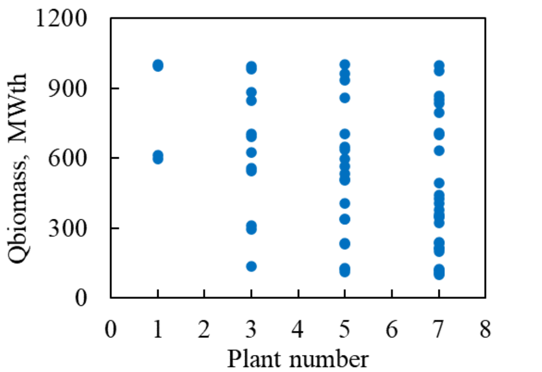
The PowSto power capacities of the W2G plants employed in all scenarios are illustrated in Figure 13d, showing a similar trend as the PowGen power capacities of each plant in Figure 13c: (1) Employing one single W2G plant, the PowSto power capacity of the plant deployed in four scenarios is at their maximum capacity, 160 MWe; (2) Increasing the number of plants to 3, 5, 7 and 10, the newly-deployed PowSto capacities will be decreased down to 150, 100, 70 and 50 MWe, respectively. Similarly, this is due to the

8.3.2 Deployment of grid balancing plants using EFG gasifier (100–1000 MW_{th})

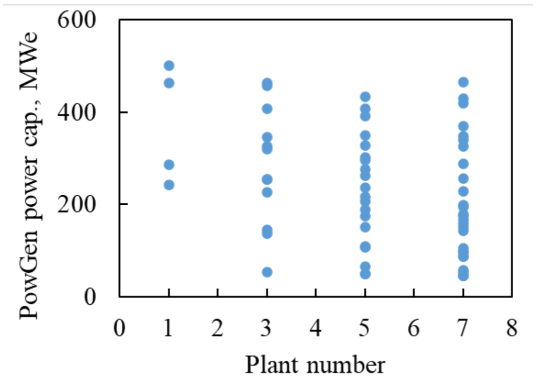
Entrained-flow gasifier with direct heating (EFG, 1200–1500 C, 30–80 bar) is usually for large-scale applications (100–1000 MW_{th}). The maximum **total** plant capacities for all cases, S1-DK1, S2-DK2, S1-SUD and S2-SUD are illustrated in Figure 14a, which are 1000, 2500, 3500, and 4300 MW_{th} for deployment with 1, 3, 5, and 7 W2G plants, meaning that the plant capacities are also lower than the maximum capacity 1000 MWth when employing over 3 plants, due to that the remaining power imbalance is reduced with more plants deployed.



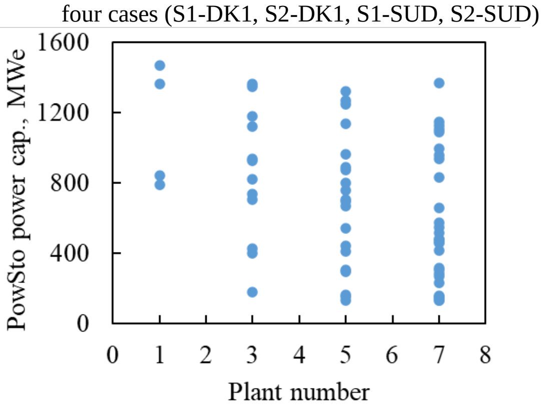
(a) Maximum total $Q_{biomass}$ among the four cases, which is S1-SUD



(b) Distribution of $Q_{biomass}$ of all plants deployed in all four cases (S1-DK1, S2-DK1, S1-SUD, S2-SUD)



(c) Distribution of PowGen capacity of all plants deployed in all four cases (S1-DK1, S2-DK1, S1-SUD, S2-SUD)



(d) Distribution of PowSto capacity of all plants deployed in all four cases (S1-DK1, S2-DK1, S1-SUD, S2-SUD)

Figure 14 The statistics of the deployment of different numbers of W2G plants in all four cases. The plant capacity is represented by the input biomass energy, MW_{th}.

Plant capacities for all four cases of S1-DK1, S2-DK1, S1-SUD and S2-SUD are shown in Figure 14b. Employing one single W2G plant, the plant capacity in optimal deployments reaches the maximum 1000 MW_{th}. Increasing the number of plants to 3, the economically optimal plant capacities are in 150–1000 MW_{th}. Further increasing the number of plants to 5 and 7, the capacities of the plants deployed are decreased to the minimum 100 MW_{th}. Most of the W2G plants (> 80%) are not at the maximum capacity (1000 MW_{th}) to reduce the utilization hours of PowNeu mode. The percentage of the W2G plants lower than the maximum capacity of the EFG option (80%) is higher than the percentage of the FICFB option (30%).

The PowGen power capacities of all W2G plants deployed in all four cases are illustrated in Figure 14c, showing a similar trend as the $Q_{biomass}$ (MW_{th}) for each plant in Figure 14b: (1) Employing a single W2G plant, the PowGen power capacities are higher than 250 MWe; (2) Increasing the number of W2G plants to 3, 5 and 7, the PowGen power capacities are ranging in the minimum capacity 50 MWe to the maximum capacity 500 MWe, converted from the maximum input biomass energy and the mode efficiency.

The PowSto power capacities of the W2G plants deployed in all cases are illustrated in Figure 14d, showing a similar trend as the PowGen power capacities for each plant in Figure 14c: (1) Employing one single plant, the PowSto power capacities should be over 800 MWe to maximize the profits from the grid-balancing services, and even up to the maximum of 1500 MWe; (2) Increasing the number of W2G plants to 3, 5, and 7, the PowSto power capacities can be reduced down to 150 MWe.

8.4 Dispatch (S1-DK1 as an example)

The dispatch of the W2G plants for **S1-DK1** is taken as an example (Figure 15). The maximum flexibility needs are 1650 MWe for UP regulation and 4000 MWe for DOWN regulation.

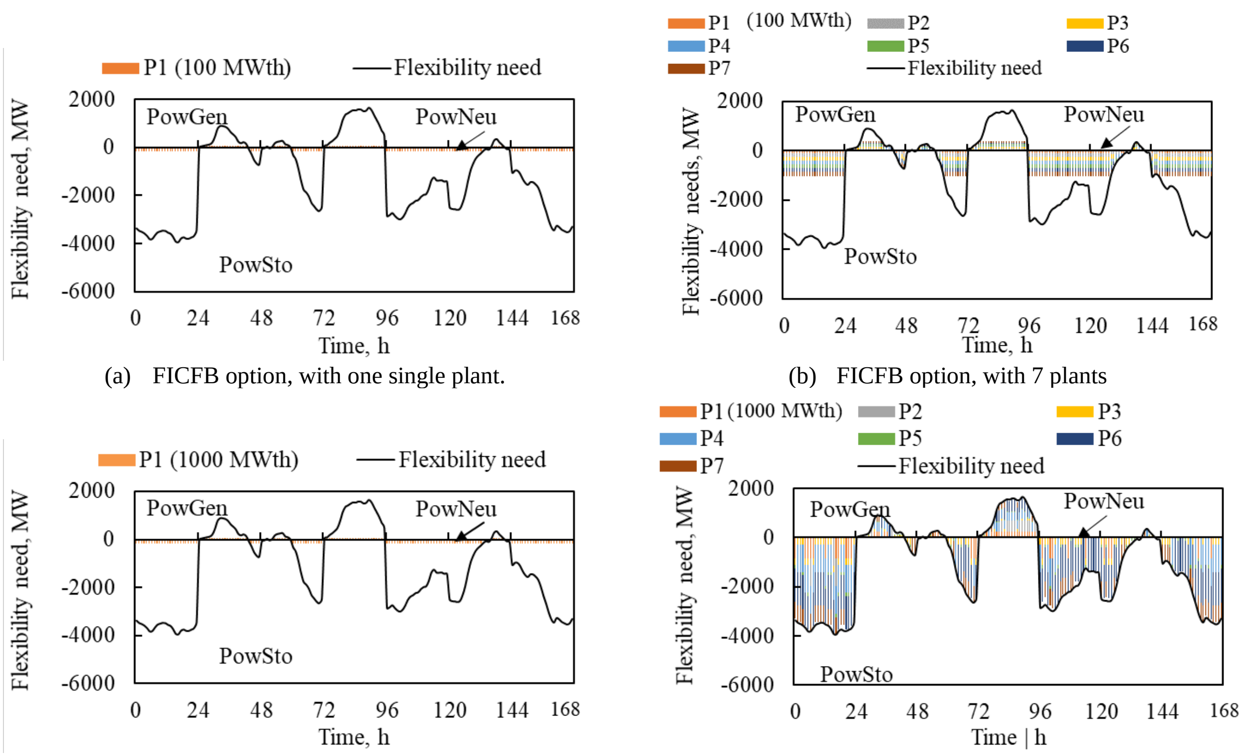


Figure 15 The dispatch of W2G plants to cope with the flexibility needs in S1-DK1.

For the FICFB option (Figure 15a,b), the plant capacity is limited to 100 MW_{th} biomass input. When employing a single centralized plant (Figure 15a), the capacity factor (Eq. (38)) reaches only 0.03. **The plant itself is operated mostly under PowGen and PowSto modes and rarely under PowNeu mode**. Employing 7 centralized W2G plants (Figure 15b), with the capacity factor x reaching 0.25, the W2G plants are coordinated to address more flexibility needs. This coordination also increases the operating hours of PowNeu mode.

For the EFG option (Figure 15c,d), the plant capacity is limited to 100–1000 MW_{th} biomass input. Employing one single plant to reach a maximum profit, the capacity factor x reaches 0.3, with the PowGen and PowSto power capacities reaching 250 MWe and 850 MWe, respectively. When the power imbalance 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. Employing 7 W2G plants, the optimal PowGen and PowSto capacities reach 1900 and 5600 MW_{th} in total, i.e., 1.3 times of the maximum grid flexibility needs, which corresponds to a capacity factor x of 1.3. Over 80% of the flexibility needs can be covered as shown in Figure 15d at the cost of increased utilization of the PowNeu mode.

The average annual PowNeu utilization hours of the W2G plants in all four cases are shown in Figure 16, under which the W2G plants are not interacting with the electrical grid. High PowNeu utilization over the year indicates low utilization of the PowSto and PowGen modes. This results in reduced profit, due to that (1) there is no extra grid-balancing gain under the PowNeu mode, and (2) the PowNeu mode reaches a lower efficiency than the PowSto and PowGen modes.

For the FICFB option, the average annual utilization hours of the PowNeu mode reach 300–3500 h, which is much lower than that of the EFG option, i.e., 2500–6000 h. Thus, small plants tend to be more flexible and economically potential (Figure 11).

Under different scenarios of flexibility needs, the utilization hours of PowNeu mode under the scenario S2 is higher than those of scenario S1 with larger flexibility needs. Taking the DK1 as an example, the utilization hours of the PowNeu mode are in 2000–3500 h under scenario S2, which is much higher than that of the scenario S1, i.e., 1000–2000 h.

Increasing the total capacities of W2G plants, represented by an increasing capacity factor x or the number of plants in Figure 16, the average PowNeu utilization hours of the W2G plants increase and the profitability reduces. Taking the case S1-DK1 as an example, the average annual utilization hour of the PowNeu mode increases from 900 to 1900 hours with the increase of the number of plants from 1 to 7, corresponding to the capacity factor x from 0.03 to 0.25.

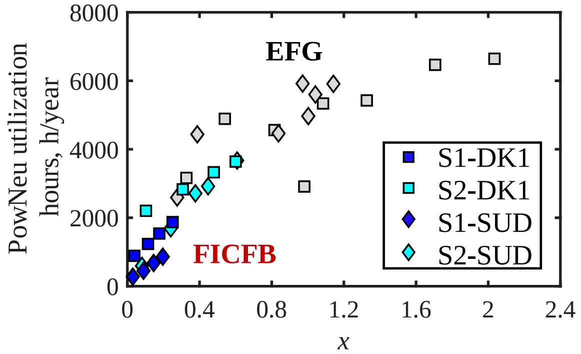


Figure 16 Average annual PowNeu mode utilization hours.

