

## Article

# Decarbonizing Hard-to-Abate Sectors with Renewable Hydrogen: A Real Case Application to the Ceramics Industry

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**Abstract:** Hydrogen produced from renewable energy sources is a valuable energy carrier for linking growing renewable electricity generation with the hard-to-abate sectors, such as cement, steel, glass, chemical, and ceramics industries. In this context, this paper presents a new model of hydrogen production based on solar photovoltaics and wind energy with application to a real-world ceramics factory. For this task, a novel multipurpose profit-maximizing model is implemented using GAMS. The developed model explores hydrogen production with multiple value streams that enable technical and economical informed decisions under specific scenarios. Our results show that it is profitable to sell the hydrogen produced to the gas grid rather than using it for self-consumption for low-gas-price scenarios. On the other hand, when the price of gas is significantly high, it is more profitable to use as much hydrogen as possible for self-consumption to supply the factory and reduce the internal use of natural gas. The role of electricity self-consumption has proven to be key for the project's profitability as, without this revenue stream, the project would not be profitable in any analysed scenario.

**Keywords:** wind energy; solar energy; renewable hydrogen; industry decarbonization; ceramics industry; energy systems modelling; optimization



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## 1. Introduction

Hard-to-abate industries such as cement, steel, glass, chemicals, and ceramics play an important role in meeting the Paris Agreement targets with relevant potential to mitigate industrial greenhouse gas (GHG) emissions and their subsequent consequences, including global warming [1]. As the global climate continues to deteriorate, traditional carbon-intensive energy resources, such as coal and oil, can no longer adequately support the requirements of sustainable economic growth [2]. Thus, several alternatives are needed for both the industrial process and the substitution of natural gas.

The Group of Seven (G7) supports the International Renewable Energy Agency's (IRENA) call to accelerate renewable energy deployment, essential for reducing emissions, enhancing energy security, fostering economic growth, and creating jobs. The report on decarbonizing hard-to-abate sectors with renewables [3] offers actionable recommendations for the G7 to expedite global decarbonization, particularly in five hard-to-abate sectors: road freight transport, shipping, aviation, iron and steel, and chemicals and petrochemicals, which together consume 25% of global energy and produce 20% of CO<sub>2</sub> emissions. To limit the global temperature rise to 1.5 °C by 2050, substantial new investments and major changes in energy systems are required. The G7's focus on these sectors, through targeted

investments and policy measures, can lead to significant emissions reductions, driving a sustainable, low-carbon future.

In 2021, the steel industry, a significant high-emissivity sector, contributed to 7.4% of global CO<sub>2</sub> emissions due to its chemical processes and high thermal demands, often exceeding 500 °C. A detailed analysis of the benefits and challenges of hydrogen adoption in the steel industry [4] provides insights into hydrogen's role in decarbonizing industrial processes and promotes further exploration of its applications in other challenging sectors.

Similarly, the ceramics industry, known for manufacturing products like ceramic tiles, is a high-intensity energy sector that involves several processes such as burning, drying, and heating, with approximately 70% of the total energy cost coming from natural gas consumption. The burning phase is responsible for more than half of the total consumption of natural gas, followed by the spray drying process [5]. The industry's dependence on high-temperature heat, which cannot be sustained without significant GHG emissions from fossil fuels [6], raises economic risks for regions with minimal fossil fuel resources [7] and requires careful energy management in this sector. To address this problem, transitioning to renewable energy sources like solar PV, wind, and renewable hydrogen is essential [8]. In this regard, hydrogen is expected to reduce emissions where electrification is not easily implemented, such as heavy industries and transportation sectors [9].

