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of combining renewable electricity and gas
policies**

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Abstract

Energy system models are needed to help policy makers design renewable energy policies that combine support for renewable electricity with support for renewable gas. In this paper, we advance a stylized model that includes demand for electricity, heating, and hydrogen in industry that is supplied by competing technologies. We first show that the status quo in most countries, which is a combination of carbon pricing with support for renewable electricity, only supports green gases indirectly and in a limited way. When we then add direct support for renewable gas to the model, we have two main findings. First, a Renewable Energy Sources - Gas (RES-G)¹ target is more effective in supporting biomethane than in supporting green hydrogen. Second, there are strong interaction effects between a RES-E target and a RES-G target that can be both complementary and substitutive.

Keywords

Renewable energy policies; renewable gas; policy interaction effects; sector coupling.

¹ Renewable Energy Sources – Electricity or Gas (RES-E, RES-G)

1. Introduction*

The decarbonization of the energy sector has so far mainly been about integrating wind and solar power into the electricity system. This transition has been enabled by carbon pricing in combination with direct support for these renewable electricity technologies. The issue that is currently debated is whether the policies that have been successful at bringing down the costs for renewable electricity can be replicated for renewable gas, i.e., hydrogen and biomethane. With the recent hydrogen strategies released by the European Commission and some member states (MSs), the European Union (EU) aims for 40 GW of electrolyzers domestically by 2030, however this ambition has yet to be translated into specific support schemes (European Commission, 2020). Only some MSs have specific targets concerning biomethane, although many have support schemes (Regatrace, 2020). For example, France aims for 10% of gas consumption to be supplied by biomethane in 2030. The support of biomethane may be limited by a link to its end-use consumption. For example, biomethane is supported in Germany when designated for electricity generation and in Italy for transport (IFRI Centre for Energy, 2019). With the upcoming revision of the EU renewable energy directive, some stakeholders have advocated for a gas target to support low-carbon and or green gas technologies. If the recent experience in the electricity sector is regarded as largely successful in deploying renewable electricity generation technologies, then such a policy tool may have provided some inspiration for a gas target. Alongside this debate, Pototschnig and Conti (2021) propose guarantees of origin as one mechanism to promote decarbonized and renewable gases at the EU level.

In this paper, we advance an energy system model to help policy makers design renewable energy policies that combine support for renewable electricity with support for renewable gas. Our stylized model includes demand for electricity, heating, and hydrogen in industry that is supplied by competing technologies. The model has been inspired by a few recent publications that are available with numerical energy system model simulations (Härtel and Korpås, 2021; Koirala et al., 2021; Li and Mulder, 2021; Roach and Meeus, 2020; Schlund and Schöfnisch, 2021). These authors however did not yet study the impact of combined renewable electricity and gas policies, which is the focus of our paper. Schlund and Schöfnisch (2021) did study the impact of a green hydrogen quota on the deployment of electrolyzers and how that changes electricity and gas market prices and welfare. In our model, renewable gas policies can support the investment in electrolyzers to produce green hydrogen as well as the investment in biomethane production which is subsequently injected into the gas network.

The policy contributions of this paper are twofold. Many countries are considering introducing a renewable gas policy or increasing the ambition of the policy that is already in place. Such a policy typically consists of a target in combination with direct support to achieve the target. We aim to answer two research questions. First, how effective is a renewable gas (RES-G) target in supporting renewable gas? Second, are interaction effects between a RES-E and RES-G target relevant in a cross-sector energy market setting and are they substitutive or complementary policies. We first model the status quo in most countries, which is a combination of carbon pricing with support for renewable electricity, and then add direct support for renewable gas to the model. Others have discussed the effects of combining carbon pricing policies (to address the negative externality of carbon emissions) and RES-E policies (to address the positive externality of technology learning or other market failures) (Amundsen and Bye, 2018; Böhringer, and Rosendahl, 2011; De Jonghe et al., 2009; del Río

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González, 2008; Lecuyer and Quirion, 2013; Newbery, 2018; Weigt et al., 2013), but a study has not yet been done for combined RES-E and RES-G policies. As the energy system is becoming increasingly integrated and the number of policy instruments is increasing, we expected to find significant interaction effects. This is confirmed by the results we present in this paper. Policy makers therefore need to be aware of these effects when they design their policies to avoid surprises regarding the costs of the policies and/or the effectiveness of these policies in supporting renewable gas technologies.

The paper is structured in 4 sections. Section 2 summarizes our stylized modelling approach and details the mathematical formulation. Section 3 presents the assumptions underpinning a numerical example and discusses the results of model solutions. Section 4 acknowledges the modelling limitations and summarizes the main conclusions. Table 1 summarizes the literature we referred to in this introduction. As can be seen from the table, previous publications that addressed energy policy interactions, did so with a modelling scope that was limited to the electricity sector, while the more recent studies with a broader modelling scope did not yet focus on policy interactions, which is the contribution of this paper. The contribution is timely because many countries in Europe are reconsidering their policies for renewable gas triggered by the EU Green Deal reforms.

Table 1: Literature overview

| | model scope² | policy instruments³ | includes renewable gas | interactions between policies |
|-------------------------------|--------------------------------|---------------------------------------|-------------------------------|--------------------------------------|
| del Río González (2008) | E | RES-E & CO2 | | X |
| Newbery (2018) | E | RES-E & CO2 | | X |
| De Jonghe et al. (2009) | E | RES-E & CO2 | | X |
| Lecuyer and Quirion (2013) | E | RES-E & CO2 | | X |
| Weigt et al. (2013) | E | RES-E & CO2 | | X |
| Amundsen and Bye (2018) | E | RES-E & CO2 & EE | | X |
| Koirala et al. (2021) | ES | | X | |
| Härtel and Korpås, (2021) | ES | CO2 | X | |
| Schlund and Schönfisch (2021) | ES | RES-H2 | X | |
| Li and Mulder, (2021) | ES | | X | |
| Roach and Meeus (2020) | ES | RES-E | X | |
| contribution of this paper | ES | RES-E & RES-G, CO2 | X | X |

² Abbreviations: Electricity (E); Energy System (ES)

³ Abbreviations: Energy Efficiency (EE); Hydrogen (H2)

2. Methodology

Nomenclature

Sets

| | |
|---------------------------|---|
| $t \in T$ | Set of time periods |
| $e \in E$ | Set of energy technologies |
| $v \in V \subseteq E$ | Set of conventional technologies |
| $r \in R \subseteq E$ | Set of renewable technologies |
| $b \in B \subseteq R$ | Set of biomethane production technologies |
| $ng \in NG \subseteq V$ | Set of natural gas shippers |
| $rg \in RG \subseteq R$ | Set of renewable generators |
| $gg \in GG \subseteq V$ | Set of gas generators |
| $pth \in PTH \subseteq R$ | Set of electrolysis-based power-to-hydrogen production technologies |
| $gh \in GH \subseteq V$ | Set of gas-based hydrogen production technologies |
| $c \in C$ | Set of heat consumers |
| $hp \in HP \subseteq R$ | Set of heat pump technologies |
| $gb \in GB \subseteq V$ | Set of gas boiler technologies |

Parameters

| | |
|----------------------|---|
| H_t | Weight of each time period |
| I_e | Equivalent annualized cost of energy technology e , €/MW. |
| V_e | Variable cost of energy technology e , €/MWh. |
| η_e | Efficiency of energy technology e , % |
| $\gamma_{hp,t}$ | Efficiency of heat pump technology hp in period t , % |
| α | Efficiency of hydrogen storage injection and withdrawal, % |
| EMF | Emission Factor of natural gas, tCO ₂ /MWh |
| E, G | Target share of renewable energy sources based on electricity and gas formulations, % |
| GGs | Gas Generation Share for iterative loop, % |
| R | Available CO ₂ emissions allowances, tCO ₂ |
| CO ₂ P | Exogenous emission allowance price, €/tCO ₂ |
| $AV_{rg,t}$ | Availability of renewable generator rg in period t |
| D_t^{EL}, D_t^{HY} | Hourly aggregate electricity EL and hydrogen HY demand in period t , MWh |
| $D_{c,t}^{HE}$ | Hourly heat HE demand of consumer c in period t , MWh |

Variables

| | |
|------------------------|--|
| cp_b | Installed capacity of biomethane producer b , MW. |
| $q_{b,t}, q_{ng,t}$ | Output energy of biomethane producer b and natural gas shipper ng , MWh. |
| cp_{gg}, cp_{gh} | Installed capacity of gas generator gg and gas-based hydrogen producer gh MW. |
| $cp_{c,gb}$ | Installed capacity of gas boiler technology gb by heating consumer c , MW. |
| $q_{gg,t}, q_{gh,t}$ | Natural gas-sourced input energy of gas generator gg and hydrogen producer gh in period t , MWh. |
| $q_{c,gb,t}$ | Natural gas-sourced input energy of gas boiler technology gb by heat consumer c in period t , MWh. |
| $qb_{gg,t}, qb_{gh,t}$ | Biomethane-sourced input energy of gas generator gg and hydrogen producer gh in period t , MWh. |
| $qb_{c,gb,t}$ | Biomethane-sourced input energy of gas boiler gb by heat consumer c in period t , MWh. |