8.5 Supply chain optimization and costs

8.5.1 Key hypotheses

Key hypotheses of inlet technical and economic data, e.g., assumed unit transport cost, are introduced. Firstly, the pre-treatment method to consider is drying and a rotatory drum dryer is considered. Key specifications are:

- Moisture content: 10% after drying.
- Maximum size of the drier: 100 t/h with a reference investment of 7.4 $MEUR_{2019}$ for the dryer and the capacity can be scaled down to any size.
- Annual operation and maintenance (O&M) cost is set to 3% of the initial investment, and the scale factor for investment calculation is 0.7.
- The utility consumption is calculated as the product of 0.06 and the evaporated water (result in tonne of diesel).

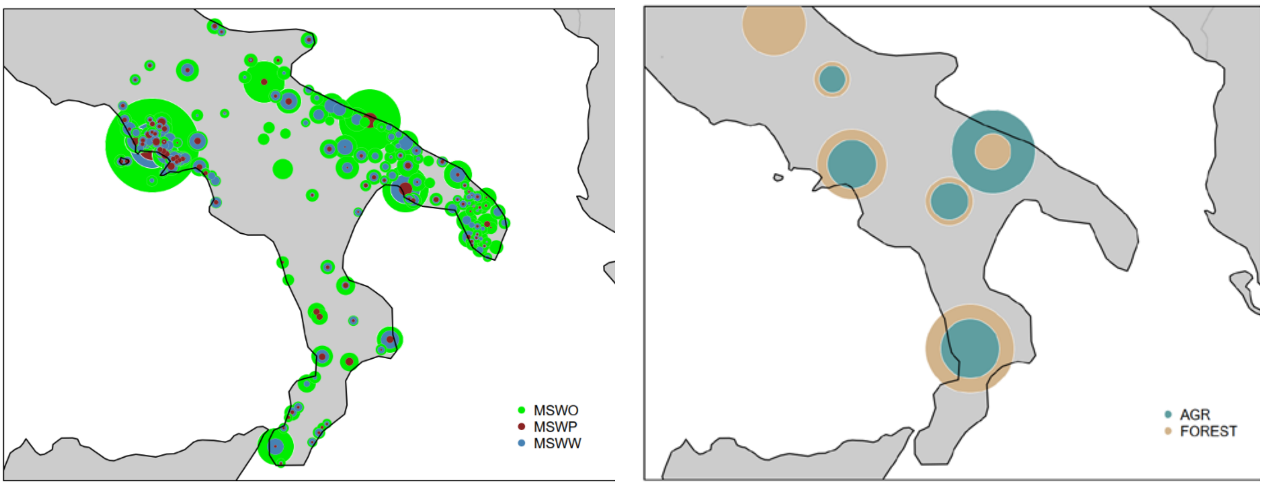
Secondly, covered storage (open-air) and silo storage technologies are employed, with the specifications:

- The covered storage with no initial investment but with an O&M cost of 0.47 $MEUR_{2019}/m^3$ per month, corresponding to both a 3% of dry matter loss and 1.5% of moisture content gain per month. The reference scale and investment of silo storage are 5000 m^3 and 0.49 $MEUR_{2019}$, respectively. Moreover, the annual operation and maintenance (O&M) cost is 3% of the initial investment, and the economic scaling factor is 0.7.

For transportation, the biomass is transported by rented trucks assuming that the size and maximum amount of biomass can be handled by the truck. The transportation distances are assumed to be linear with a tortuosity factor of 1.4. The truck capacity is 130 m^3. Unit transportation cost is 1.26 EUR per km and unit fuel consumption is 18.09 MJ/km (the high heat value of diesel is 45.8 MJ/kg and the price of diesel is 1747 EUR/t). Moreover, the load and unload costs are 0.74 EUR/m^3.

8.5.2 Supply chain optimized for zone IT-SUD

The annual amount and geographical distribution of the biomass are illustrated in Figure 17:



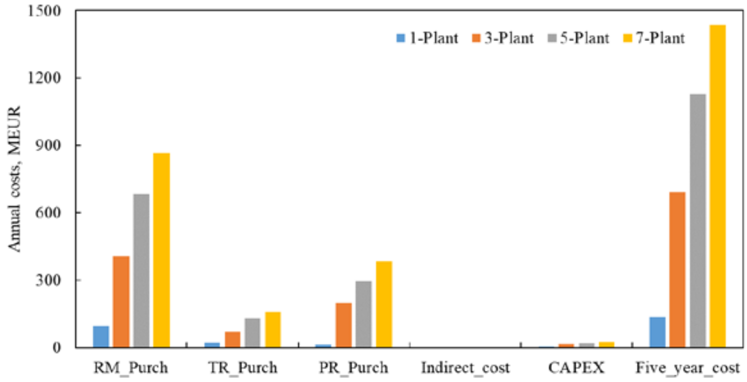
(a) Municipal solid waste (175 locations with the supply above the selection threshold)

(b) Agricultural and forest biomass

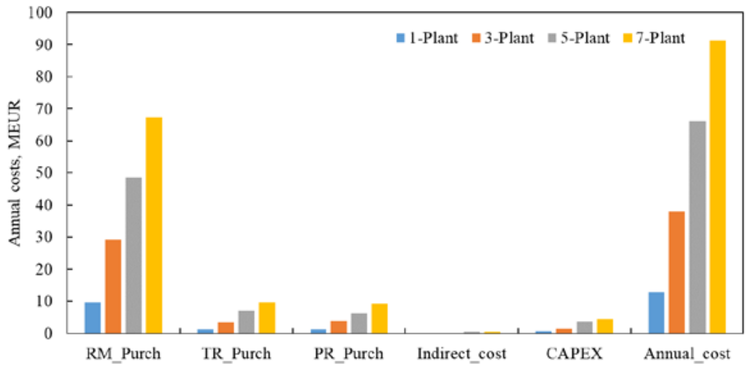
Figure 17 Biomass availability of municipal solid waste, agriculture and forest sectors in the zone in-around IT-SUD.

- Figure 17a for municipal solid waste organic (MSWO), municipal solid waste paper (MSWP), and municipal solid waste wood (MSWW). The total energy supplied by municipal solid waste is 2711 GWh/year with 1481 locations in IT-SUD; however, considering the complexity of collection and transport, some candidate positions with smaller biomass amount are neglected and 175 large biomass supply locations are selected for the design of supply chain and the total amount remains 1897 GWh/year.
- Figure 17b for agricultural and forest biomass. The detailed distribution of these types of biomass is not available. We consider only these six locations, in which the total agricultural and forest biomass amounts are 8653 GWh/year and 8017 GWh/year, respectively.

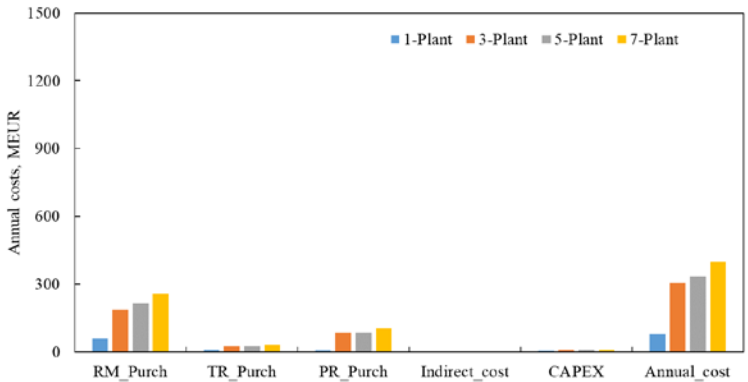
(a) S1-EFG



(b) S1-FICFB



(c) S2-EFG



(d) S2-FICFB

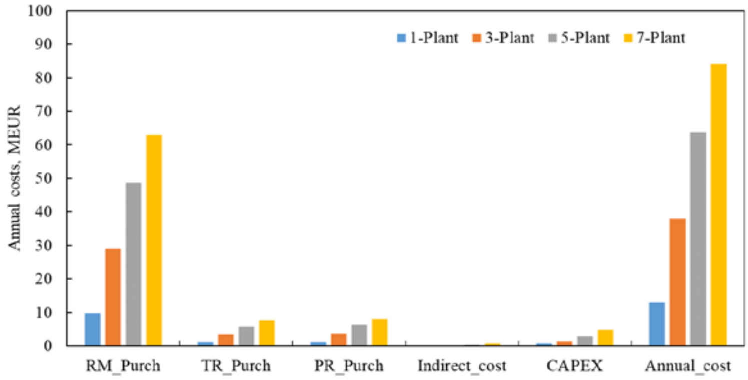
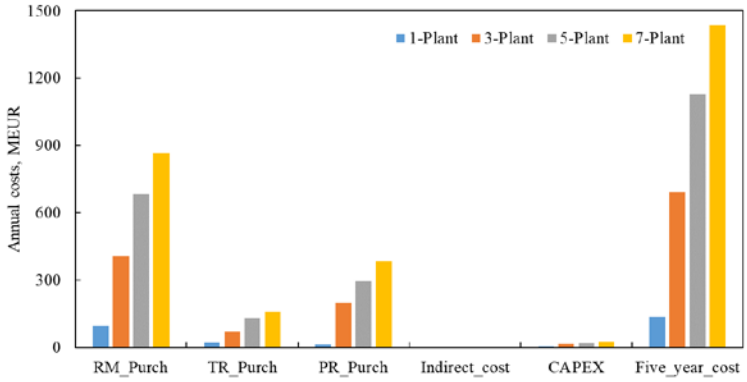


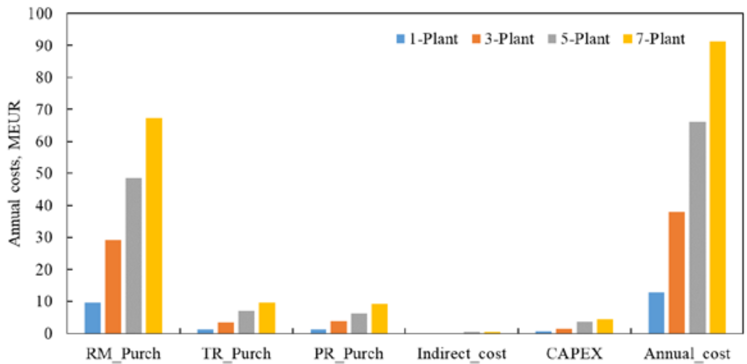
Figure 18 Cost breakdown of the optimal biomass supply chain to fulfill the W2G plants deployed in IT-SUD for the combination of (a) S1-EFG, (b) S1-FICFB, (c) S2-EFG, and (d) S2-FICFB. (RM_Purch: raw material purchase costs, TR_Purch: biomass transportation costs, PR_Purch: biomass production costs, Indirect_cost: operational and maintenance costs, CAPEX: capital investment costs).

The biomass supply chain is designed and dimensioned to fulfill the biomass requirements of all W2G plants deployed, which are derived in section 8.3 by optimizing the capital and operating expenditure of all supply chains. The biomass supply costs of these cases are compared in

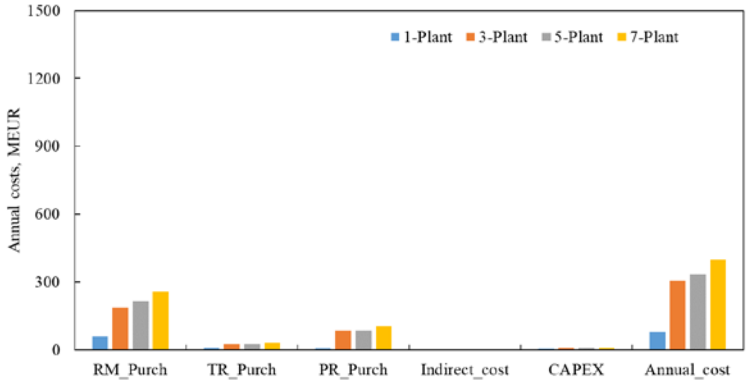
S1-EFG



(e) S1-FICFB



(f) S2-EFG



(g) S2-FICFB

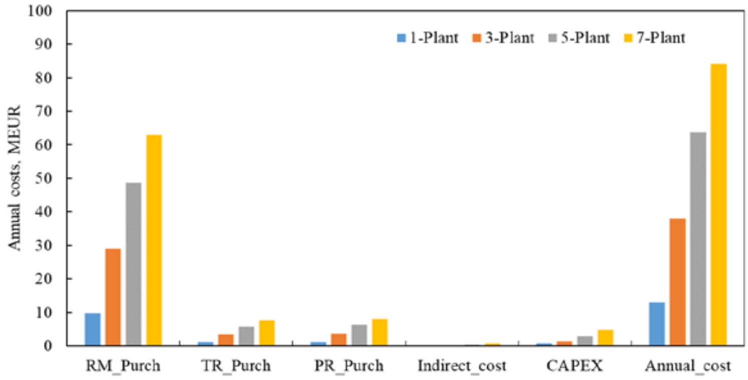
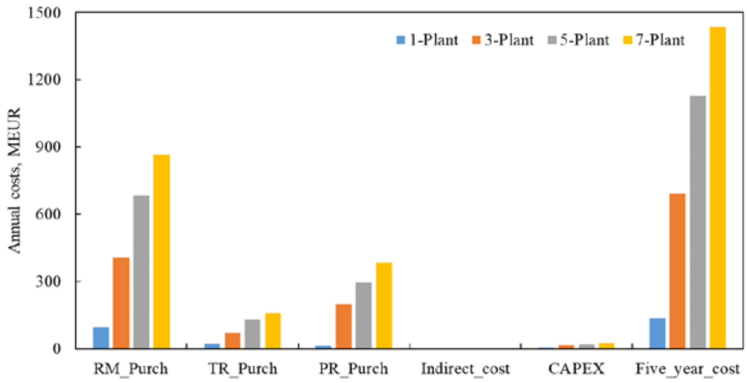