The role of hydrogen in decarbonization is crucial due to its versatility and compatibility with existing industrial processes; however, for hydrogen to be an effective energy carrier, it must be sustainably produced. A clear understanding of energy balance and demand within each process is vital to harness its cost-effectiveness and environmental benefits. Green hydrogen, produced from renewable sources, aligns with decarbonization goals but poses challenges due to the low energy density of renewables like solar power, complicating integration with hard-to-abate sectors. In [10], the authors provide a comprehensive analysis of hydrogen utilization in these sectors, evaluating technologies, energy balance considerations, potential applications, and implementation challenges. This study emphasizes a holistic view of the entire hydrogen cycle, from production to utilization, highlighting the interconnectedness and implications of each stage. This approach bridges the gap between specific technological analyses and broader energy system contexts, contributing to a deeper understanding of hydrogen's role in addressing decarbonization challenges.

The rising prices of natural gas and its environmental impact, particularly over the past two years, have spurred interest in new technologies and energy vectors as potential replacements. Hydrogen is gaining prominence in the industrial sector's decarbonization due to its zero GHG emissions, energy storage capacity, and ability to balance renewable energy production. Ref. [11] presented a detailed mathematical model of a price-driven, demand-responsive, multi-energy industrial facility, which is an ideal candidate for implementing hydrogen technologies due to its high and diverse energy consumption. Systematic analyses were conducted across various scenarios of local production, considering different hydrogen technologies and a range of natural gas and electricity prices. The findings indicate that integrating hydrogen technology into industrial processes results in zero local emissions, high autonomy, and resilience to market disturbances.

Research has focused on hydrogen production using renewable energy sources, especially solar and wind energy. Solar energy offers more opportunities for hydrogen production compared to wind energy. Various types of electrolysis systems utilizing renewable energy sources are described in [12], including photovoltaic systems, concentrated solar power systems, and wind turbines for hydrogen production. Despite extensive studies on green hydrogen, limited research exists on supply chain risk identification and analysis, particularly for Europe's hard-to-abate sectors. Identifying and analyzing risk factors within the European green hydrogen supply chain [13] reveals high capital investment for production and delivery technology as the highest-ranked risk factor, followed by insufficient electrolyser capacity and the need for policy and regulatory development.

Hydrogen produced by electrolysis involves the decomposition of water into hydrogen and oxygen using an electrolyser, where an electric current induces and sustains redox reactions that separate hydrogen (H<sub>2</sub>) from oxygen (O<sub>2</sub>) [14,15]. There are two crucial inputs in this process: the electricity powered by a direct current (DC) source, which is required to be from renewable sources for the hydrogen to be considered renewable, and water for the electrolyser.

The increasing use of these variable renewable energy sources is driven by political support and significant cost reductions in renewable technologies [16]. Consequently, renewable hydrogen is pivotal for creating a sustainable future [17], offering benefits such as thermal energy storage, energy carrier applications, and fuel cell usage [18], and it can be used in power-to-gas applications, for direct injection into an existing natural gas infrastructure, and as a fuel for fuel-cell vehicles in power-to-fuel applications [19].

One of the most widely used methods to produce renewable hydrogen is the use of solar photovoltaic technology, since solar energy has the advantage of being an abundant resource and widely distributed worldwide. In addition to the solar energy reflected by the atmosphere, the Earth's surface receives around  $3.9 \times 10^{24}$  MJ of incident solar energy per year, representing almost 10,000 times more than the world's current annual energy consumption [20]. Another method involved in generating electricity is wind power, converting wind energy into electrical energy. The rotor of the wind turbine is rotated using the kinetic energy generated by the wind, and this energy is transferred, via a transmission system, to a generator that converts the shaft energy into electricity [21]. The wind turbine control system is affected by the selection of the appropriate nominal wind speed [22].

Despite the variability in and uncertainty of renewable energy systems, integrating them into hybrid energy systems enhances reliability and cost-effectiveness [23].

The cost of hydrogen production is influenced by factors such as the type of electrolysis, installation costs, daily productivity, and a system lifespan's. Although it is more expensive, renewable hydrogen production generates zero emissions. Research aims to reduce these costs through scale and technological advancements, with common approaches including the levelized cost of energy (LCOE) from wind and solar power [24] and the levelized cost of hydrogen (LCOH).