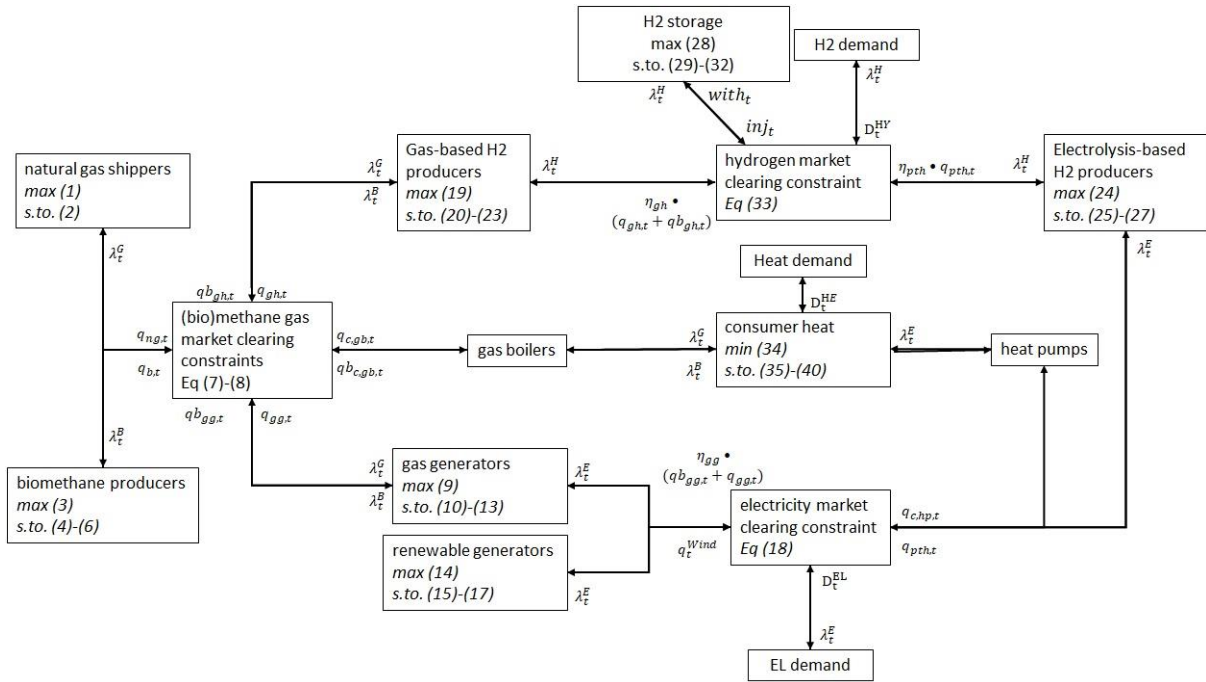
| | |
|--|---|
| cp_{rg} | Installed capacity of renewable generator rg , MW. |
| $q_{rg,t}$ | Output energy of renewable generator rg , MWh. |
| cp_{eh} | Installed capacity of electrolysis hydrogen producer eh , MW. |
| $q_{pth,t}$ | Input energy of electrolysis hydrogen producer pth , MWh. |
| $cp_{c,hp}$ | Installed capacity of heat pump technology hp by consumer c , MW. |
| $q_{c,hp,t}$ | Input energy of heat pump technology hp by heat consumer c , MWh. |
| c_{psp} | Injection and withdrawal capacity of hydrogen storage, MW |
| c_{pse} | Energy capacity of hydrogen storage |
| es_t | Storage capacity of hydrogen storage, MWh |
| inj_t | Injection into hydrogen storage in period t , MWh |
| $with_t$ | Withdrawal from hydrogen storage in period t , MWh |
| $\lambda_t^E, \lambda_t^G, \lambda_t^H, \lambda_t^B$ | Dual variable of energy market clearing condition and market price in period t , €/MWh |
| ζ^E, ζ^G | Dual variable of renewable energy market clearing condition and certificate price, €/MWh |
| μ^C | Dual variable of CO ₂ emissions market clearing condition and CO ₂ emission allowance price, €/tCO ₂ |

2.1 Modelling approach

We advance a stylized energy system model to simulate the long-run equilibrium of an integrated electricity, gas and hydrogen market which is constructed as a noncooperative game. We assume agents only respond to energy-only and renewable energy certificate (REC) or emission allowance market prices given complete information. The agents independently and simultaneously make both investment and production decisions in a single shot under the assumption of perfect competition. In this way, each agent decides its strategy in its set of strategies which maximizes its utility. The Nash Equilibrium is applied as a solution method to determine the strategy profile such that none of the agents has an incentive to deviate from its strategy given the strategies of other agents. We reformulate the problem as a mixed complementarity problem in Generalized Algebraic Modeling System (GAMS) and solve using PATH.

We define a set of agents which utilize technologies characterized as either renewable or conventional, as described in detail in section 2.2. Biomethane producers and natural gas shippers supply the gas market. Renewable generators and conventional gas generators serve an aggregate inelastic electricity demand. Electrolysis-based and gas-based hydrogen production serve an aggregate inelastic industrial hydrogen demand. Residential heating consumers meet their inelastic demand with gas boilers and heat pumps. A market operator simultaneously sets the prices in all markets, both for energy and renewable energy certificates, as well as for an emissions market in one of the policies considered, which is equivalently obtained using the dual variables of the market clearing conditions. A schematic overview depicting the model setup and referencing the agents' optimization problems to the mathematical formulation is presented in Figure 1.

Figure 1: Schematic overview of integrated market model, including references to optimization problems of the agents (cf. section 2.2)



A renewable energy or emissions policy is exogenously imposed on the model reflecting the choices of a policymaker agent. A RES target policy is a volumetric target stating the ambition of renewable energy deployment and is defined as a percentage of a sector's demand. It also specifies which renewable technologies are eligible or not for support. Given an RES target policy is represented as a Renewable Energy Certificate (REC) market, a REC is earned for each MWh of renewable energy generated or produced and can be retired to obtain supplemental revenue in the form of a feed-in premium. Two sets of renewable energy policies are considered, summarized in Table 2. The binary parameter B indicates which exogenous RES policy set is active and ζ is the certificate price for eligible technologies supported. The full description of the RES policies is described in section 2.2.5. The first policy set is a sector-specific RES-E target which supports renewable generators and biomethane designated for electricity generation. The second policy set is a dual RES-E and RES-G target, in which the latter supports biomethane and green hydrogen. Aside from renewable energy policies, an emissions reduction policy is also examined, which can be implemented either with an exogenous carbon price or an emissions market which is cross-sector covering all natural gas consumption.

Table 2: RES policies and eligible technologies for support

| Policies | No policy | RES-Electricity | RES-Electricity & RES-Gas | |
|-----------------------------------|-----------|-----------------|---------------------------|-----------|
| Binary parameter | | B^E | B^{EG} | |
| Renewable Generators | | ζ^E | ζ^E | |
| Biomethane-sourced gas generators | | ζ^E | | |
| Biomethane producers | | | | ζ^G |
| Electrolysis-based H2 producers | | | | ζ^G |
| Heat pumps | | | | |

The time horizon of the model is compressed into one year using the equivalent annualized cost of available technology data. The model is designed to have several representative days d to capture the seasonal and daily characteristics of demand, as well as the variability of renewable generators or heat pumps. However, shorthand the model is formulated with t periods. Each representative day consists of 24 periods, $24 \cdot d$ periods in total. A period t is weighted by $H_t = \frac{8760h}{24 \cdot d}$, which means that we assume each period t is repeated H_t times in a year. Decisions of agents and input data are based on an hourly resolution.

The agents, sectors, and pathways that we present are not exhaustive, but are intended to capture sector coupling aspects of renewable energy policies. Neither dynamic operational constraints nor network constraints are included in the model. In this model specification, we assume a greenfield investment such that no initial capacity installed.

2.2 Mathematical formulation

In this section, the optimization problems of all agents are presented. The KKT conditions are detailed in annex C.

2.2.1 Gas Market

2.2.1.1 Natural gas supplies

The upstream natural gas production activities, including investment and contracting are not represented in detail. Instead, we assume that gas shippers hold a portfolio of long-term contracts with a constant procurement variable cost V_{ng} and investment costs are sunk. Gas shippers (set NG) maximize profits in transporting quantities of natural gas $q_{ng,t}$ and in selling at the gas market price λ_t^G . The optimization problem of gas shippers is defined in equations (1)-(2) :

$$\text{Maximize } \sum_{t \in T} ((\lambda_t^G - V_{ng}) \cdot q_{ng,t} \cdot H_t) \quad (1)$$

Subject to

$$0 \leq q_{ng,t} ; \lambda_{ng,t}^2 \quad \forall ng \in NG, \forall t \in T \quad (2)$$

2.2.1.2 Biomethane producers

Biomethane producers (set B) provide a renewable alternative to conventional natural gas supplies. Biomethane may be produced directly in a thermal gasification process or upgraded from biogas following anaerobic digestion. Although biogas production also has the potential to be utilized for on-site power generation or on-site combined heat and power, we assume all biogas produced is upgraded and injected into the gas network. Biomethane producers must invest in the means of production cp_b and procure feedstocks to produce a quantity of biomethane $q_{b,t}$. The energy output $q_{b,t}$ of biomethane is constrained by the installed capacity cp_b . The feedstocks costs are approximated as a constant variable cost V_b . Biomethane producers are eligible for additional support ζ according to the implemented RES policy. The optimization problem of biomethane producers is defined as equations (3)-(5).

$$\begin{aligned} \text{Maximize} \quad & \sum_{t \in T} ((\lambda_t^B - V_b) \cdot q_{b,t} \cdot H_t) - I_b \cdot cp_b \\ & + \sum_{t \in T} H_t \cdot (B^E \cdot q_{b,t} \cdot \zeta^E \\ & + B^{EG} \cdot q_{b,t} \cdot \zeta^G) \end{aligned} \quad (3)$$

Subject to

$$0 \leq cp_b - q_{b,t} ; \lambda_{b,t}^4 \quad \forall b \in B, \forall t \in T \quad (4)$$

$$0 \leq q_{b,t} ; \lambda_{b,t}^5 \quad \forall b \in B, \forall t \in T \quad (5)$$

$$0 \leq cp_b ; \lambda_b^6 \quad \forall b \in B \quad (6)$$

2.2.1.3 Gas market clearing condition

The role of gas market operator is equivalently substituted with gas market clearing conditions, equation (7) and (8), where the dual variable is the gas market price λ_t^G for natural gas and λ_t^B for biomethane. Natural gas shippers supply the market to serve the demand from gas generators $q_{gg,t}$, gas-based hydrogen producers $q_{gh,t}$ and gas boilers for residential heating $q_{c,gb,t}$. In the same way, these gas consumers may source and purchase biomethane tracked via $qb_{gg,t}$, $qb_{gh,t}$, $qb_{c,gb,t}$. Given the emissions factor of methane in the gas network is not administratively adjusted as more biomethane is injected, this formulation allows the exemption of gas consumers from paying a CO₂ price when purchasing biomethane.

$$\sum_{ng \in NG} q_{ng,t} = \sum_{gg \in GG} q_{gg,t} + \sum_{gh \in GH} q_{gh,t} + \sum_{c \in C} \sum_{gb \in GB} q_{c,gb,t} ; \lambda_t^G \quad \forall t \in T \quad (7)$$

$$\sum_{b \in B} q_{b,t} = \sum_{gg \in GG} qb_{gg,t} + \sum_{gh \in GH} qb_{gh,t} + \sum_{c \in C} \sum_{gb \in GB} qb_{c,gb,t} ; \lambda_t^B \quad \forall t \in T \quad (8)$$