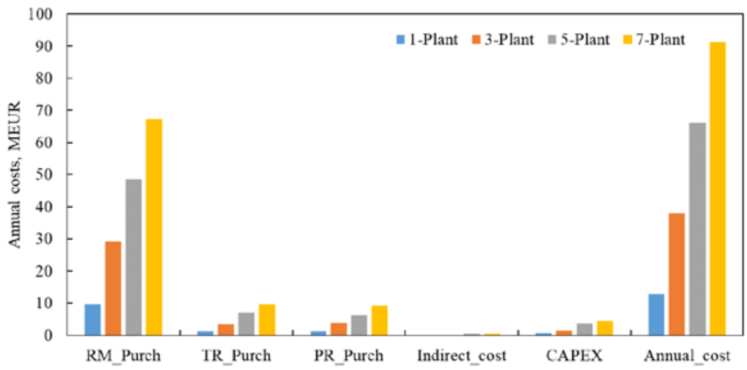
Figure 18.

The overall cost of the designed biomass supply chain in IT-SUD for the case S1-EFG (

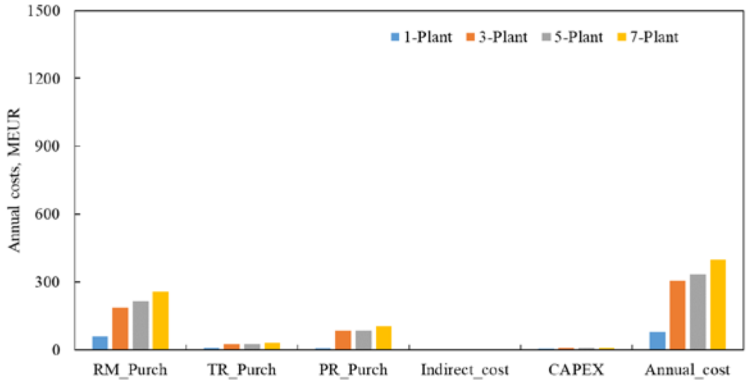
S1-EFG



(h) S1-FICFB



(i) S2-EFG



(j) S2-FICFB

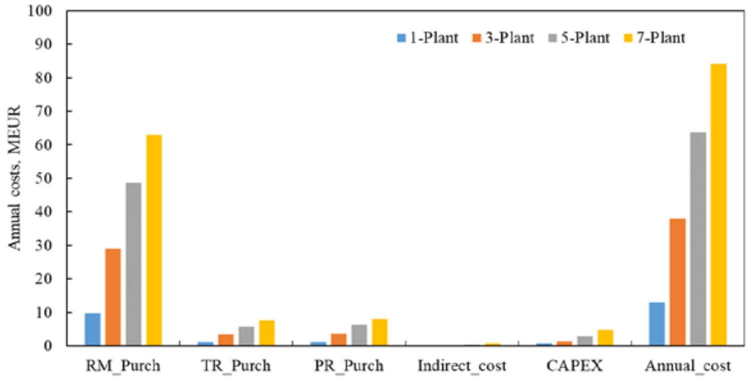


Figure 18a) is higher than the other three cases, due to the higher biomass requirements of all EFG-based W2G plants. Taking the schemes with 7 plants as an example, the total annual cost SI-EFG is 1437 M€ while those of the other three cases are 91 M€ (S1-FICFB), 399 M€ (S2-EFG), and 84 M€ (S2-FICFB), respectively. Accordingly, the total biomass consumption of the 7 plants is 36100 GWh/y (S1-EFG), 6132 GWh/y (S1-FICFB), 15120 GWh/y (S2-EFG), and 5688 GWh/y (S2-FICFB), respectively.

The biomass supply chain is designed for all cases of 1, 3, 5, or 7 W2G plants. With the increase in the number of plants, the overall cost of corresponding biomass supply chains increases. For the S1-EFG case, the biomass supply costs are 137, 692, 1129, and 1437 M€ for 1, 3, 5, and 7 plants, respectively.

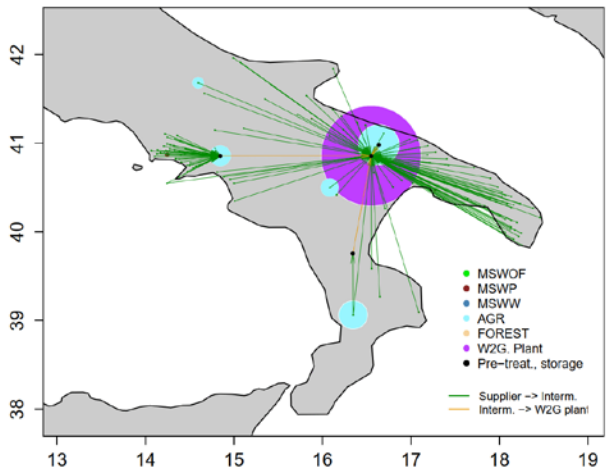
The overall biomass supply costs are mainly contributed by the purchase of raw material, while the indirect costs are ignorable. When employing one plant, the direct costs are mainly from the raw-materials purchase, biomass transportation and production, which are similar for other cases with more plants deployed. The trends of the change of each contributor with the number of plants are similar.

The biomass supply chains for multiple (from 1 to 7) EFG-based W2G plants under the flexibility-need scenario S1 and S2 are illustrated in Figure 19 and Figure 20, showing the raw biomass collection points involved and the transportation of the treated biomass among various suppliers, the pre-treatment sites, and the W2G plant locations. **Generally, the pre-treatment sites and W2G plants are in places with rich raw biomasses, which can reduce transportation costs. One W2G plant is served by multiple pre-treatment plants due to that the biomass requirement is larger than the capacity of a single pre-treatment plant. The pre-treatment plant is in a site with large biomass availability and thus only needs to receive a smaller amount of biomass from the neighboring sites. The potential sites for deploying EFG-based W2G plants in IT-SUD include:**

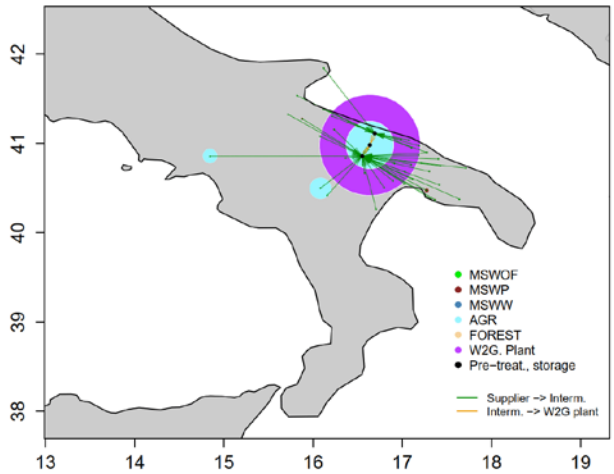
- **Potential locations if deploying 1 plant: Altamura in scenario S1; Puglia in scenario S2;**

- **Potential locations if deploying 3 plants: Avellino, Vibo Valentia and Puglia in scenario S1; Campania, Puglia, and Calabria in scenario S2;**
- **Potential locations if deploying 5 plants: Cosenza, Gioia Tauro, Campania, Puglia and Basilicata in scenario S1; Bari, Lamezia Terme, Avellino and Puglia (with 2 plants) in scenario S2;**
- **Potential locations if deploying 7 plants: Reggio Di Calabria, Bitonto, Avellino, Catanzaro, Vibo Valentia, Cosenza, and Abruzzo in scenario S1; Casoria, Abruzzo, Campania, Puglia (with 2 plants), Basilicata and Calabria in scenario S2.**

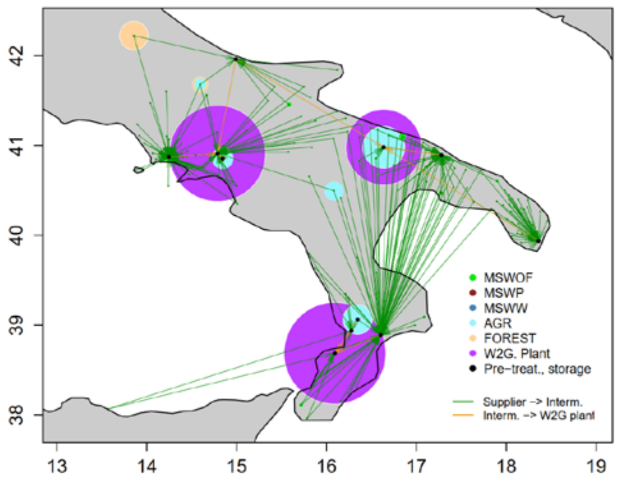
For the deployment of 3, 5 and 7 EFG-based W2G plants **under scenario S1**, **there is a lot of biomass imported from the left bottom position (13.5, 38), which is assumed as a fictitious position with enough biomass derived from other districts or countries**. This is due to that the grid balance requirements are much larger than local biomass availability.



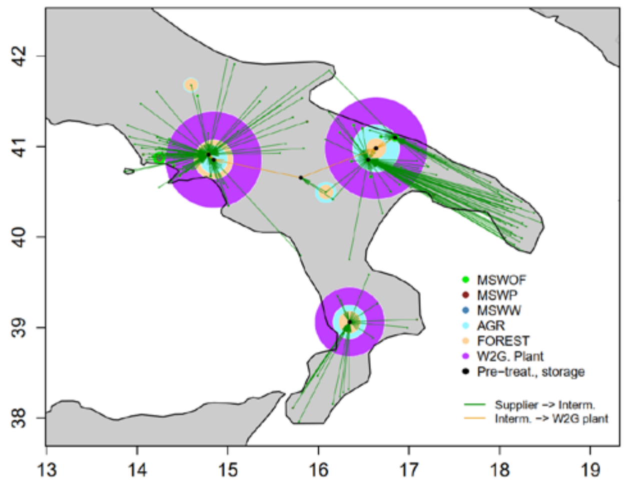
(a) S1: 1 plant



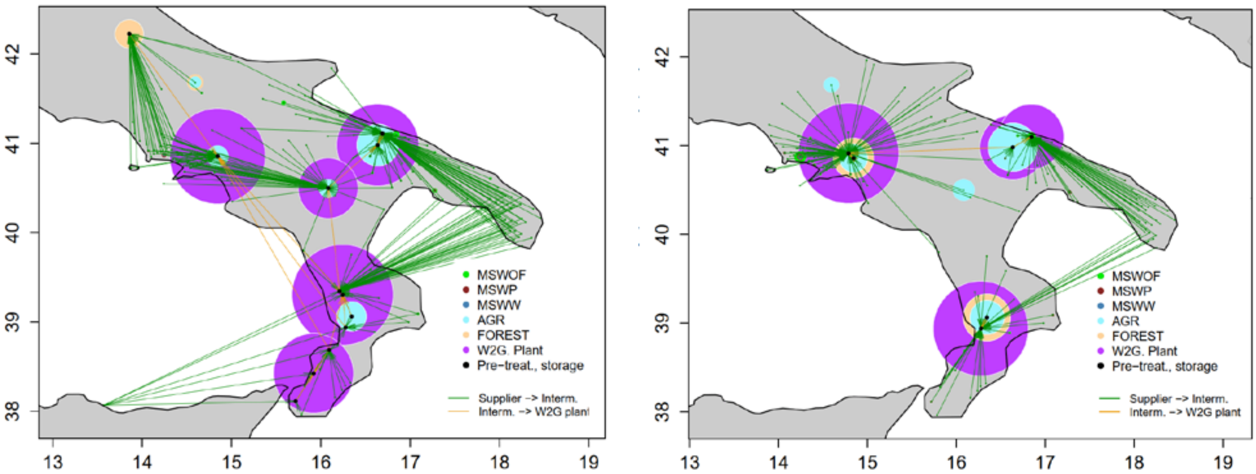
(b) S2: 1 plant



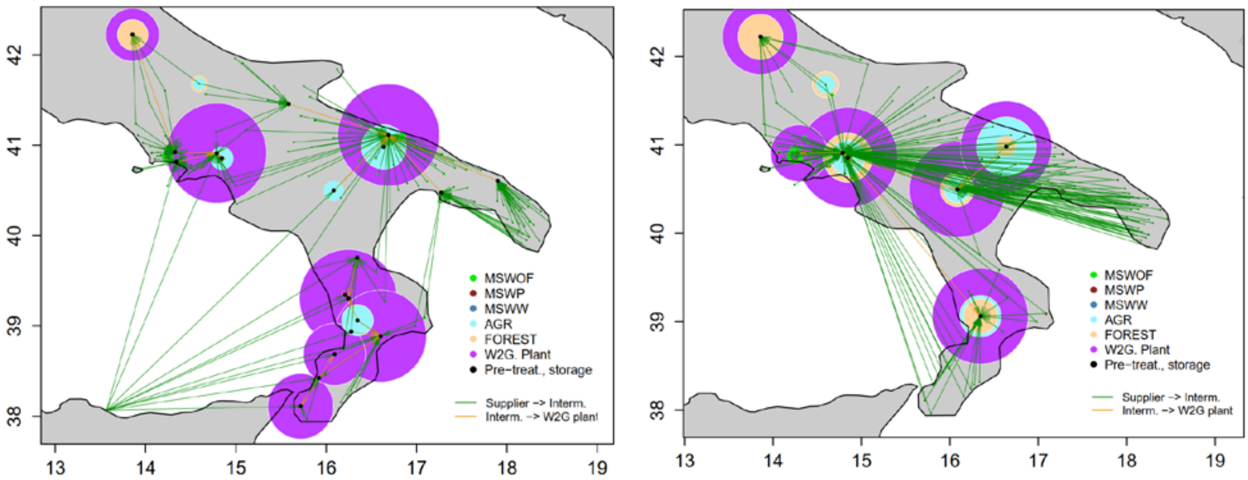
(c) S1: 3 plants with (13.5, 38) as a fictious location for import



(d) S2: 3 plants



(e) S1: 5 plants (13.5, 38) as a fictious location for import (f) S2: 5 plants

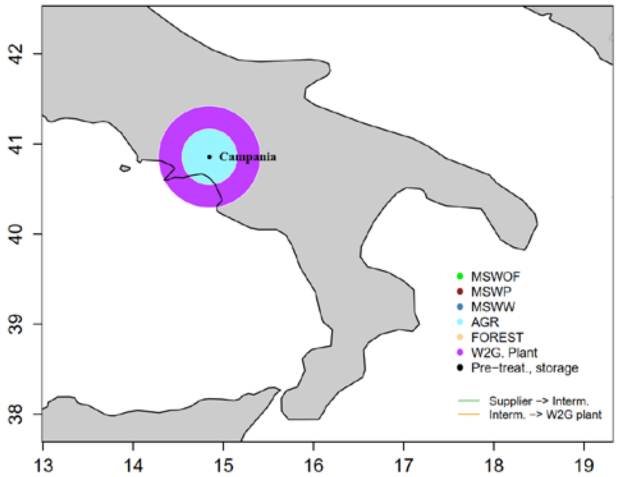


(g) S1: 7 plants (13.5, 38) as a fictious location for import (h) S2: 7 plants

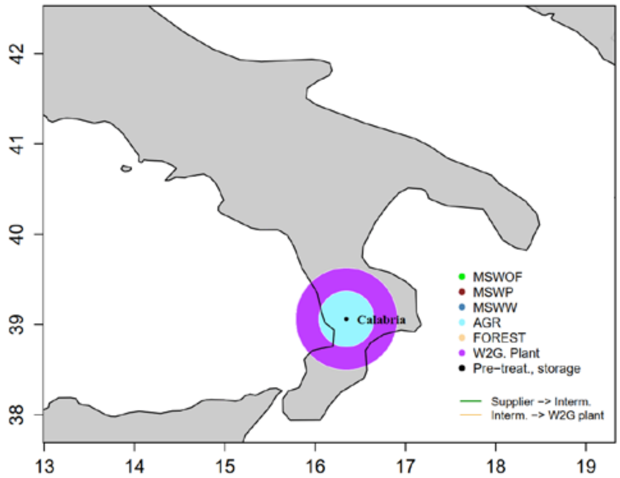
Figure 19 The biomass supply chain for deploying EFG-based W2G plants in IT-SUD.

For the deployment of FICFB-based W2G plants (Figure 20), which are much smaller than the EFG-based plants, the plants are mainly located in the biomass-rich positions and there are much less long-distant biomass transportation. The biomass is supplied by a maximum of two or three sites. **Note that more than one W2G plant can be deployed closely**, and not each of the W2G plants is illustrated in Figure 20. Since biomass is enough to drive the FICFB-based W2G plants, the biomass from the agriculture sector is a prior option, due to its higher heating value (LHV, 15 MJ/kg), lower moisture (MC, 15%), and price (45 €/t). **The potential sites for deploying FICFB-based W2G plants in IT-SUD include:**

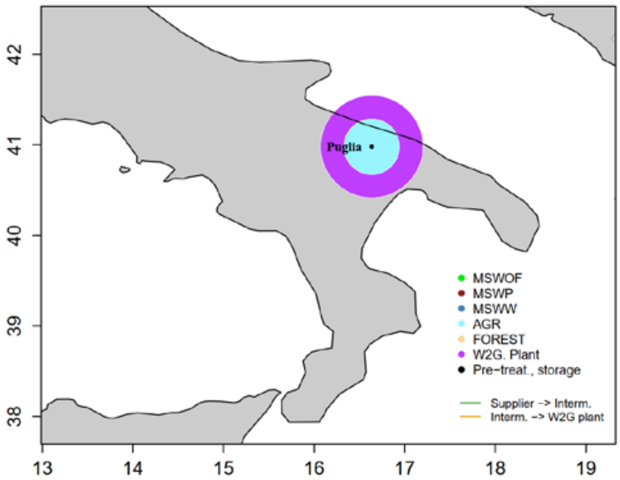
- **Potential locations if deploying 1 plant: Campania in scenario S1; Calabria in scenario S2;**
- **Potential locations if deploying 3 plants: Puglia (with 3 plants) in scenario S1 and S2;**
- **Potential locations if deploying 5 plants: Puglia (with 3 plants) and Calabria (with 2 plants) in scenario S1 and S2;**
- **Potential locations if deploying 7 plants: Campania (with 2 plants), Puglia (with 3 plants) and Calabria (with 2 plants) in scenario S1; Campania, Puglia (with 4 plants) and Calabria (with 2 plants) in scenario S2.**



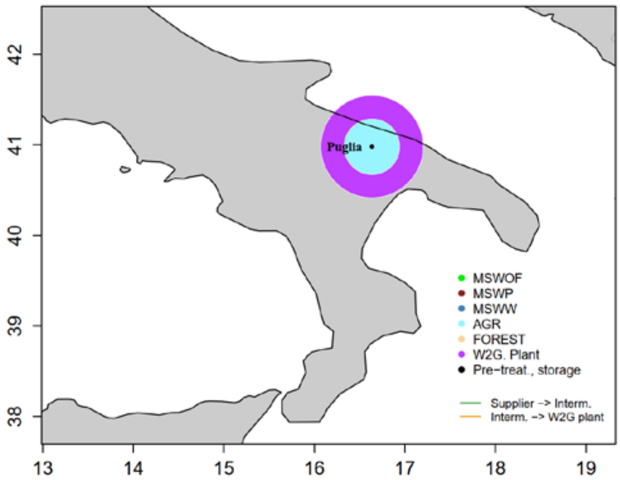
(a) S1: 1 plant



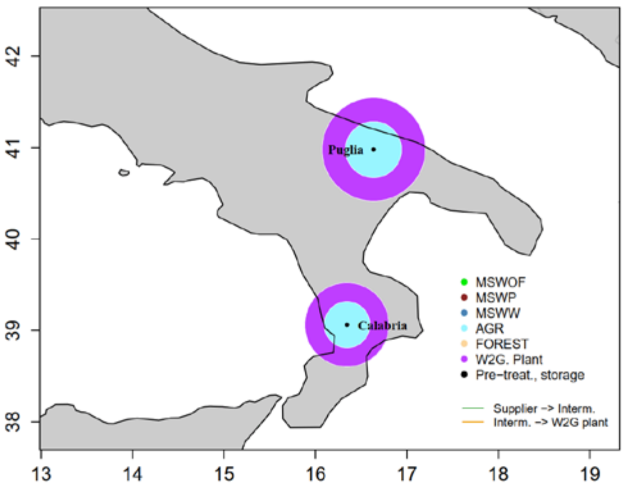
(b) S2: 1 plant



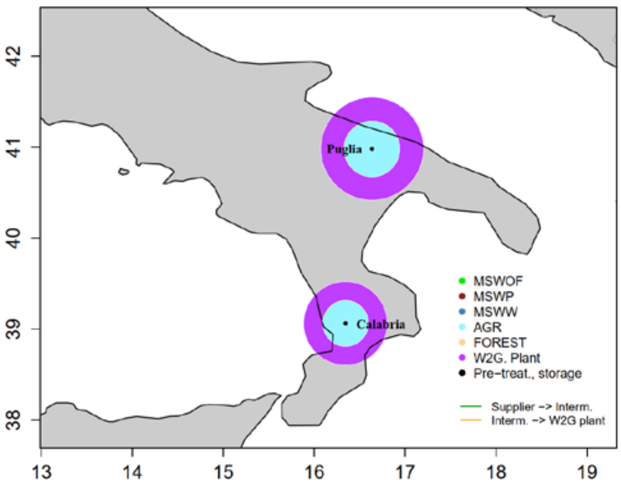
(c) S1: 3 plants (multiple plants deployed in the same place)



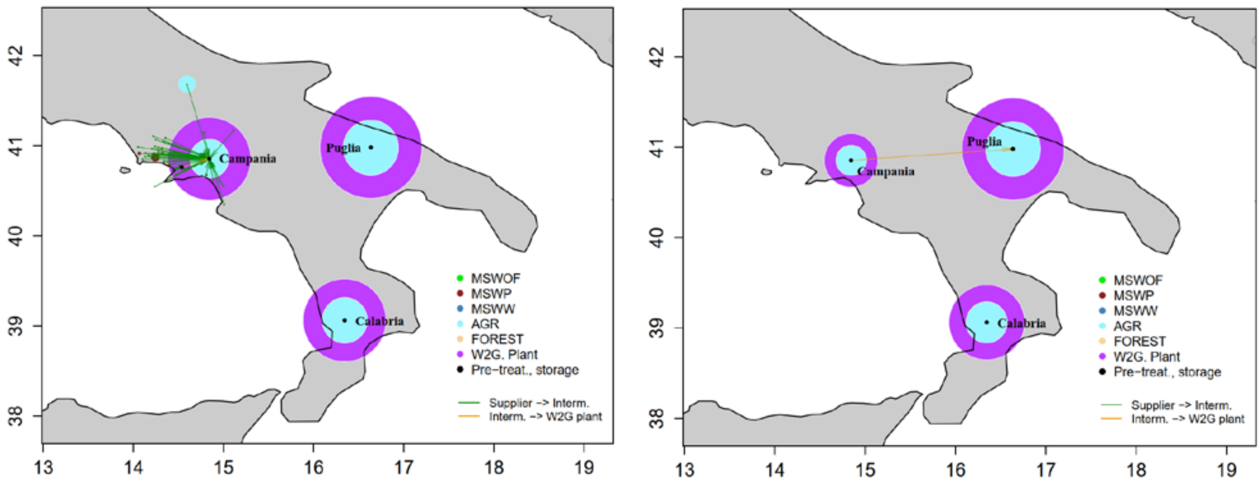
(d) S2: 3 plants (multiple plants deployed in the same place)



(e) S1: 5 plants (multiple plants deployed in the same place)