2.2.2 Electricity Market

2.2.2.1 Gas generators

Gas generators (set GG) maximize profits in transforming natural gas and biomethane into electricity as defined in equations (9)-(13). They purchase a quantity $q_{gg,t}$ of natural gas at price λ_t^G and $qb_{gg,t}$ of biomethane at price λ_t^B , convert it at a loss based on an energy conversion efficiency of η_{gg} and sell at price λ_t^E . Gas generators are subject to an exogenous or endogenous CO_2 price only for natural gas consumption $q_{gg,t}$. The energy output $(q_{gg,t} + qb_{gg,t}) \cdot \eta_{gg}$ is constrained by the installed capacity cp_{gg} .

$$\text{Maximize } \sum_{t \in T} \left(\left((-\lambda_t^G + \lambda_t^E \cdot \eta_{gg} - \text{EMF} \cdot \mu^C) \cdot q_{gg,t} + (-\lambda_t^G + \lambda_t^B \cdot \eta_{gg}) \cdot qb_{gg,t} \right) \cdot H_t \right) - I_{gg} \cdot cp_{gg} \quad (9)$$

Subject to

$$0 \leq cp_{gg} - (q_{gg,t} + qb_{gg,t}) \cdot \eta_{gg}; \lambda_{gg,t}^{10} \quad \forall gg \in GG \quad \forall t \in T \quad (10)$$

$$0 \leq q_{gg,t}; \lambda_{gg,t}^{11} \quad \forall gg \in GG \quad \forall t \in T \quad (11)$$

$$0 \leq qb_{gg,t}; \lambda_{gg,t}^{12} \quad \forall gg \in GG \quad \forall t \in T \quad (12)$$

$$0 \leq cp_{gg}; \lambda_{gg}^{13} \quad \forall gg \in GG \quad (13)$$

2.2.2.2 Renewable generators

Renewable generators (set RG) are constrained by the resource availability $AV_{rg,t}$ stated as a percentage of its installed capacity cp_{rg} in each period and they earn the electricity market price λ_t^E for the hourly generation $q_{rg,t}$, as described in equations (14)-(17). Renewable generators are eligible for additional support ζ according to the implemented RES policy.

$$\text{Maximize } \sum_{t \in T} (\lambda_t^E \cdot q_{rg,t} \cdot H_t) - I_{rg} \cdot cp_{rg} + \sum_{t \in T} H_t \cdot (B^E \cdot q_{rg,t} \cdot \zeta^E + B^{EG} \cdot q_{rg,t} \cdot \zeta^E) \quad (14)$$

Subject to

$$0 \leq cp_{rg} \cdot AV_{rg,t} - q_{rg,t}; \lambda_{rg,t}^{15} \quad \forall rg \in RG \quad \forall t \in T \quad (15)$$

$$0 \leq q_{rg,t}; \lambda_{rg,t}^{16} \quad \forall rg \in RG \quad \forall t \in T \quad (16)$$

$$0 \leq cp_{rg}; \lambda_{rg}^{17} \quad \forall rg \in RG \quad (17)$$

2.2.2.3 Electricity market clearing condition

The role of electricity market operator is equivalently substituted with an electricity market clearing condition, equation (18), where the dual variable is the electricity market price λ_t^E . Renewable generators and gas generators supply the market to serve the aggregate inelastic demand D_t^{EL} , electrolysis-based power-to-hydrogen producers $q_{pth,t}$ and heat pumps for residential heating consumers $q_{c,hp,t}$.

$$\begin{aligned} \sum_{rg \in RG} q_{rg,t} + \sum_{gg \in GG} (q_{gg,t} + qb_{gg,t}) \cdot \eta_{gg} \\ = D_t^{EL} + \sum_{pth \in PTH} q_{pth,t} + \sum_{c \in C} \sum_{hp \in HP} q_{c,hp,t} ; \lambda_t^E \quad \forall t \in T \end{aligned} \quad (18)$$

2.2.3 Hydrogen Market

2.2.3.1 Conventional Hydrogen producers

Gas-based hydrogen (set GH) producers maximize their profit in transforming natural gas and biomethane into hydrogen, as defined in equations (19)-(23). They purchase a quantity of natural gas $q_{gh,t}$ at price λ_t^G and biomethane $qb_{rg,t}$ at price λ_t^B , convert it as a loss based on an energy conversion efficiency of η_{gh} and sell at price λ_t^H . The energy output $(q_{gh,t} + qb_{gh,t}) \cdot \eta_{gh}$ is constrained by the installed capacity cp_{gh} . Conventional hydrogen producers are subject to an exogenous or endogenous CO₂ price only for natural gas consumption $q_{gh,t}$.

$$\begin{aligned} \text{Maximize} \quad \sum_{t \in T} \left(\left((-\lambda_t^G + \lambda_t^H \cdot \eta_{gh} - \text{EMF} \cdot \mu^C) \cdot q_{gh,t} + (-\lambda_t^B + \lambda_t^H \cdot \eta_{gh}) \cdot qb_{gh,t} \right) \right. \\ \left. \cdot H_t \right) - I_{gh} \cdot cp_{gh} \end{aligned} \quad (19)$$

Subject to

$$0 \leq cp_{gh} - (q_{gh,t} + qb_{gh,t}) \cdot \eta_{gh} ; \lambda_{gh,t}^{20} \quad \forall gh \in GH \quad \forall t \in T \quad (20)$$

$$0 \leq q_{gh,t} ; \lambda_{gh,t}^{21} \quad \forall gh \in GH \quad \forall t \in T \quad (21)$$

$$0 \leq qb_{gh,t} ; \lambda_{gh,t}^{22} \quad \forall gh \in GH \quad \forall t \in T \quad (22)$$

$$0 \leq cp_{gh} ; \lambda_{gh}^{23} \quad \forall gh \in GH \quad (23)$$

2.2.3.2 Electrolysis-based power-to-hydrogen producers

Electrolysis-based power-to-hydrogen (set PTH) producers can absorb otherwise spilled renewable generation or can source renewable electricity to produce green hydrogen. Power-to-hydrogen producers maximize profit in transforming electricity into hydrogen, as defined in equations (24)-(27). They purchase a quantity $q_{pth,t}$ at price λ_t^E , convert it as a loss based on an energy conversion efficiency of η_{pth} and sell at price λ_t^H . The electricity input $q_{pth,t}$ is constrained by the installed capacity cp_{pth} . In the case of a RES policy, B^{EG} , with dual RES-E and RES-G targets, the hydrogen producer pays the electricity price λ_t^E and electricity certificate price ζ^E for its electricity consumption but receives the hydrogen price λ_t^H and gas certificate price ζ^G for its hydrogen production. Based on this formulation, the power-to-

hydrogen producer must procure RES-E certificates to cover its annual electricity consumption to justify that the production is green hydrogen to be eligible to receive gas certificates.

$$\begin{aligned} \text{Maximize} \quad & \sum_{t \in T} \left((-\lambda_t^E + \lambda_t^H \cdot \eta_{pth}) \cdot q_{pth,t} \cdot H_t \right) - I_{pth} \cdot cp_{pth} \\ & + \sum_{t \in T} H_t \cdot (-B^{EG} \cdot q_{pth,t} \cdot \zeta^E + B^{EG} \cdot q_{pth,t} \cdot \eta_{pth} \cdot \zeta^G) \end{aligned} \quad (24)$$

Subject to

$$0 \leq cp_{pth} - q_{pth,t} \cdot \eta_{pth}; \lambda_{pth,t}^{25} \quad \forall pth \in PTH \quad \forall t \in T \quad (25)$$

$$0 \leq q_{pth,t}; \lambda_{pth,t}^{26} \quad \forall pth \in PTH \quad \forall t \in T \quad (26)$$

$$0 \leq cp_{pth}; \lambda_{pth}^{27} \quad \forall pth \in PTH \quad (27)$$

2.2.3.3 Hydrogen storage

A hydrogen storage operator is included to integrate potential variable hydrogen injections coming from power-to-hydrogen producers. This storage agent makes a profit in arbitraging across time periods and is constrained by the energy storage balance and its installed capacity cp_{sp} and cp_{se} , as defined in equations (28)-(32). We assume a storage efficiency factor α of for injecting and withdrawing, and no investment costs for simplicity.

$$\text{Maximize} \quad \sum_{t \in T} H_t \cdot (-\lambda_t^H \cdot inj_t + \lambda_t^H \cdot with_t) \quad (28)$$

Subject to

$$es_t - H_t \cdot inj_t \cdot \alpha + H_t \cdot \frac{with_t}{\alpha} - es_{t-1} = 0; \lambda_t^{29} \quad \forall t \in T \quad (29)$$

$$0 \leq cp_{sp} - inj_t; \lambda_t^{30} \quad \forall t \in T \quad (30)$$

$$0 \leq cp_{sp} - with_t; \lambda_t^{31} \quad \forall t \in T \quad (31)$$

$$0 \leq cp_{se} - es_t; \lambda_t^{32} \quad \forall t \in T \quad (32)$$

2.2.3.4 Hydrogen market clearing condition

The role of hydrogen market operator is equivalently substituted with a hydrogen market clearing condition, equation (33), where the dual variable is the hydrogen market price λ_t^H . Electrolysis-based and gas-based hydrogen producers serve the inelastic hydrogen demand D^{HY}_t or is temporarily stored.

$$\begin{aligned} & \sum_{gh \in GH} q_{gh,t} \cdot \eta_{gh} + \sum_{gh \in GH} qb_{gh,t} \cdot \eta_{gh} - \sum_{pth \in PTH} q_{pth,t} \cdot \eta_{pth} \\ & = D^{HY}_t - inj_t + with_t; \lambda_t^H \quad \forall t \in T \end{aligned} \quad (33)$$

2.2.4 Residential heating consumers

A residential heating consumer (set C) minimizes its costs in selecting from a mix of heat pumps (set HP) and gas boilers (set GB) to satisfy its heat demand $D_{c,t}^{HE}$, as described in equations (34)-(40). Given binary variables cannot be included in the model because they violate optimality conditions, we assume that a consumer can invest in a heat pump and gas boiler simultaneously to meet its demand. The efficiency of the heat pump $\gamma_{hp,t}$ varies per period t. The heat output from heat pumps $q_{c,hp,t} \cdot \gamma_{hp,t}$ and from gas boilers $(q_{c,gb,t} + qb_{c,gb,t}) \cdot \eta_{gb}$ are constrained by the installed capacity $cp_{c,hp}$ and $cp_{c,gb}$, respectively. Gas boilers are directly subject to an exogenous or endogenous CO₂ price only for their natural gas consumption $q_{c,gb,t}$.