(f) S2: 5 plants (multiple plants deployed in the same place)



(g) S1: 7 plants (multiple plants deployed in the same place) (h) S2: 7 plants (multiple plants deployed in the same place)

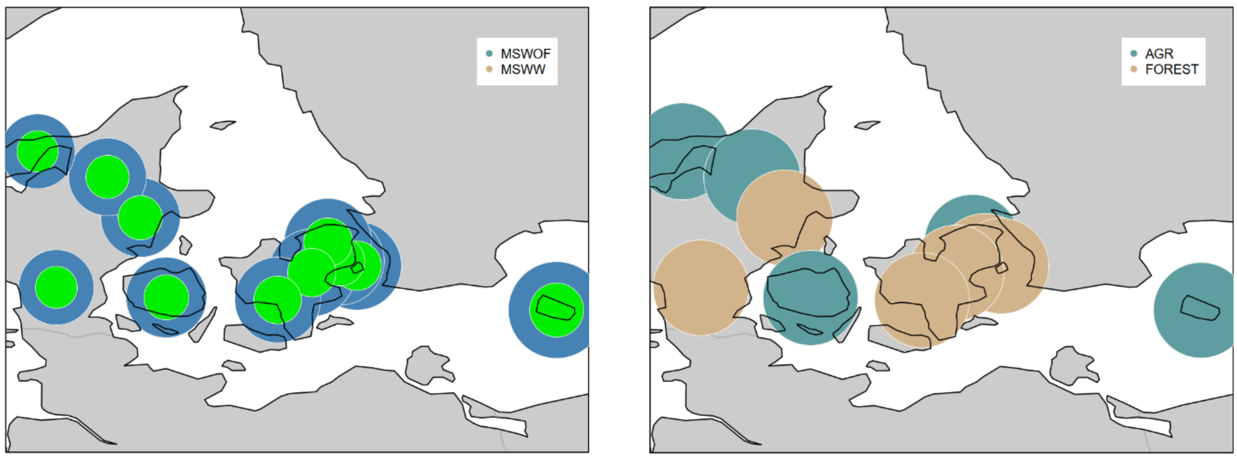
Figure 20 The biomass supply chain for deploying the FICFB-based W2G plants in IT-SUD.

8.5.3 Supply chain optimized for zone DK-DK1

The annual amount and geographical distribution of the biomass in DK are illustrated in Figure 21:

- Figure 21a: municipal solid waste organic (MSWO) and municipal solid waste wood (MSWW)
- Figure 21b: agricultural and forest biomass

The energy that could be supplied by the total municipal solid waste is 5475 GWh/year with 11 locations in DK, while agricultural and forest biomass can offer more energy of 8937 GWh/year and 7106 GWh/year, respectively. Considering that the biomass amount in each of the total 11 candidate positions, the deployment of the W2G plants is further restricted to 5 candidate positions.



(a) Municipal solid waste (11 locations) (b) Agricultural and forest biomass (11 supply positions)

Figure 21 Biomass availability of municipal solid waste, agriculture and forest sectors in the zone in-around DK-DK1.

The supply chain is designed and dimensioned to fulfill the biomass needed by the W2G plants by optimizing the capital and operating expenditure of the supply chain (shown in Figure 22). When deploying the same number of W2G plants reaching a similar capacity factor *x*, **there are only small differences of the total annual costs among the optimal (SS0) and sub-optimal solutions (SS1-SS3)**, as shown in Figure 22.

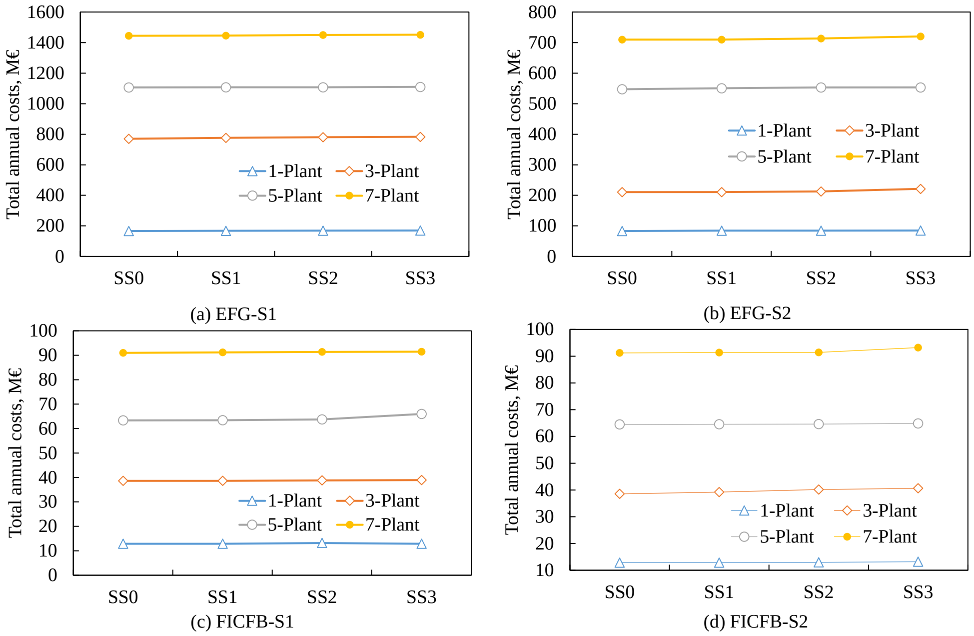
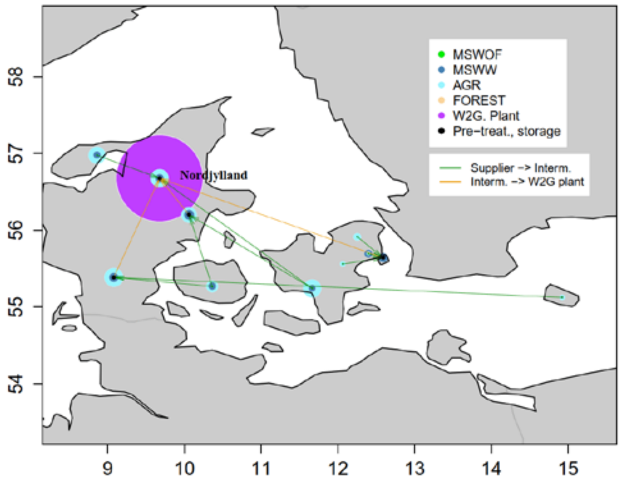


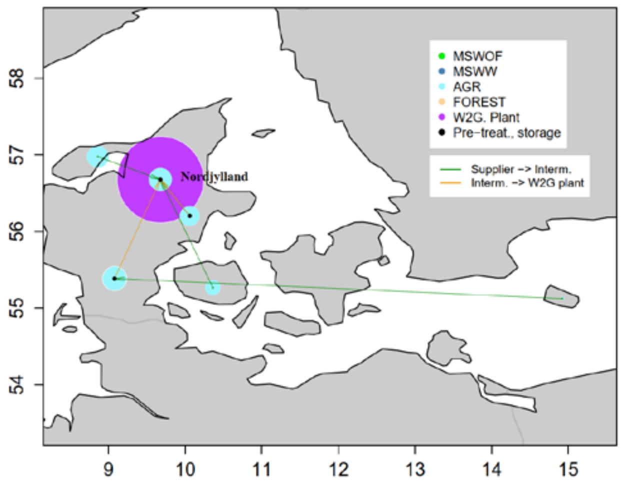
Figure 22 The total annual cost of the optimal (SS0) and near-optimal (SS1-SS3) supply chain in DK.

The biomass supply chains derived for deploying the W2G plants in DK under both scenarios S1 and S2 are illustrated in Figure 23 (for the EFG-based plants) and Figure 24 (for the FICFB-based plants), which show the configuration of raw biomass suppliers, treated biomass transportation among various suppliers, pre-treatment sites, and plant locations. The key information observed from the supply chain optimized for the DK-DK1 has been the same as the supply chain designed for the IT-SUD and will not be repeated here. **The potential sites for deploying EFG-based W2G plants in DK include:**

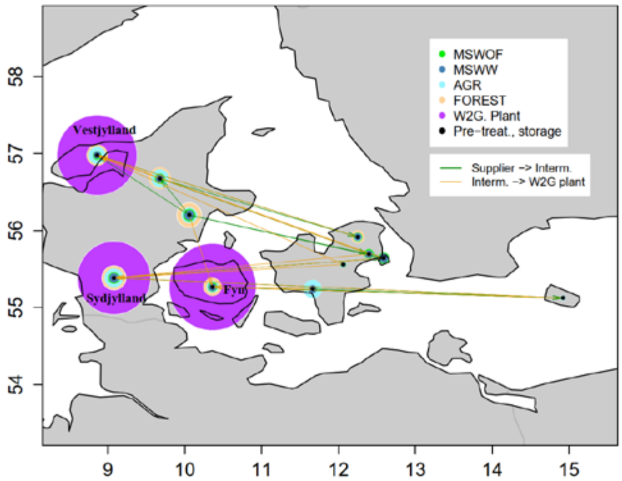
- **Potential locations if deploying 1 plant: Nordjylland in scenario S1 and S2;**
- **Potential locations if deploying 3 plants: Vestjylland, Sydjylland and Fyn in scenario S1; Vestjylland, Ostjylland and Sydjylland in scenario S2;**
- **Potential locations if deploying 5 plants: Nordjylland, Vestjylland, Sydjylland and Fyn (with 2 plants) in scenario S1; Nordjylland (with 2 plants), Vestjylland, Ostjylland and Fyn in scenario S2;**
- **Potential locations if deploying 7 plants: Nordjylland, Vestjylland, Ostjylland, Sydjylland and Fyn (with 3 plants); Nordjylland (with 3 plants), Ostjylland, Sydjylland, and Fyn (with 2 plants) in scenario S2.**