$$\text{Minimize } \sum_{t \in T} H_t \cdot ((\lambda_t^E \cdot q_{c,hp,t}) + ((\lambda_t^G - \text{EMF} \cdot \mu^C) \cdot q_{c,gb,t}) + (\lambda_t^B \cdot qb_{c,gb,t})) + I_{hp} \cdot cp_{c,hp} + I_{gb} \cdot cp_{c,gb} \quad (34)$$

Subject to

$$0 \leq cp_{c,hp} - q_{c,hp,t} \cdot \gamma_{hp,t}; \lambda_{c,hp,t}^{35} \quad \forall c \in C \quad \forall hp \in HP \quad \forall t \in T \quad (35)$$

$$0 \leq cp_{c,gb} - (q_{c,gb,t} + qb_{c,gb,t}) \cdot \eta_{gb}; \lambda_{c,gb,t}^{36} \quad \forall c \in C \quad \forall gb \in GB \quad \forall t \in T \quad (36)$$

$$0 = q_{c,hp,t} \cdot \gamma_{hp,t} + (q_{c,gb,t} + qb_{c,gb,t}) \cdot \eta_{gb} - D_{c,t}^{HE}; \lambda_{c,t}^{37} \quad \forall c \in C \quad \forall t \in T \quad (37)$$

$$0 \leq q_{c,hp,t}; \lambda_{c,hp,t}^{38} \quad \forall c \in C \quad \forall hp \in HP \quad \forall t \in T \quad (38)$$

$$0 \leq q_{c,gb,t}; \lambda_{c,gb,t}^{39} \quad \forall c \in C \quad \forall gb \in GB \quad \forall t \in T \quad (39)$$

$$0 \leq qb_{c,gb,t}; \lambda_{c,gb,t}^{40} \quad \forall c \in C \quad \forall gb \in GB \quad \forall t \in T \quad (40)$$

2.2.5 Renewable energy certificate market clearing conditions

The approach to the RES target formulations assumes the renewable energy ambition E or G is stated as a percentage term, therefore how much renewable energy is required depends on a percentage of total demand and is not a fixed MWh quantity target. Each RES target is technology-neutral in terms of supporting the least cost means of achieving the target in terms of static efficiency. The allocation of policy costs to different agents is outside the scope of the model.

The first RES policy set, equation (41), consists of one sector-specific RES-E target in which only renewable generators and biomethane sourced in gas generation are eligible for support. Their combined production must be greater than the renewable energy ambition percentage E applied to the combined demand from aggregate, heat pumps, and electrolysis-based hydrogen.

$$\sum_{t \in T} H_t \cdot \left(\sum_{rg \in RG} q_{rg,t} + \sum_{gg \in GG} qb_{gg,t} \cdot \eta_{gg} \right) \geq \sum_{t \in T} H_t \cdot \left(\sum_{pth \in PTH} q_{pth,t} + E \cdot \left(D_t^{EL} + \sum_{c \in C} \sum_{hp \in HP} q_{c,hp,t} \right) \right); (\zeta^E) \quad (41)$$

The second RES policy set consists of a sector-specific RES-E target, equation (41), and a cross-sector RES-G target, equation (42). The RES-G target supports biomethane and green hydrogen. Their combined production must be greater than the renewable energy ambition percentage G applied to the combined natural gas $q_{ng,t}$ and biomethane $q_{b,t}$ demand from gas generators, gas-based hydrogen producers, and gas boilers, as well as hydrogen production from power-to-hydrogen $q_{pth,t} \cdot \eta_{pth}$.

$$\begin{aligned} \sum_{t \in T} H_t \cdot \left(\sum_{pth \in PTH} q_{pth,t} \cdot \eta_{pth} + \sum_{b \in B} q_{b,t} \right) &\geq \\ \sum_{t \in T} H_t \cdot G \cdot \left(\sum_{pth \in PTH} q_{pth,t} \cdot \eta_{pth} + \sum_{b \in B} q_{b,t} + \sum_{ng \in NG} q_{ng,t} \right) &; (\zeta^G) \end{aligned} \quad (42)$$

Given biomethane production $q_{b,t}$ is already subsidized by the RES-G target, all the biomethane production $q_{b,t}$ would be redirected to gas generation $q_{b,gg,t}$ to meet the RES-E target. Whereas the biomethane produced should be proportionally allocated to the share of gas generation in total gas demand. For this reason, the RES-E target equation (41) is replaced by equation (43). An iterative loop over the parameter Gas Generation Share (GGS) is carried out to determine how much biomethane used in gas generation can be counted towards the RES-E target. This loop is explained in more detail in Annex 0.

$$\begin{aligned} \sum_{t \in T} H_t \cdot \left(\sum_{rg \in RG} q_{rg,t} + \sum_{b \in B} q_{b,t} \cdot GGS \right) &\geq \\ \sum_{t \in T} H_t \cdot \left(\sum_{pth \in PTH} q_{pth,t} + E \cdot \left(D_t^{EL} + \sum_{c \in C} \sum_{hp \in HP} q_{c,hp,t} \right) \right) &; (\zeta^E) \end{aligned} \quad (43)$$

2.2.6 CO₂ emissions market clearing condition

The CO₂ emissions market is cross-sector covering natural gas consumption from electricity generation, hydrogen production and residential heating. A carbon emissions reduction policy which puts a price on carbon is endogenously formulated as a cap-and-trade CO₂ market in equation (44) and the dual variable is the annual emissions price μ^C . The emissions reductions ambition R is the total CO₂ emission allowances available. This emissions price can also be simply substituted by an exogenous price when implemented alongside a RES policy, such that μ^C is substituted by CO₂P.

$$R \geq \sum_{t \in T} H_t \cdot \left(EMF \cdot (q_{gg,t} + q_{gh,t} + \sum_{c \in C} q_{c,gb,t}) \right); (\mu^C) \quad (44)$$

3. Results

First, we introduce the assumptions underpinning a numerical example. Second, we present the results of the energy system model simulations.

3.1 Numerical example

The numerical example relies on assumptions related to energy demand, technology characteristics, and economic costs. Only a single representative technology is considered for each agent in the mathematical model, except for gas generators, as depicted in Table 3. The representative technologies' conversion efficiency and financial data are obtained from Danish Energy Agency and Energinet (2021). One exception is the conversion efficiency of Steam Methane Reformers, which is retrieved from Berger et al. (2020).

Table 3: Technology and costs

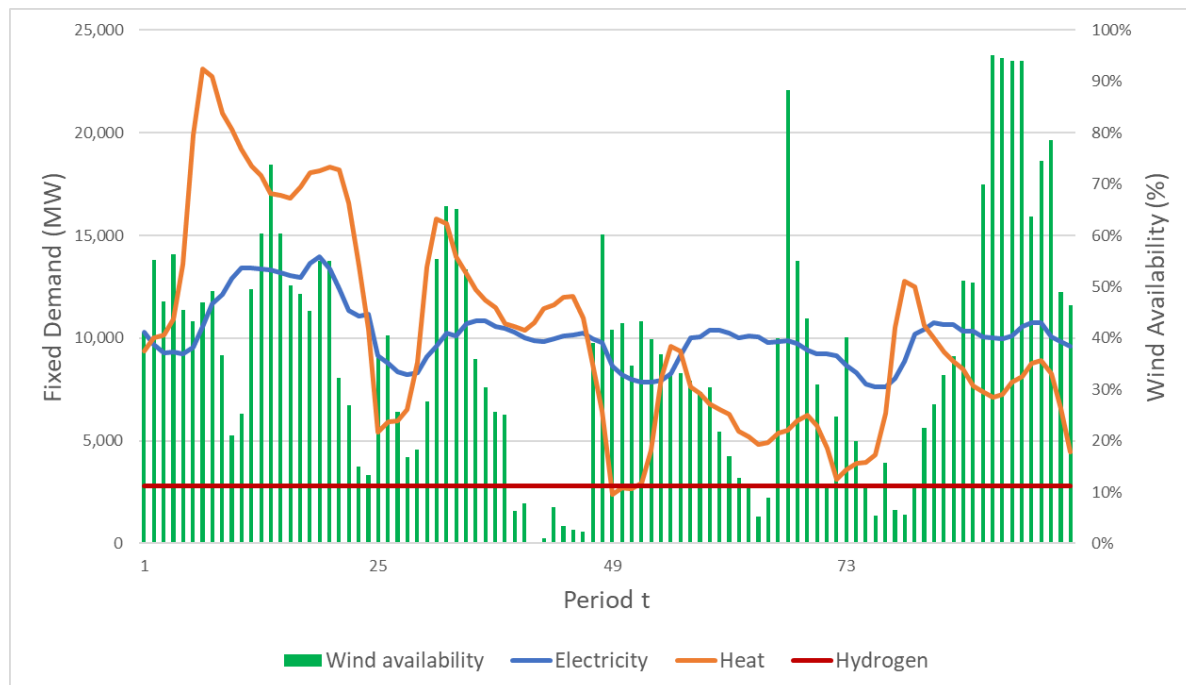
| Agent | Representative technology | Conversion efficiency %: η | Equivalent annualized costs (€2020)/MW: I | Variable costs €/MWh: V |
|--|---|---------------------------------|---|-------------------------|
| Gas shippers | - | - | | 18 |
| Biomethane producers | Biogas plant, anaerobic digester basic configuration, and upgrading plant | - | 401,250 | 42 |
| Renewable generator | Wind turbines, offshore | - | 212,028 | 0 |
| Gas generator | Gas turbine, combined cycle, extraction plant | 59% | 91,087 | - |
| Gas generator | Open cycle gas turbine | 42% | 42,736 | - |
| Heating consumer – Heat pump | Heat-pump, 9 kW air-to-water, single family house, existing building | $\gamma_{hp,t}$ | 158,140 | - |
| Heating consumer – gas boiler | Natural gas boiler – single family house, existing buildings | 97% | 80,074 | - |
| Electrolysis-based power-to-hydrogen producers | Alkaline electrolysis | 66.5% | 97,810 | - |
| Gas-based hydrogen producers | Steam Methane Reforming | 80% | 50,480 | - |

Some of the representative technologies have a fixed conversion efficiency η . In the case of heat pumps, this conversion efficiency $\gamma_{hp,t}$ varies hourly reflecting the coefficient of performance which depends on climate conditions. The equivalent annualized cost is calculated based on capital costs, fixed O&M, lifespan and 6% weighted average cost of capital

(WACC). Costs are expressed in 2020€. The variable cost at which natural gas can be accessed by shippers is fixed. The exogenous CO₂ price can impose additional costs on the agents, where applicable. We assume a CO₂ intensity of 205 kg CO₂/MWh for natural gas based on higher heating value (Gómez and Watterson, 2006; Patteeuw et al., 2015). The variable cost of anaerobic digestion depends on the price of feedstocks which can vary by country and region. In the case of Belgium, we take one estimation from a study conducted by ValBiom (2019) as a medium costs of 42 €/MWh and run sensitivities taking lower and higher values of 18 and 66 €/MWh.