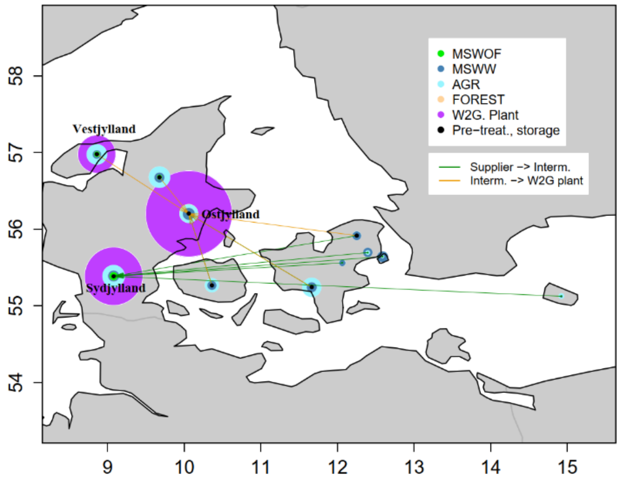
(a) S1: 1 plant



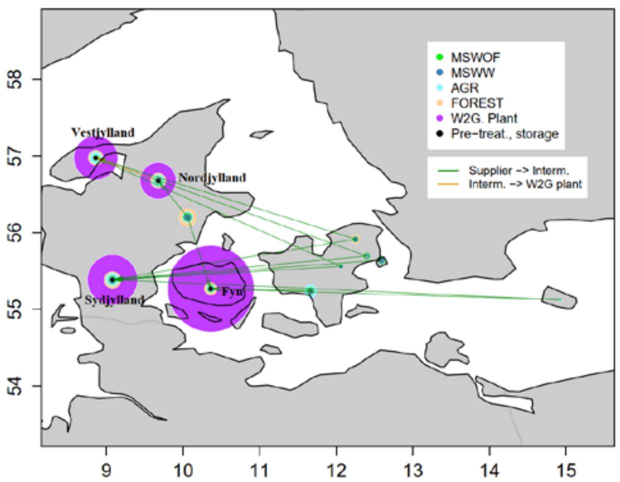
(b) S2: 1 plant



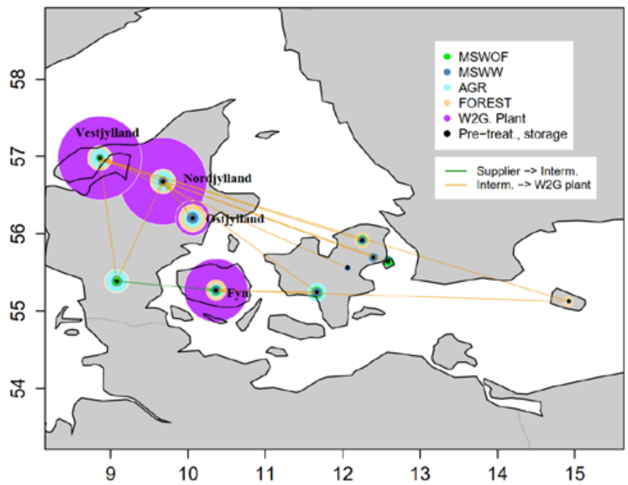
(c) S1: 3 plants



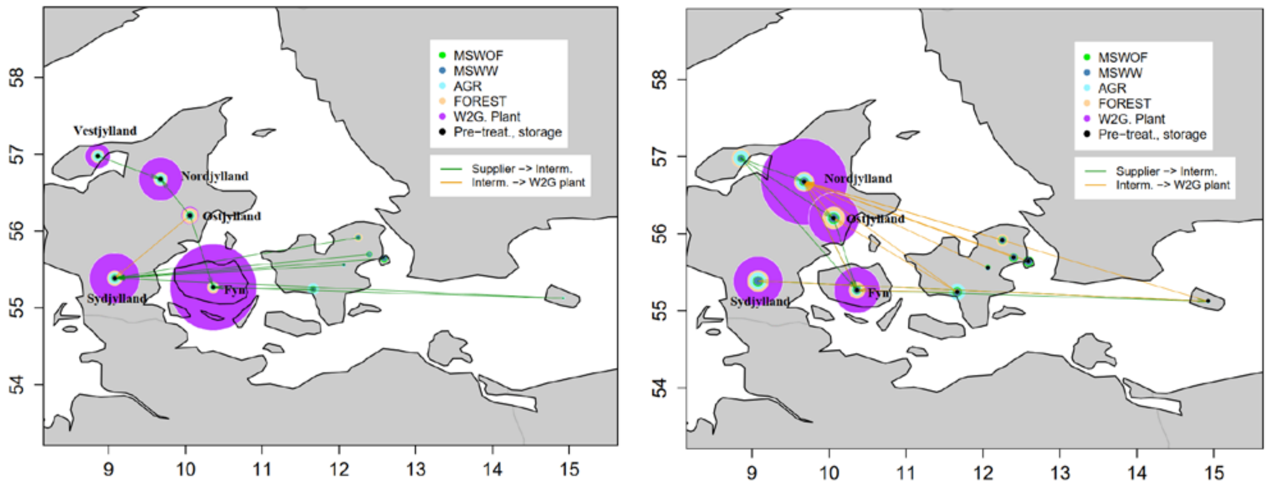
(d) S2: 3 plants



(e) S1: 5 plants



(f) S2: 5 plants



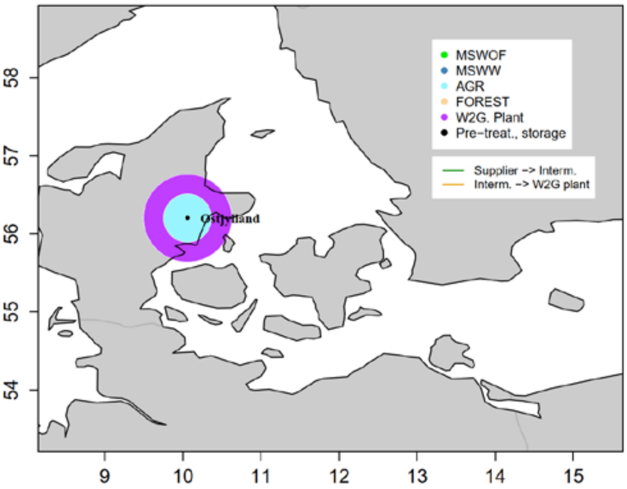
(g) S1: 7 plants (h) S2: 7 plants

Figure 23 The biomass supply chain for deploying EFG-based W2G plants in DK-DK1.

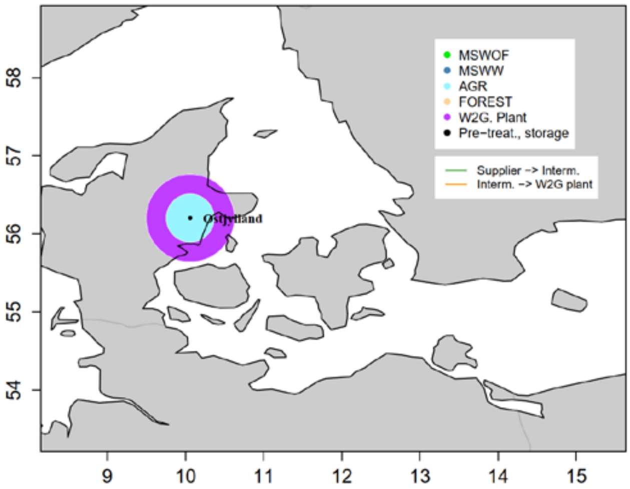
Note that when deploying larger EFG-based W2G plants, there is a lot of biomass imported from the right bottom position (i.e., Bornholm), which is assumed as a fictitious biomass source supplied by other countries or regions.

The biomass supply chain for deploying the FICFB-based W2G plants in DK-DK1 has been illustrated in Figure 24. The key information observed from the supply chain optimized for the DK-DK1 has been the same as the supply chain designed for the IT-SUD and will not be repeated here. **The potential sites for deploying FICFB-based W2G plants for DK include:**

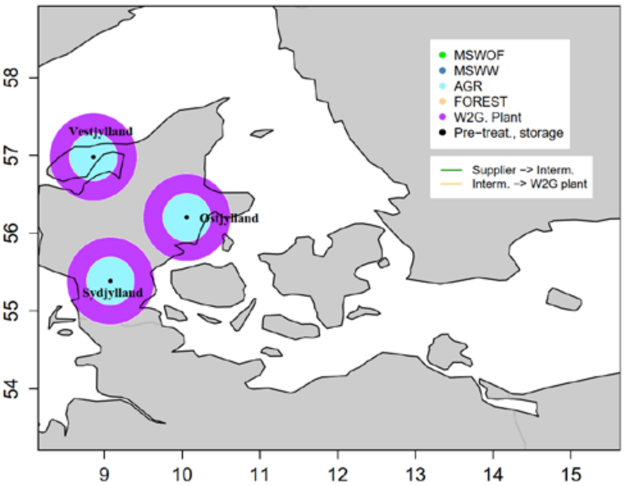
- **Potential locations if deploying 1 plant: Ostjylland in scenario S1 and S2;**
- **Potential locations if deploying 3 plants: Vestjylland, Ostjylland, and Sydjylland in scenario S1; Nordjylland, Vestjylland and Ostjylland in scenario S2;**
- **Potential locations if deploying 5 plants: Nordjylland (with 2 plants), Ostjylland, and Sydjylland (with 2 plants) in scenario S1; Nordjylland (with 2 plants), Vestjylland, Ostjylland and Sydjylland in scenario S2;**
- **Potential locations if deploying 7 plants: Nordjylland (with 2 plants), Vestjylland, Ostjylland, Sydjylland (with 2 plants) and Fyn in scenario S1; Nordjylland (with 2 plants), Vestjylland, Sydjylland (with 2 plants) and Fyn (with 2 plants) in scenario S2.**



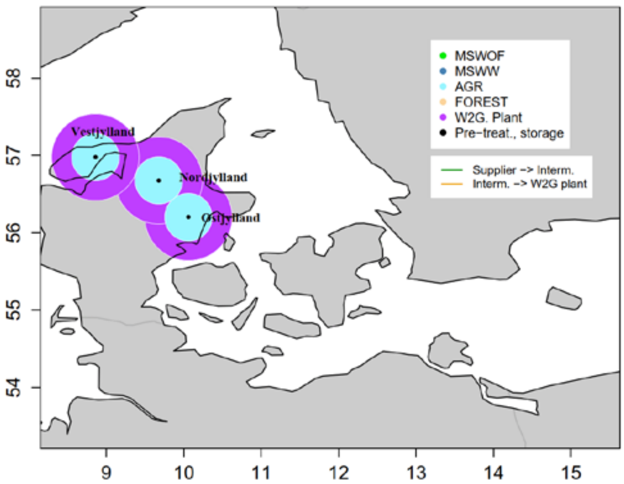
(a) S1: 1 plant



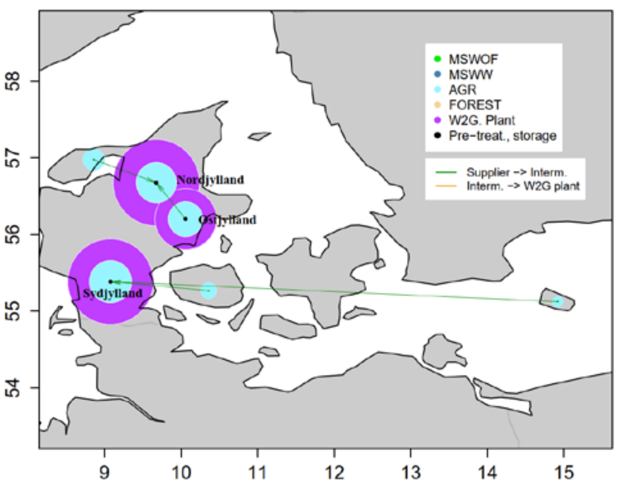
(b) S2: 1 plant



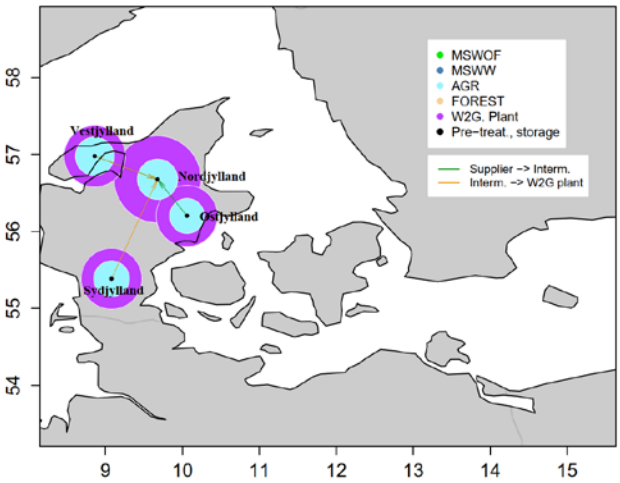
(c) S1: 3 plants



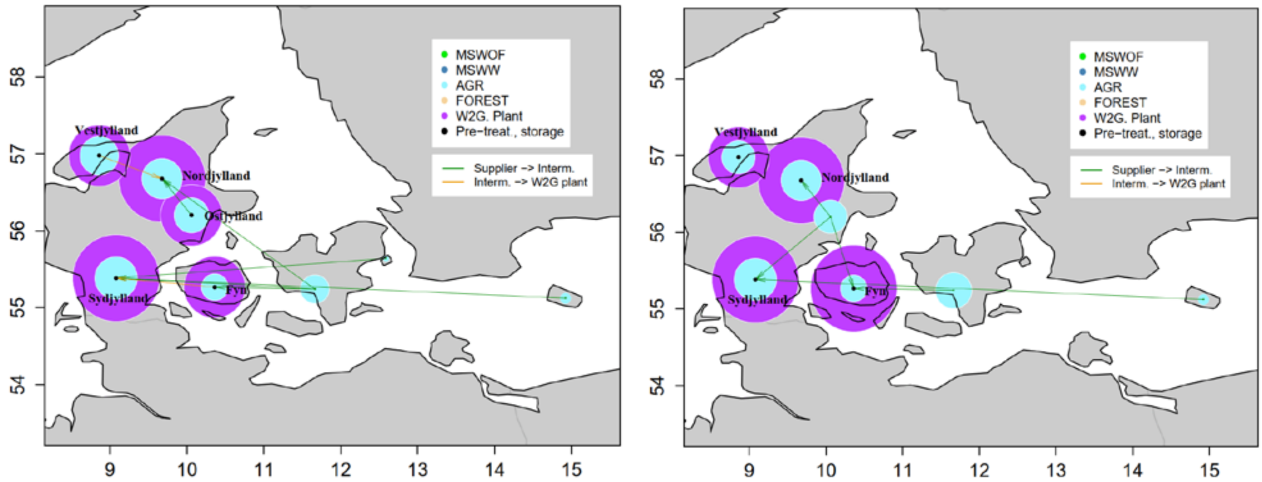
(d) S2: 3 plants



(e) S1: 5 plants



(f) S2: 5 plants



(g) S1: 7 plants (h) S2: 7 plants

Figure 24 The biomass supply chain for deploying the FICFB-based W2G plants in DK-DK1.

The practical deployment of W2G plants and the selection of plant locations are more complicated; thus, three suboptimal solutions for each case are also obtained providing a set of additional alternatives for biomass supply. For DK, the costs of suboptimal biomass supply are close to the optimal one, e.g., the four (sub-)optimal biomass supply chains vary in the range of 1444–1451 M€ when deploying 7 plants of EFG-based plants.

A detailed cost breakdown is given in Figure 25 (EFG-based plants) and Figure 26 (FICFB-based plants) and shows that **the purchase costs of raw materials are the largest contributor, while the indirect cost is ignorable**. For deploying only one EFG-based plant under scenario S1, direct cost including raw materials purchase cost, biomass transportation and production cost accounts for most of the overall cost. When deploying more than 3 W2G plants, the cost breakdown presents similar trends with the 3 W2G plants. The cost breakdown of the biomass supply chain for the EFG-based plants under S2 also shows a similar observation as EFG-S1. Figure 26 shows the breakdown of the biomass supply chain for the FICFB-based W2G plants, presenting a similar cost distribution among various contributors in the optimal or near-optimal solutions with Figure 25: the raw material purchase cost is part of the overall cost while the indirect cost is ignorable.

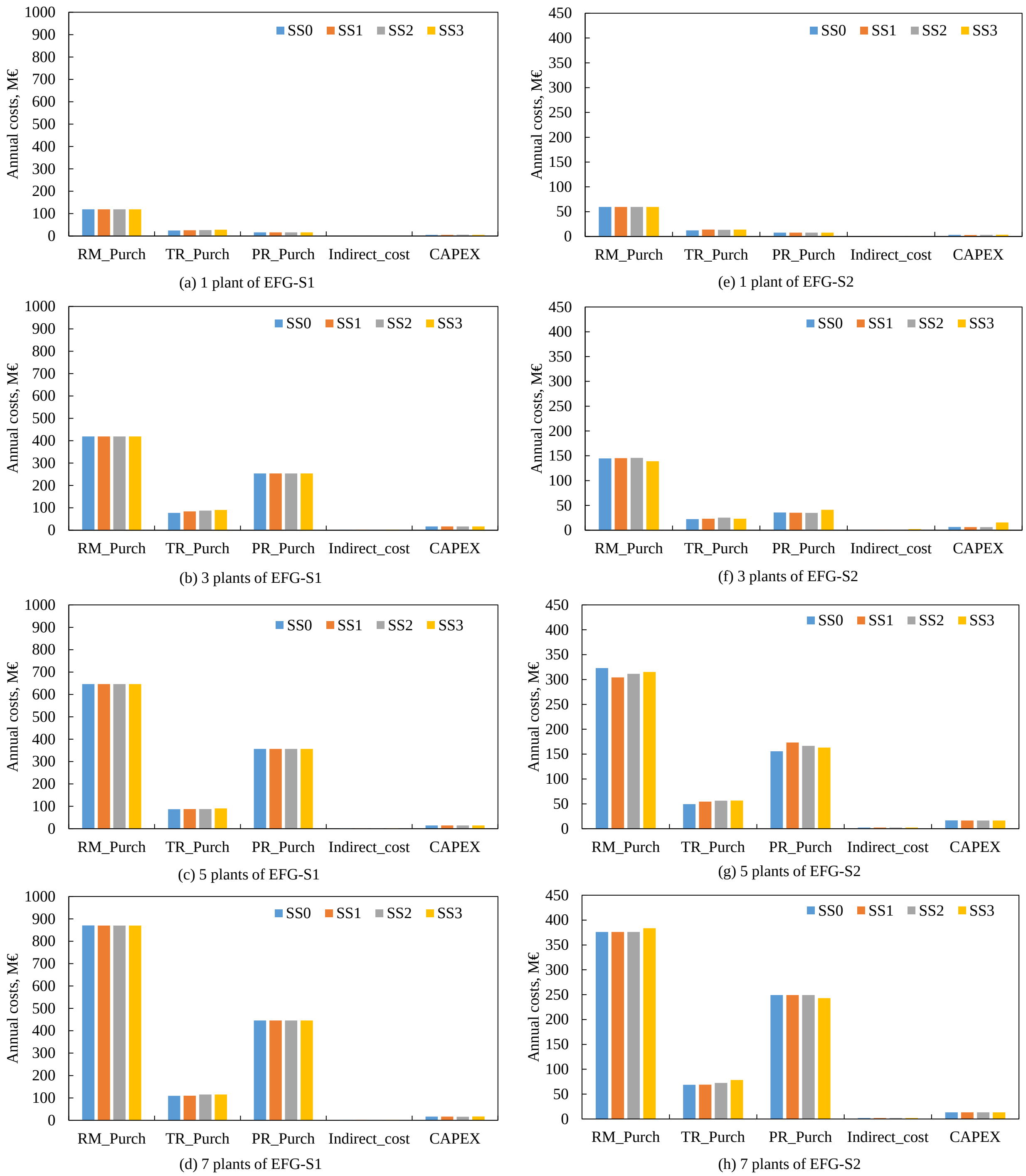
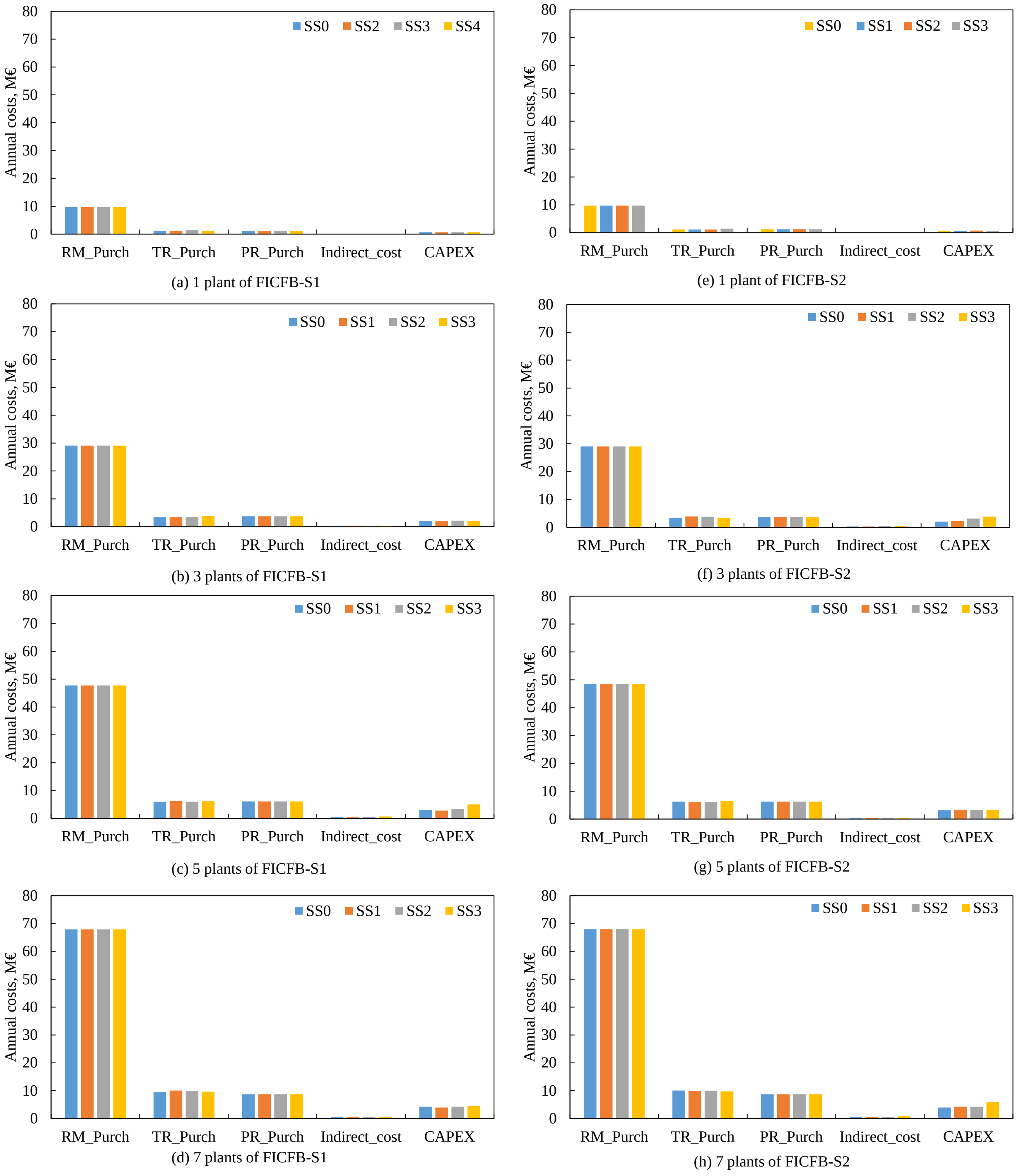


Figure 25 Cost breakdown of biomass supply chain for EFG-based W2G plants under scenario S1 and S2.



(a) 1 plant of FICFB-S1

(e) 1 plant of FICFB-S2

(b) 3 plants of FICFB-S1

(f) 3 plants of FICFB-S2

(c) 5 plants of FICFB-S1

(g) 5 plants of FICFB-S2

(d) 7 plants of FICFB-S1

(h) 7 plants of FICFB-S2

Figure 26 Cost breakdown of biomass supply chain for FICFB-based W2G plants under scenario S1 and S2.

8.5.4 Specific supply chain costs versus plant sizes

For normal biomass plants, the plant capacity is limited by the biomass supply radius. Increasing the plant capacity, the specific costs of biomass supply will also increase, which is the major reason for the reduced economics of larger biomass plants. The effect of biomass supply radius on the economics of W2G plants is also elaborated in Figure 27.

- **For IT-SUD and DK-DK1 cases, when the plant capacity lower than 400 MW_{th}, the specific supply chain costs stay at a level of 15 €/MWh**. The biomass requirements of the W2G plant can be satisfied by the agricultural biomass in the centralized area.
- **With the increase in plant capacity (from 400 to 1870 MW_{th}), the specific supply chain costs increase from 15 €/MWh to 39 €/MWh.** Such a big increase results from the inferior MSW and forest biomass utilization, much larger production costs for drying, and larger transportation supply networks. Thus, super-huge W2G plants are not economically-feasible.

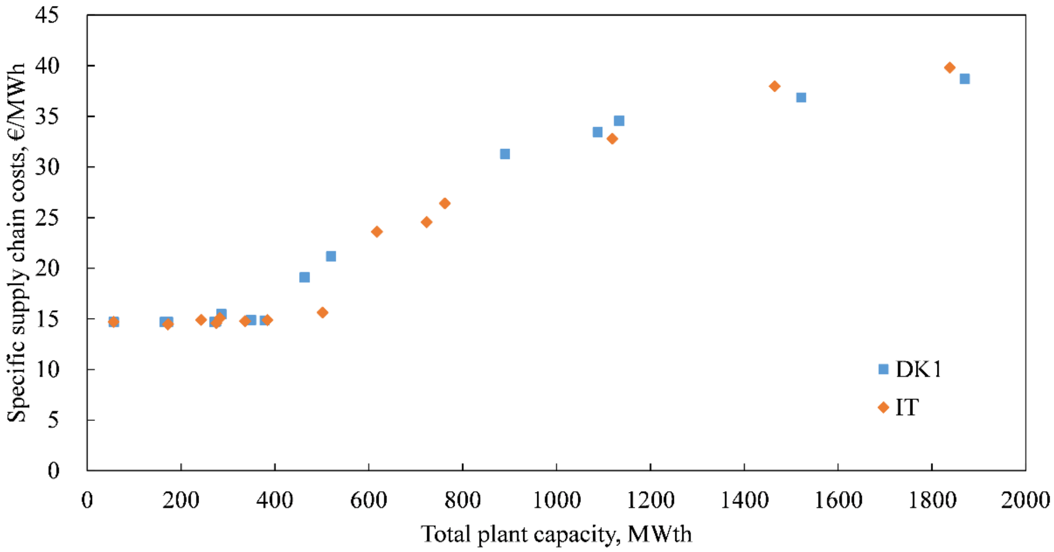


Figure 27 The specific supply chain costs versus total plant capacity.