The numerical example consists of 4 representative days or 96 time periods equally weighted by H_t , such that $\sum_{t \in T} H_t = 8760 \text{ hours}$. The input data underlying these representative days are selected in a heuristic manner to capture relevant seasonal or daily characteristics, as depicted in Figure 2. Electricity, heat, and hydrogen demand are all assumed to be inelastic.

Figure 2: Input data of numerical example



Aggregate electricity demand D_t^{EL} and offshore wind generation availability $AV_{rg,t}$ are extracted from Elia (2019) timeseries data during the 2019 calendar year. The average offshore wind availability for each representative day selected is verified to be consistent with the quarterly and annual average. The heat demand of buildings and the coefficient of performance of an air-source heat pump in Belgium is extracted from the time series dataset created by Ruhnau et al. (2019). The coefficient of performance of an air-source heat pump is provided in terms of space and water heating, so a weighted average is calculated to obtain $\gamma_{hp,t}$. Space and water heating demand of commercial, multi-family and single-family homes are only expressed in MW/TWh with an hourly resolution, which requires scaling to obtain $\sum_{c \in C} D_{c,t}^{HE}$. The 4 representative days selected are scaled such that the annual heat demand is equivalent to the annual electricity demand. Industrial hydrogen demand in Belgium is estimated using natural gas demand in petroleum refineries, iron and steel, and chemical and petrochemical sectors (JRC, 2019), from statistics published by Statbel (2019). This annual natural gas demand data

is multiplied by the efficiency of steam methane reformers η_{gh} and divided by 8760 hours to reflect a constant hydrogen demand across the year.

3.2 Results & Discussion

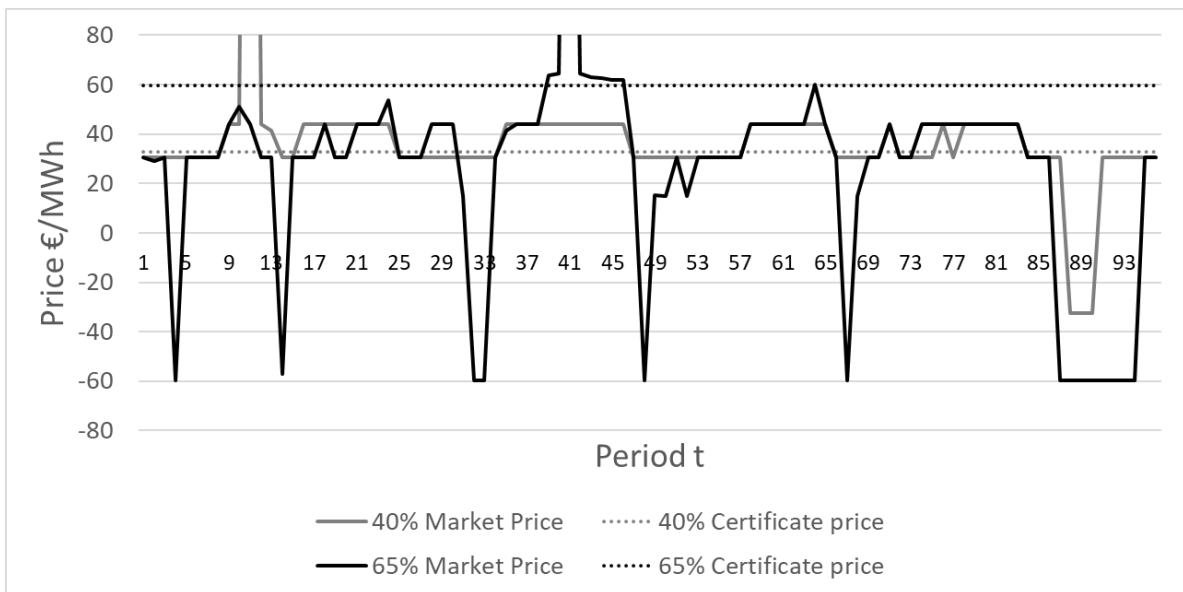
First, we will analyze the effectiveness of existing policies in supporting green gases, namely the RES-E target or CO₂ emissions market. Second, potential interaction effects between dual RES-E and RES-G target policies are analyzed.

3.2.1 RES-E target

A RES-E target is close to the status quo and highlights the extent of stylization of the model. Wind and biomethane-sourced gas generation are eligible and compete for a subsidy to achieve the RES-E target. In running scenarios which change the RES-E target ambition and investigating the solution of each scenario, the conditions that indirectly support green gases are characterized. In summary, depending on the relative cost of green gases, both biomethane and power-to-hydrogen can contribute to integrating variable generation from wind. However, their profitability depends on conditions where negative electricity prices prevail, which may be limited by market regulations in practice. Therefore, green gases are only indirectly supported by a RES-E target.

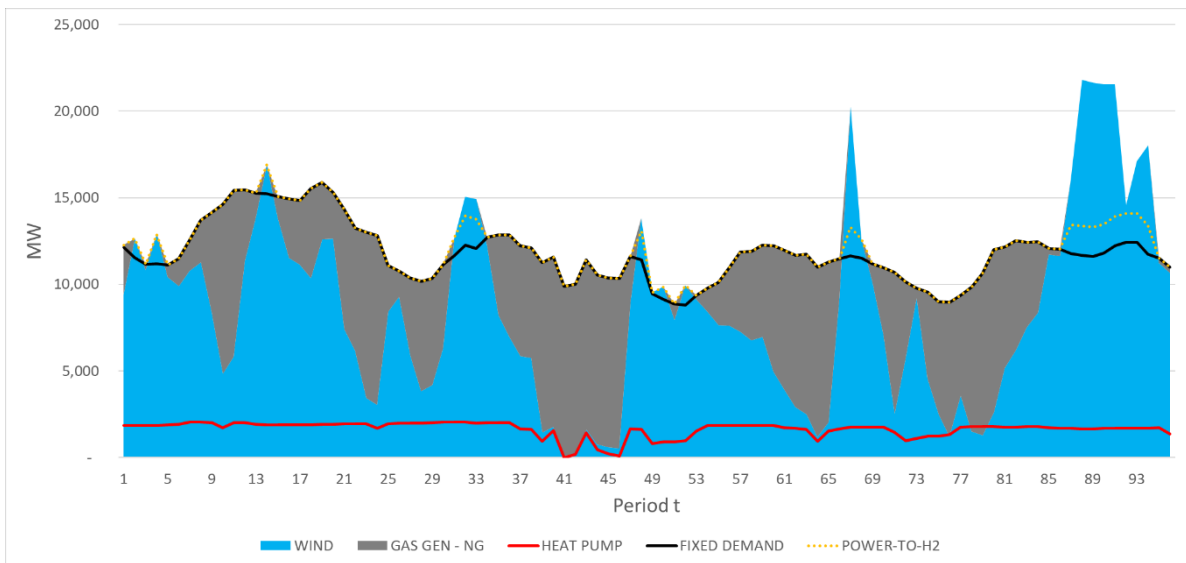
Given wind is the least cost renewable technology to meet the RES-E target when compared with biomethane-sourced gas generation, a higher RES-E ambition supports the deployment of more wind capacity. At and above a 40% RES-E target, additional wind capacity causes spillage. In this scenario, approximately 3% of the periods have negative electricity prices with a price of -32.62 €/MWh. The negative electricity prices in these periods with spillage reflects at which price the wind generator is indifferent and willing to reduce its output because of the opportunity cost associated with foregone subsidies. In other words, the negative electricity price is equal to the negative value of the certificate price associated with the RES-E target, and the wind generator earns no revenues in these periods with spillage. The wind generator relies on an increase in the certificate price in other non-negative electricity price periods to remain profitable. In this way, an increase in the RES-E target ambition can cause more periods with spillage and it follows that the certificate price must rise to ensure the wind generators' profitability. At a 65% RES-E target, approximately 15% of the periods have negative electricity prices with a price of -59.75 €/MWh and this is sufficient to render power-to-hydrogen profitable. The electricity market price and certificate price for these two scenarios are depicted in Figure 3.

Figure 3: Electricity market price and RES-E certificate price in 40% and 65% RES-E target scenarios



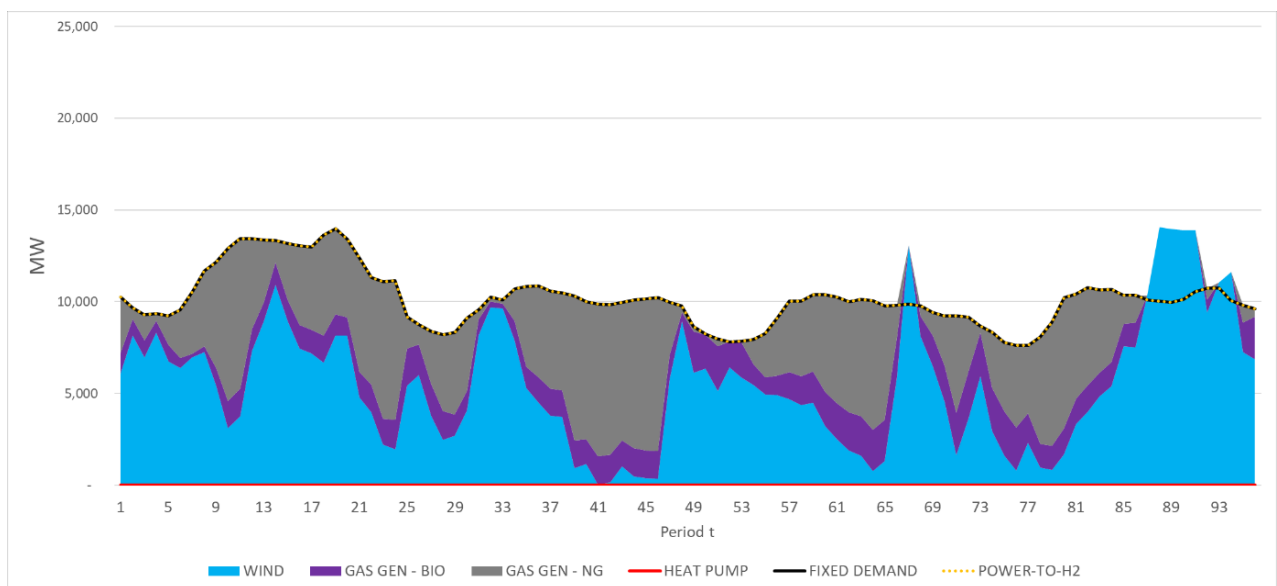
The 65% RES-E target scenario in which power-to-hydrogen evacuates some of the wind generation spillage is depicted in Figure 4. In this case, power-to-hydrogen is paid to consume in those periods with significant negative electricity prices and this can be considered as indirect support. Given the limited operating hours of periods with spillage, only 1672 MW of electrolyzers are installed. However, when power-to-hydrogen evacuates all the surplus wind generation, it plays a price-setting role in the electricity market. As can be observed in period 50 and 52, given a hydrogen price of 22.50 €/MWh and a power-to-hydrogen efficiency of 66.5%, the electricity price is 14.96 €/MWh because all the spillage has been absorbed. This price-setting behavior may prevent more negative electricity prices from forming, to a limited extent, however this erodes power-to-hydrogen’s own profitability, as discussed in Roach and Meeus (2020). The residential heating consumers only install heat pumps in the presence of negative electricity prices.

Figure 4: RES-Electricity Target 65% scenario - hourly profile of electricity generation and demand



In lowering the biomethane variable costs from 42 to 18 €/MWh, such a sensitivity illustrates how biomethane could potentially also receive indirect support. Biomethane sourced for gas generation can contribute to the RES-E target and reduce the need to build out wind capacity by 35.5%, as depicted in Figure 5 compared to Figure 4. Although part of this wind capacity decrease can be explained by the decrease of electricity demand due to the absence of heat pumps. As the negative electricity prices are equal to the negative value of the certificate price, this certificate is also offered to biomethane-sourced gas generation. Biomethane prevents even greater negative electricity prices from forming if more wind capacity is deployed to meet the RES-E target.

Figure 5: RES-Electricity Target 65% scenario with low biomethane variable cost - hourly profile of electricity generation and demand

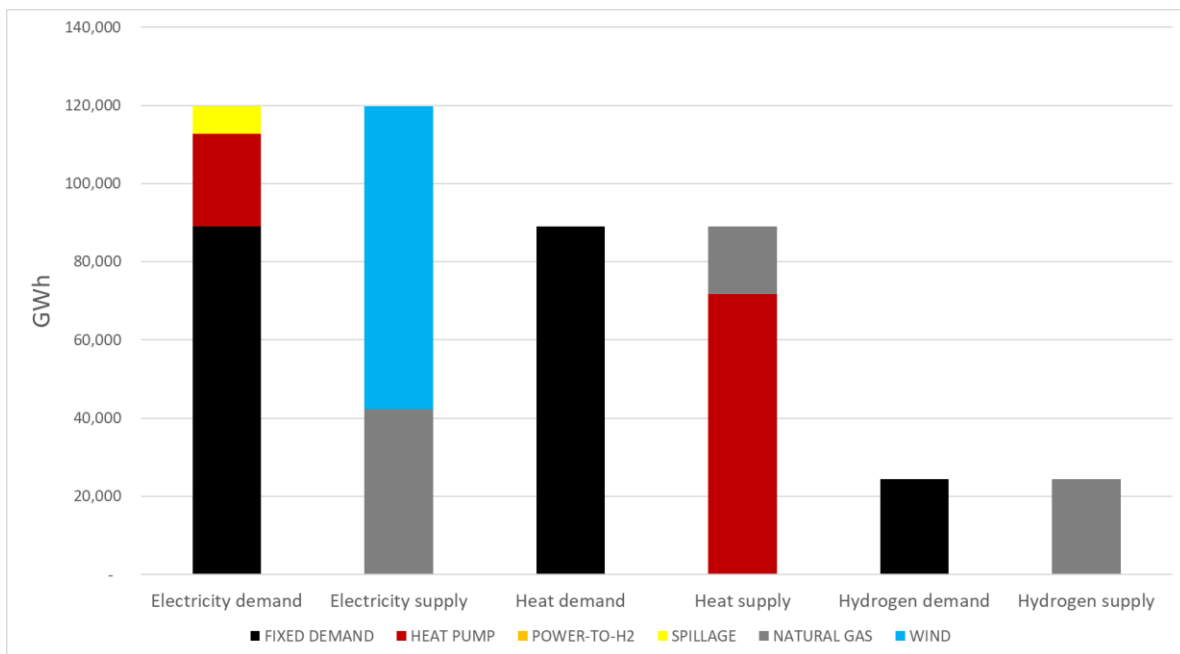


3.2.2 CO₂ emissions market

The outcome of a carbon emissions policy promotes the least cost means of achieving emissions reductions. A CO₂ price increases the variable costs of conventional technologies and has the side effect of increasing market revenues for renewable energy. For comparison, the total emissions resulting from the 65% RES-E target is first utilized as the emissions reductions target. The main takeaway is that green gases require significant CO₂ prices to be profitable but must still compete against more mature or electricity-based renewables.

As depicted in Figure 6, nearly all the emissions reductions are achieved through the electricity sector from renewable generation and heat pumps. The least cost means to achieve CO₂ emissions reductions ultimately depend on the cost of renewable alternatives. Based purely on current costs such a policy supports more mature renewables, and in this case wind. Additionally, as the CO₂ price applies to all natural gas consuming technologies, the cost-competitiveness of heat pumps improves. Even if gas generators are the marginal unit in the electricity market in most periods, heat pumps have efficiency gains per se, so natural gas boilers are relatively more expensive than heat pumps as the CO₂ price increases. Additionally, negative prices from periods with spillage improve the cost-competitiveness of heat pumps which are paid to consume.

Figure 6: Annual supply and demand per segment in emissions reductions policy equal to 65% RES-E equivalent



A CO₂ price of 212 €/tCO₂ is necessary to reach the equivalent emissions reductions of a 65% RES-E policy. Given there is no certificate for renewable generators, the electricity market price is 0 €/MWh in periods with spillage. However, a more stringent CO₂ emissions reductions target drives more wind deployment and spillage, so the CO₂ price must rise even further to offset zero price periods in which wind earns no revenue. In this way, power-to-hydrogen could be supported by the arbitrage between zero-price electricity and a higher hydrogen price set by steam methane reformers which must internalize the CO₂ costs.

3.2.3 Dual RES-Electricity and RES-Gas

The second set of RES policies represents a possible way forward which consists of dual RES-G and RES-E targets. Green hydrogen and biomethane are eligible and compete for certificates to achieve the RES-G target. One may expect that the combination of RES-E and RES-G target ambitions leads to at least as much renewable energy deployment as the sum of individual targets, but this is not always observed. On the one hand, the two targets are responsive to one another, meaning a RES-E target can contribute to the RES-G target, and vice versa. On the other hand, the combined impact of a RES-E and RES-G target can lead to more (complementary) or less (substitutive) total RES depending on the combination of RES target ambitions. These interaction effects arise from overlapping areas defined by the two RES targets and from sector coupling technologies.

The scenarios we assess in more depth are summarized in Table 4. In these scenarios, the change in renewable energy, in terms of renewable electricity generation and green gas production, will be compared as the exogenous RES-E and RES-G target ambition is modified. In this way, we will draw insights about the interdependence of these RES targets, as well as identify possible interaction effects and their strength. All the scenarios have a low RES-E target ambition which does not lead to significant spillage from wind triggering power-to-hydrogen on its own, as was seen in section 3.2.1. Model variation refers to adaptations of the model to carry out additional sensitivities with the same renewable energy target ambitions.

Table 4: Dual RES target scenarios

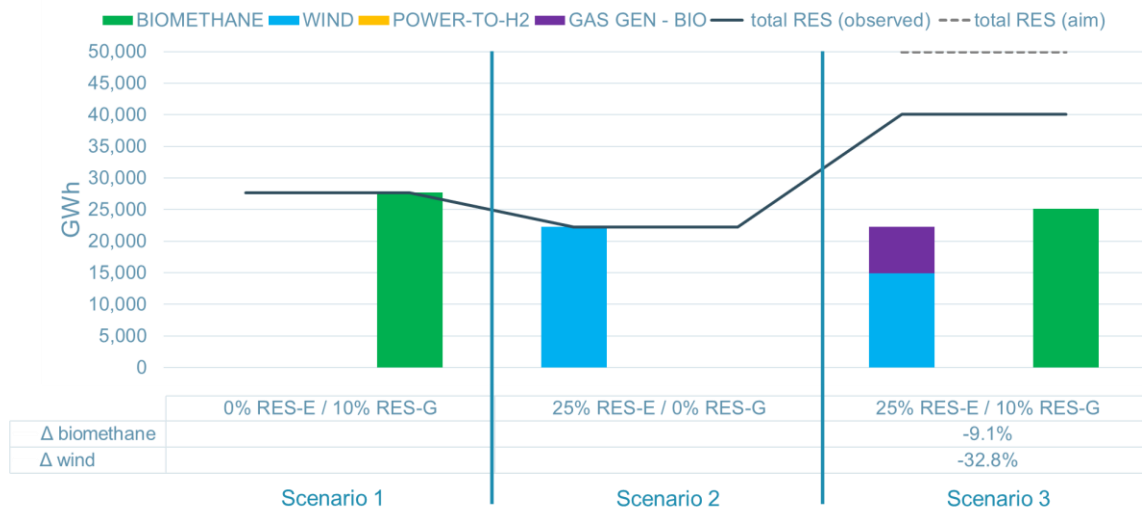
| Scenario | RES-E | RES-G |
|-----------------|--------------|--------------|
| 1 | 0% | 10% |
| 2 | 25% | 0% |
| 3 | 25% | 10% |
| 4 | 50% | 10% |
| 5 | 25% | 20% |
| 6 | 50% | 20% |

Figure 7 and Figure 8 illustrate the contribution of a renewable technology in meeting the RES-E or RES-G target within each scenario considered. On the left, wind and biomethane-sourced gas generation are necessary to meet the RES-E target. On the right, biomethane and green power-to-hydrogen production are necessary to meet the RES-G target. In each scenario, how much total RES results is analyzed, which is equal to the sum of biomethane production and wind generation. A comparison is made between the total RES (aim), meaning in the absence of interaction effects, and the total RES (observed) resulting from the model.