8.5.5 Supply chain costs versus profit

Biomass energy is needed for all three modes of the W2G plants. However, only operations on PowGen and PowSto modes contribute to the revenue from grid balancing service. Thus, the utilization hours of the PowNeu mode mainly reflect the proportions of supply chain cost on profit under different scenarios, plant technology combination, and capacity factors. The ratio of biomass supply cost and the profit is given in Figure 28 for all calculations.

- **Using FICFB technology, the biomass supply chain costs are in 10–50% of the profits.** The proportion of supply chain cost on profit increases within the increase in plant capacity factor, mainly due to the PowNeu utilization hours.
- **Using EFG technology, the annual biomass energy needs are sharply increased to 5–37 TWh/year due to the large plant capacities, costing 80–1400 M€/year. Such big biomass supply chain costs make the EFG-based W2G plants hardly economically-feasible, i.e., the plant CAPEX targets below zero (Figure 28).** High PowNeu utilization hour of plants with EFG is another influencing factor.

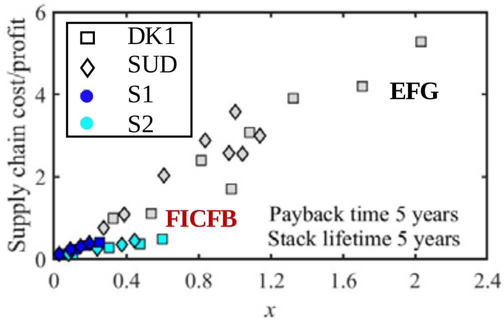


Figure 28 The proportion of biomass supply cost on profit, with FICFB technology highlighted.

8.6 Sensitivity analysis

8.6.1 Regulating price and payback time

The plant CAPEX target is evaluated with regulating price 20–80 €/MWh and payback time 1–4 years as shown in Figure 29 for the case S1-DK1. In general, the plant CAPEX target will be decreased at lower regulating prices or to reach a shorter payback time, indicating the strong need for reducing system CAPEX for high economic feasibility. The plant CAPEX target may reach 8600 €/ref-stack with 5 payback years, if the regulating price is up to 80 €/MWh. While, if the regulating price is down to 20 €/MWh, the plant CAPEX target should be lower than 700 €/ref-stack to have the chance of being profitable for a 1-year payback time.

The plant CAPEX target evaluated with a payback time of 1–4 years is affected by the oxygen tank costs incurred at the first year and the sum of the revenue from providing grid balancing service occurring before reaching the set payback year. Under 20 €/MWh grid balancing price, the plant CAPEX targets are reduced from 3300 €/ref-stack for a payback time of 5 years to 1400 €/ref-stack for a payback time of 3 years.

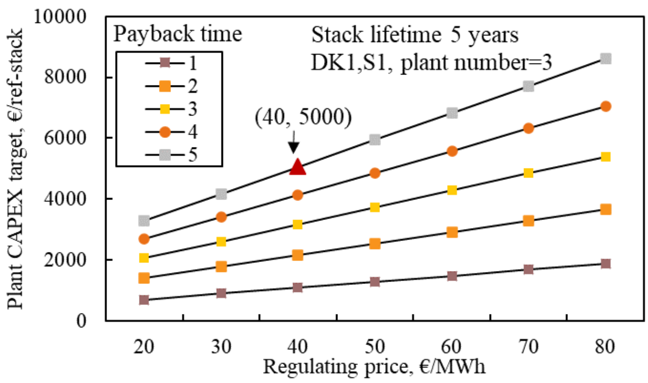
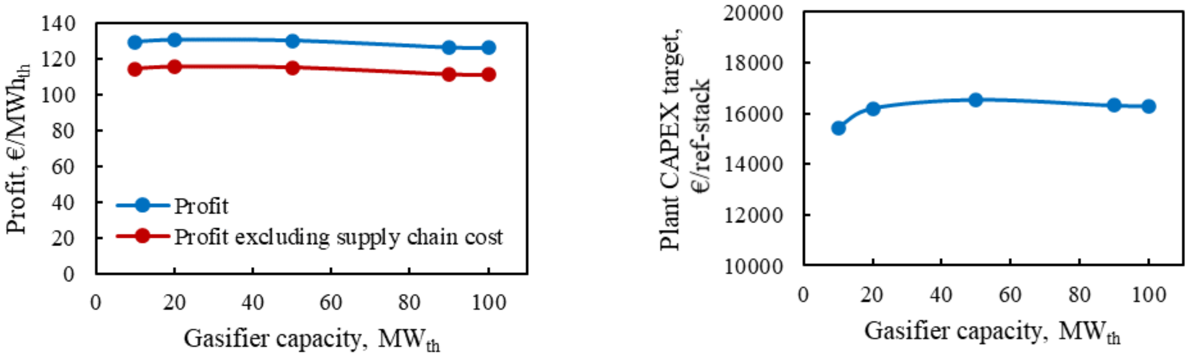


Figure 29 Plant CAPEX target under different payback time and regulating price for the case S1-DK1.

8.6.2 The pre-set capacity range of biomass gasification technology

Triple-mode RSOC plants have the highest plant CAPEX target when their contribution to the flexibility needs remains at a relatively low level so that the annual utilization hours of the PowGen and PowSto modes are maximized for the grid-balancing profits (Figure 11). In this case, the W2G plants deployed can operate with the same strategy and there is no coordination among plants. The total plant capacities will reach the maximum of the capacity range, i.e., 100 MW_{th} of the FICFB technology. Figure 30 explores whether this upper-bound of the FICFB gasifier size could affect the economic feasibility of such W2G plants.



(a) Profit, € /MWh$_{th}$

(b) Plant CAPEX target, € /ref-stack

Figure 30 The profit and plant CAPEX target of W2G plants using FICFB for S1-DK1 with one W2G plant deployed.

The maximum profit obtained from 1 MWh$_{th}$ biomass remains nearly 130 € /MWh$_{th}$ under gasifier capacity 10–100 MW$_{th}$ as shown in Figure 30a, The almost unchanged profit as increasing biomass capacity illustrates that the PowNeu mode utilization hours have no obvious increase when increasing plant capacities if employing a single plant, due to the low power capacities limited by FICFB gasifier sizes. The net profits, which exclude the supply chain costs from the profits under different plant capacities. For the increase in plant capacity from 10 to 100 MW$_{th}$, the net profits are almost unchanged of 110 €/MWh$_{th}$, compared to the grid-balancing profit 130 €/MWh$_{th}$, due to the increase in the costs of the biomass supply chain.

Although the profit increases with the increasing gasifier capacity, the plant CAPEX targets remain nearly constant at around 16000 €/ref-stack (Figure 30b).

8.7 Chemical sale

As introduced in section 5, there are chemicals generated from biomass via grid-balancing plants under PowSto and PowNeu modes. The final chemical product is assumed to be SNG, which can be injected into the gas transmission network for additional revenue. The SNG price is set as 0.8 €/kg, and the plant CAPEX targets under different capacity factors and scenarios for DK-DK1 and IT-SUD are shown in Figure 31. The key qualitative observations are:

- **Plant CAPEX target is further increased significantly considering the revenue from SNG sale.**
- The FICFB option achieves a higher plant CAPEX target than the EFG option under the same scenario. The plant CAPEX target is in 8000–22000 €/ref-stack for the FICFB option and is limited to 12000 €/ref-stack for the EFG option, which can even be down to 3000 €/ref-stack in IT-SUD under scenario S1.
- From the plant capacity viewpoint, the plant CAPEX target also decreases as the increase of plant capacities.
- There is still no big difference in the plant CAPEX target among different areas and different scaling factors of flexibility need when using the same gasifier type and plant number.

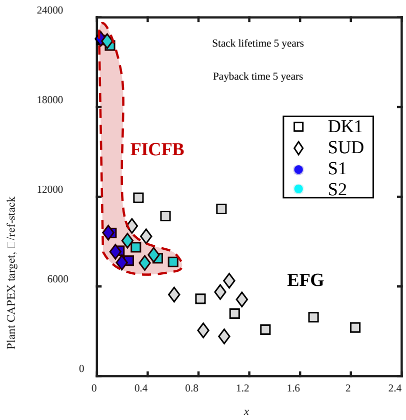


Figure 31 Plant CAPEX target considering the revenue from chemical sale to market

9 Summary and conclusions

This deliverable is one of the key deliverables of the project, in which the overall decomposition-based optimization methodology for evaluating the economic feasibility of the W2G plants is implemented. Based on the D1.1, D1.2 and D2.1, the flexibility needs, waste availability and plant design pool are fed into the optimal plant selection, sizing and scheduling to maximize the profits from the grid-balancing services, and the waste supply chain optimization to evaluate the biomass supply costs and finally the plant CAPEX target.

The key conclusions are

- The FICFB-based W2G plant concept is potentially to be with high economic feasibility with a plant CAPEX target up to 17000 €/ref-stack for a five-year payback time, 5-year stack lifetime and 40 €/MWh balancing energy price. Increasing the balancing energy price and counting the profit from chemical scale, e.g., the profit of grid integration, the plant CAPEX target can even reach 22000 €/ref-stack. We believe this suggests sound business cases.
- The economic feasibility is affected by their contribution to addressing the targeted flexibility needs. The higher the contribution, the more capacities deployed will be coordinated to operate under PowNeu mode. The increased annual utilization hours of the PowNeu mode cause a decrease in plant CAPEX target.
- There is no big difference in plant CAPEX target among different zones (DK-DK1 or IT-SUD) and the magnitudes of the flexibility needs.
- The costs of the biomass supply chain play an important role in deciding the plant CAPEX target. For large W2G plants in the range of 100-1000 MW_{th}, the biomass supply chain costs even much more than the gain from the grid-balancing profits, thus very large plants can hardly be economically feasible.

The cases listed in the table below will be taken as the case studies to be further investigated. It should be noted that this deliverable has not involved a detailed calculation of the plant CAPEX based on the process flow diagram and the component sizes of each plant deployed. This will be further done in D3.3 to eventually concludes specific business cases with the overall plant profit calculated.

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

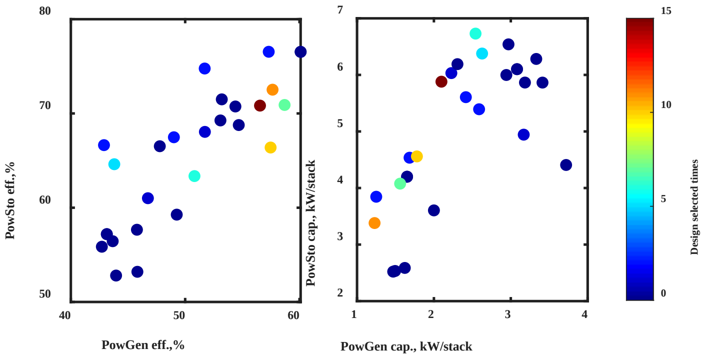
IT-SUD-S2-EFG-P5					Puglia	112	30322	49	132	44	68.19
					Bari	236	49492	110	304	46.60	63.92
					Lamezia Terme	508	105500	237	697	46.57	62.22
					Avellino	566	112992	262	756	46.28	63
DK-DK1-S1-EFG-P7	-5241	3112	1.33	7	Nordjylland	630	129179	257	834	40.76	64.29
					Fyn	974	263513	428	1150	44	68.19
					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

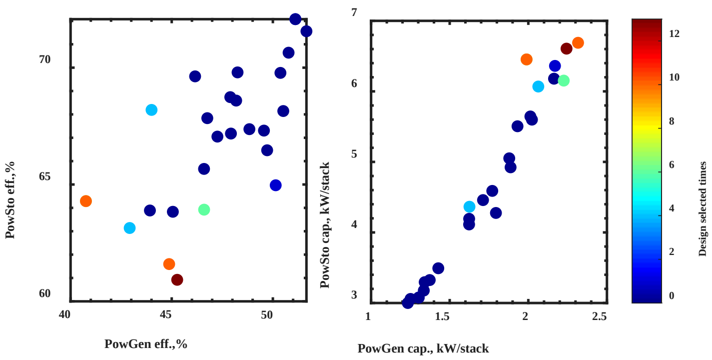
[a] The plant CAPEX target is based on 5-year payback time, 40 €/MWh balancing price and 5-year stack lifetime.
[b] The SNG selling price is considered to be 0.8 €/kg.

Supplementary materials

9.1 Design selection of plants using FICFB (10-100 MW_{th})



9.2 Design selection of plants using EFG (100–1000 MW_{th})



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