It may be logical to anticipate that the combined impact of the RES-E and RES-G target on total RES is simply the sum of both, however this is not what we observe. As depicted in Figure 7, biomethane is the least cost means of achieving the RES-G target in scenario 1 with 27,667 GWh of production and a levelized cost of approximately 88 €/MWh. Wind is the least cost means of achieving the RES-E target in scenario 2 with 22,249 GWh of generation and a levelized cost of approximately 65 €/MWh. The total RES (aim) of 49,916 GWh in scenario 3

is the sum of biomethane production in scenario 1 and wind generation in scenario 2. However, the total RES (observed) in scenario 3 is 19.7% lower, such that wind generation and biomethane production decrease by 32.8% and 9.1%, respectively. Heat pumps are not deployed in scenarios 1-6 because they are not the least cost option for residential heating consumers. Therefore, heat pumps do not alter the renewable electricity required to meet the RES-E target, as portrayed in Figure 5.

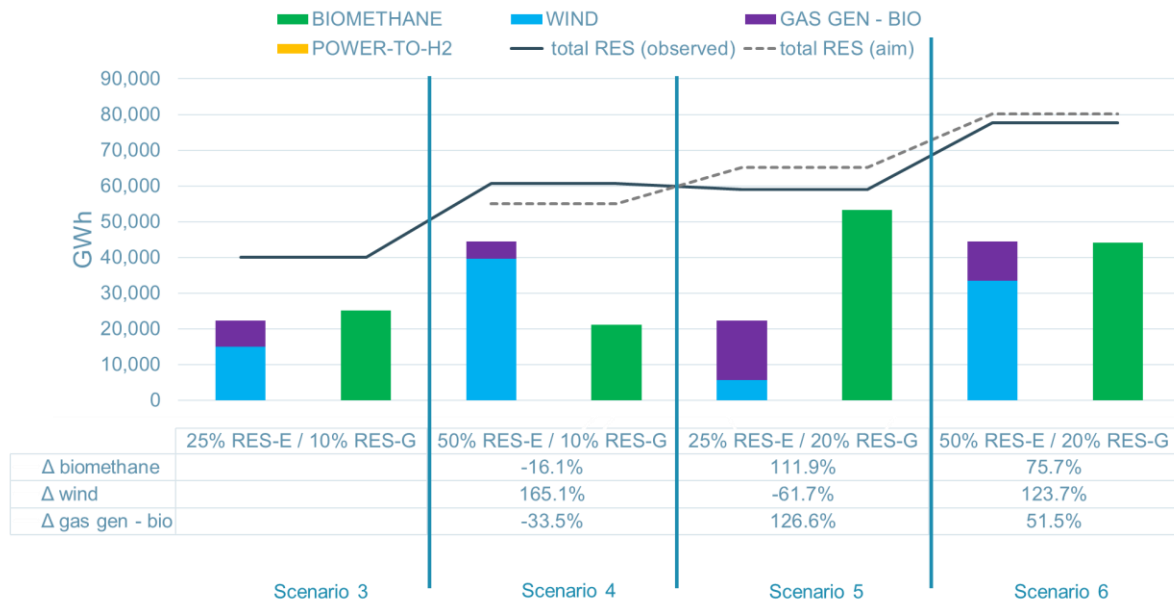
Figure 7: Annual renewable energy generation or production in scenarios 1-3



Two interaction effects play out in scenario 3. On the one hand, the gas interaction effect accounts for the fact that a share of gas generation is renewable due to the share of biomethane in the gas system. Consequently, less wind capacity is necessary to meet the 25% RES-E target. Moreover, as wind generation is displaced by gas generation, total gas demand increases and more biomethane is necessary to meet the 10% RES-G target. On the other hand, the electricity interaction effect works in reverse. As wind generation displaces gas generation, total gas demand decreases and less biomethane production is necessary to meet the 10% RES-G target. Consequently, as the share of biomethane in the gas system decreases, more wind is required to meet the 25% RES-E target because less gas generation can be counted as renewable. The interplay of both interaction effects takes place through the RES-E and RES-G target formulations described in equations (42) and (43). The decrease in biomethane and wind under dual targets compared to individual targets signify the substitutive nature of the electricity and gas interaction effects. However, in looking at more scenarios, they can be either substitutive or complementary depending on the combinations of RES target ambitions.

We consider 4 scenarios portrayed in Figure 8 that compare the impact of doubling the RES target ambitions on renewable generation and green gas production. The calculations and results for scenarios 3-6 are summarized in Table 5. Scenario 4 increases the RES-E target from 25% to 50% while holding the RES-G target at 10% and portrays the electricity interaction effect in more detail. Wind generation increases by nearly 168%, which is more than double, while biomethane production decreases by nearly 18% even though the RES-G target ambition was unchanged. The total RES (aim) in scenario 4 is equal to double the wind generation plus the biomethane production in scenario 3. The electricity substitutive effect makes the total RES (observed) 10.3% greater than the total RES (aim), which signifies that more total renewables are produced than intended. In this way, the RES targets are complementary, although wind generation provides a greater contribution to total RES production.

Figure 8: Annual renewable energy generation or production in scenarios 3-6



Scenario 5 increases the RES-G target from 10% to 20% while holding the RES-E target at 25% and captures the gas interaction effect in more detail. Biomethane production increases by nearly 112%, which is more than double, while wind generation decreases by nearly 62% even though the RES-E target ambition was unchanged. The total RES (aim) in scenario 5 is equal to the wind generation plus double the biomethane production in scenario 3. The gas interaction effect makes the total RES (observed) nearly 9.5% less than the total RES (aim), which signifies that less renewables were produced than intended. For this reason, this combination of RES target policies is substitutive, although biomethane is supported more because it provides a greater contribution to total RES production. Scenario 6 doubles the RES-E and RES-G target ambition of scenario 3, and here it appears the electricity interaction effect is stronger than the gas interaction effect. Wind generation increases by nearly 124% and biomethane production only increases by nearly 76%, which is more and less than double, respectively. The overall renewables produced, total RES (observed) is only 3.2% less than intended under the total RES (aim), however the contribution of wind generation is greater because of the stronger electricity interaction effect. These interaction effects bring attention to the coordination of RES target policies to obtain the intended support and output of renewable electricity and green gas. In summary, the total RES production can be more (complementary) or less (substitutive) depending on the combination of RES target ambitions. Additionally, a low RES-E and high RES-G target which is also characterized by a substitutive interaction effect is more effective in supporting renewable gas.

Table 5: Annual renewable energy generation or production in scenarios 3-6

| | Generation or production (GWh) | scenario 3 25% RES-E 10% RES-G | scenario 4 50% RES-E 10% RES-G | scenario 5 25% RES-E 20% RES-G | scenario 6 50% RES-E 20% RES-G |
|---------------------------|--------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| A | BIOMETHANE | 25,145 | 21,089 | 53,292 | 44,186 |
| | Δ biomethane | | -16.1% | 111.9% | 75.7% |
| B | PTH | 0 | 0 | 0 | 0 |
| A+B | RES-G | 25,145 | 21,089 | 53,292 | 44,186 |
| C | WIND | 14,957 | 39,647 | 5,728 | 33,451 |
| | Δ wind | | 165.1% | -61.7% | 123.7% |
| D | BIO - GAS GEN | 7,292 | 4,851 | 16,521 | 11,047 |
| | Δ gas gen - bio | | -33.5% | 126.6% | 51.5% |
| C+D | RES-E | 22,249 | 44,498 | 22,249 | 44,498 |
| A+C | TOTAL RES (observed) | 40,102 | 60,737 | 59,020 | 77,637 |
| i.e. S4 = S3(A) + S3(C•2) | TOTAL RES (aim) | | 55,059 | 65,247 | 80,204 |

In the scenarios discussed thus far biomethane is the least cost green gas technology to meet the RES-G target. For power-to-hydrogen to be cost-competitive against biomethane, it appears periods of spillage are necessary which only happens at high enough RES-E targets. This is confirmed by a 70% RES-E and 10% RES-G target policies where power-to-hydrogen provides only a minor contribution to the RES-G target. This brings forward two questions. First, whether the objective of a RES-G target is to support the currently least cost green gas technology or instead to support a range of green gas technologies because it is not known which has the lowest long run marginal cost? Second, is a high RES-E target as or even more critical to support power-to-hydrogen than a RES-G target?

4. Limitations, conclusions, and policy implications

4.1 Limitations of approach and implications for conclusions

In this section, we reiterate the boundaries of our analysis and the limitations in our modelling approach which could lead to overestimating or underestimating the cost-competitiveness of green gases. In balancing and recognizing these modelling choices and limitations, the main conclusions are well contextualized.

For the following reasons, it could be that the cost-competitiveness of green gases are overestimated. It is relevant to acknowledge that our analysis investigated only one possible interpretation of a gas target and considers one type of support instrument. Low-carbon gases such as steam methane reforming with carbon capture and storage or nuclear-based power-to-hydrogen may compete directly against green gases but are not included in our model. At the time of writing, these so called blue and pink hydrogen are not considered renewable

energy sources and are therefore likely outside the scope of renewable energy policies. The EU Commission is considering a range of instruments which can support the decarbonization of the gas sector more broadly and we only consider one of them, direct market-based support for green gases in the form of a feed-in premium. Other policy tools such as a carbon contracts for difference have been communicated in the EU Hydrogen Strategy as a possible instrument to send a price signal to support low-carbon and green gases. If low-carbon hydrogen pathways compete against green gases for subsidies or in a CO₂ emissions market, the uptake of green gases could be more limited. Additionally, the participation of battery storage could compete for the spillage of renewable generators and limit the cost-competitiveness of power-to-hydrogen. Battery storage is not incorporated in the model due to unintended storage cycling which occurs during zero or negative electricity price periods to artificially meet the RES-E target without meaningfully contributing to integrating renewable generation.

The role of biomethane and power-to-hydrogen are also underestimated to some extent as well. Electrolysis and biomethane technologies are still at an early stage of a large-scale commercial deployment and capturing technology learning curves with the chosen modelling approach is not possible. Biomethane feedstock costs vary widely between MSs due to resource availability and regulatory conditions, and our base assumption may not reflect a MS with favourable conditions. Moreover, in a broader perspective, resource endowments and legacy investments may favor one green gas over another based on a MSs current situation. On the modelling assumptions of power-to-hydrogen, it is subsidized by the RES-G target on the principle that the agent procures sufficient electricity RECs to justify the renewable origin of its green hydrogen. In removing this operational expenditure, power-to-hydrogen would become more cost-competitive, but the renewable origin may be questioned. A policymaker may have to balance the deployment of electrolyzer capacity to achieve technology learning by doing gains along with concerns about the origin of the electricity or impact on CO₂ emissions. Regulatory actions in this area would determine whether the power-to-hydrogen operates with a high capacity factor or only marginally to evacuate renewables. Such priority-making and concerns about additionality are not compared in this work.

4.2 Conclusions

In this paper, we discuss the policy motivations and economic rationale for supporting green gases in line with past discussions of renewable electricity policies. An energy system model with policy-induced investment decisions was advanced to investigate to what extent policies are effective in supporting green gases. Additionally, potential interaction effects between dual RES-E and RES-G targets are analyzed. Here we highlight our two main findings and their practical significance.

First, how effective is a RES-G target in supporting renewable gases? Existing renewable energy policies such as the RES-E target and carbon emissions reductions policies only indirectly support green gases in a limited way and instead support more mature or electricity-based technologies. Although a RES-G target is effective in supporting green gas, it is more effective in supporting biomethane than in supporting green hydrogen. In trying to be neutral in supporting green gases, policy makers risk to support only one technology.

Second, are interaction effects between a RES-E and RES-G target relevant in a cross-sector energy market setting, and if so, how does this inform policymaking? We find that policies consisting of a high RES-E and low RES-G target can be complementary, i.e., the combined policy provides a stronger push for renewable energy than the addition of the individual policies, and otherwise the scenarios are substitutive. The practical significance is that policymakers need to be aware of these effects when setting targets to reach the intended deployment of renewable gas and to avoid undercutting the total RES ambitions.

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B. Dual RES targets iterative loop

This formulation avoids that all the biomethane production, which has already been subsidized such that it is as cost-competitive as natural gas, is subsequently all allocated to gas generation to meet the RES-E target. It is not possible to directly incorporate shares expressed as fractions because it violates optimality conditions. This iterative loop is designed to account for the share of biomethane as a percentage of total gas production $\frac{\sum_{b \in B} q_{b,t}}{\sum_{b \in B} q_{b,t} + \sum_{ng \in NG} q_{ng,t}}$ and the share of demand of gas generators as a percentage of total gas demand $\frac{\sum_{(ocgt)} q_{(ocgt),t} + \sum_{(ccgt)} q_{(ccgt),t}}{\sum_{b \in B} q_{b,t} + \sum_{ng \in NG} q_{ng,t}}$. The contribution of biomethane in gas generation is calculated after conversion efficiency losses $\eta_{(ocgt)}$ and $\eta_{(ccgt)}$.

$$\begin{aligned}
 & \text{GGS} = 1 \\
 & \text{while (count} \leq 100, \\
 & \text{if } \left(\sum_{t \in T} H_t \cdot \sum_{b \in B} q_{b,t} = 0, \text{GGS} = 0 \right. \\
 & \text{elseif } \left(\sum_{t \in T} H_t \cdot \sum_{b \in B} q_{b,t} \cdot \text{GGS} > \right. \\
 & \sum_{t \in T} H_t \cdot \left(\frac{\sum_{(ocgt)} (q_{(ocgt),t} + q_{b(ocgt),t})}{\sum_{b \in B} q_{b,t} + \sum_{ng \in NG} q_{ng,t}} \right) \cdot \sum_{b \in B} q_{b,t} \cdot \eta_{(ocgt)} + \\
 & \sum_{t \in T} H_t \cdot \left(\frac{\sum_{(ccgt)} (q_{(ccgt),t} + q_{b(ccgt),t})}{\sum_{b \in B} q_{b,t} + \sum_{ng \in NG} q_{ng,t}} \right) \cdot \sum_{b \in B} q_{b,t} \cdot \eta_{(ccgt)} , \\
 & \text{GGS} = \text{GGS} \cdot 0.1
 \end{aligned}$$

C. KKT conditions of all agents

$$0 \leq (V_{ng} - \lambda_t^G) \cdot H_t - \lambda_{ng,t}^2 \perp q_{ng,t} \geq 0; \forall ng \in NG, \forall t \in T \quad (C.1.)$$

$$0 \leq (V_b - \lambda_t^B - B^E \cdot \zeta^E - B^{EG} \cdot \zeta^G) \cdot H_t + \lambda_{b,t}^4 - \lambda_{b,t}^5 \perp q_{b,t} \geq 0; \forall b \in B, \forall t \in T \quad (C.2.)$$

$$0 \leq I_b - \sum_{t \in T} \lambda_{b,t}^4 - \lambda_{b,t}^6 \perp cp_b \geq 0; \forall b \in B \quad (C.3.)$$

$$0 \leq (\lambda_t^G - \lambda_t^E \cdot \eta_{gg} + EMF \cdot \mu^C) \cdot H_t + \lambda_{gg,t}^{10} \cdot \eta_{gg} - \lambda_{gg,t}^{11} \perp q_{gg,t} \geq 0; \forall gg \in GG \forall t \in T \quad (C.4.)$$

$$0 \leq (\lambda_t^B - \lambda_t^E \cdot \eta_{gg}) \cdot H_t + \lambda_{gg,t}^{10} \cdot \eta_{gg} - \lambda_{gg,t}^{12} \perp qb_{gg,t} \geq 0; \forall gg \in GG \forall t \in T \quad (C.5.)$$

$$0 \leq I_{gg} - \sum_{t \in T} \lambda_{gg,t}^{10} - \lambda_{gg,t}^{13} \perp cp_{gg} \geq 0; \forall gg \in GG \quad (C.6.)$$

$$0 \leq (-\lambda_t^E - B^E \cdot \zeta^E - B^{EG} \cdot \zeta^E) \cdot H_t + \lambda_{rg,t}^{15} - \lambda_{rg,t}^{16} \perp q_{rg,t} \geq 0; \forall rg \in RG \forall t \in T \quad (C.7.)$$

$$0 \leq I_{rg} - \sum_{t \in T} \lambda_{rg,t}^{15} \cdot AV_{rg,t} - \lambda_{rg,t}^{17} \perp cp_{rg} \geq 0; \forall rg \in RG \quad (C.8.)$$

$$0 \leq (\lambda_t^G - \lambda_t^H \cdot \eta_{gh} + EMF \cdot \mu^C) \cdot H_t + \lambda_{gh,t}^{20} \cdot \eta_{gh} - \lambda_{gh,t}^{21} \perp q_{gh,t} \geq 0; \forall gh \in GH \forall t \in T \quad (C.9.)$$

$$0 \leq (\lambda_t^B - \lambda_t^H \cdot \eta_{gh}) \cdot H_t + \lambda_{gh,t}^{20} \cdot \eta_{gh} - \lambda_{gh,t}^{22} \perp qb_{gh,t} \geq 0; \forall gh \in GH \forall t \in T \quad (C.10.)$$

$$0 \leq I_{gh} - \sum_{t \in T} \lambda_{gh,t}^{20} - \lambda_{gh,t}^{23} \perp cp_{gh} \geq 0; \forall gh \in GH \quad (C.11.)$$

$$0 \leq (\lambda_t^E - \lambda_t^H \cdot \eta_{pth}) \cdot H_t + \lambda_{pth,t}^{25} - \lambda_{pth,t}^{26} \perp q_{pth,t} \geq 0; \forall pth \in PTH \forall t \in T \quad (C.12.)$$

$$0 \leq I_{pth} - \sum_{t \in T} \lambda_{pth,t}^{25} - \lambda_{pth,t}^{27} \perp cp_{pth} \geq 0; \forall pth \in PTH \quad (C.13.)$$

$$0 \leq (\lambda_t^H - \lambda_t^{29} \cdot \alpha) \cdot H_t + \lambda_t^{30} \perp inj_t \geq 0; \forall t \in T \quad (C.14.)$$

$$0 \leq (-\lambda_t^H + \lambda_t^{29}) \cdot H_t + \lambda_t^{31} \perp with_t \geq 0; \forall t \in T \quad (C.15.)$$

$$0 \leq \lambda_t^{29} - \lambda_{t+1}^{29} + \lambda_t^{32} \perp es_t \geq 0; \forall t \neq \{tmax\} \quad (C.16.)$$

$$0 \leq \lambda_{tmax}^{32} \perp es_t \geq 0; \forall t = tmax \quad (C.17.)$$

$$0 \leq \sum_{t \in T} -\lambda_t^{32} \perp cpse \geq 0 \quad (C.18.)$$

$$0 \leq \sum_{t \in T} -\lambda_t^{30} - \lambda_t^{31} \perp cpsp \geq 0 \quad (C.19.)$$

$$0 \leq (\lambda_t^{\text{EL}} + \lambda_{c,t}^{37} \cdot \gamma_{\text{hp},t}) \cdot H_t + \lambda_{c,\text{hp},t}^{35} \cdot \gamma_{\text{hp},t} - \lambda_{c,\text{hp},t}^{38} \perp q_{c,\text{hp},t} \geq 0; \forall c \in C \forall \text{hp} \in \text{HP} \forall t \in T \quad (\text{C.20.})$$

$$0 \leq (\lambda_t^{\text{G}} + \lambda_{c,t}^{37} \cdot \eta_{\text{gb}}) \cdot H_t + \lambda_{c,\text{gb},t}^{36} \cdot \eta_{\text{gb}} - \lambda_{c,\text{gb},t}^{39} \perp q_{c,\text{gb},t} \geq 0; \forall c \in C \text{ gb} \in \text{GB} \forall t \in T \quad (\text{C.21.})$$

$$0 \leq (\lambda_t^{\text{B}} + \lambda_{c,t}^{37} \cdot \eta_{\text{gb}}) \cdot H_t + \lambda_{c,\text{gb},t}^{36} \cdot \eta_{\text{gb}} - \lambda_{c,\text{gb},t}^{40} \perp qb_{c,\text{gb},t} \geq 0; \forall c \in C \text{ gb} \in \text{GB} \forall t \in T \quad (\text{C.22.})$$

$$0 \leq I_{\text{hp}} - \sum_{t \in T} \lambda_{c,\text{hp},t}^{35} \perp cp_{c,\text{hp}} \geq 0; \forall c \in C \forall \text{hp} \in \text{HP} \quad (\text{C.23.})$$

$$0 \leq I_{\text{gb}} - \sum_{t \in T} \lambda_{c,\text{gb},t}^{36} \perp cp_{c,\text{gb}} \geq 0; \forall c \in C \text{ gb} \in \text{GB} \quad (\text{C.24.})$$

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