Energy system modelling and simulation has become widespread, with models being upgraded in order to include the changes in energy systems [25,26] and local applications such as energy communities [27] and on-site hydrogen production.

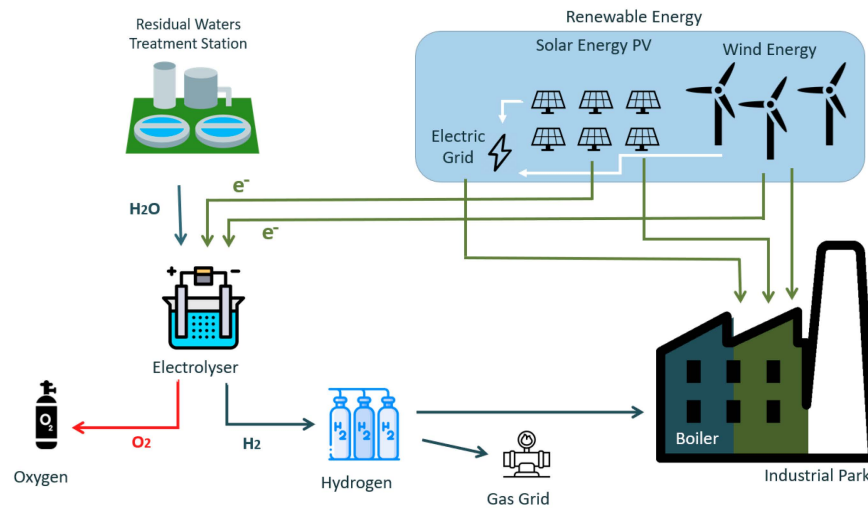
Existing research primarily focuses on the economic costs of hydrogen production, with fewer studies analyzing the financial interactions between hydrogen, gas, and electricity. Addressing this gap, we propose a multipurpose planning model that considers multivariate inputs and outputs, characterizing green hydrogen production under various scenarios.

This study introduces a novel integrated optimization model that sizes renewable hydrogen production systems based on solar PV and wind sources while thoroughly analyzing financial dynamics and operational feasibility in hard-to-abate sectors by considering a real-world ceramics factory. It offers actionable insights for effective decarbonization strategies.

The remainder of this paper is organized as follows: Section 2 describes the methodology used, Section 3 presents the results of the ceramic industry case under analysis, Section 4 presents some discussions, and Section 5 draws the main conclusions.

## 2. Methodology

This section presents a general hybrid model with renewable electricity generation and renewable hydrogen production. Figure 1 illustrates the system under analysis, which includes a ceramic factory supplied by electricity and natural gas.



**Figure 1.** Layout of the overall system of renewable hydrogen production and supply to the ceramics factory.

In this setting, the development of renewable projects such as wind and PV had the potential for replacing electricity supplied by the grid with renewable self-consumption and natural gas demand by renewable hydrogen.

The electricity produced by renewable sources (PV and wind) could be used for electricity self-consumption by the ceramics factory, applied as the energy source needed to power the electrolyser or sold to the electricity grid. In addition, the renewable hydrogen produced could be used for self-consumption, used as a substitute for natural gas, or sold to the gas grid.

This system was modelled with its technical and economical features by a profit maximization constrained problem, as presented in (1). The model was implemented using the General Algebraic Modelling System (GAMS [28]) as a linear programming problem and run with the CPLEX solver [29].

$$\begin{aligned}
 \max \pi = & \sum_t V_{SellGrid_t}^{H_2} \cdot \lambda_t^{H_2} + \sum_t V_t^{O_2} \cdot \lambda_t^{O_2} + \sum_t V_{SellGrid_t}^{Elec} \cdot \lambda_{Surplus_t}^{Elec} \\
 & - \sum_t buyGrid_t^{Elec} \cdot \lambda_t^{Elec} - \sum_t buyGrid_t^{Gas} \cdot \lambda_t^{Gas} \\
 & - \sum_t buy_t^{greenElec} \cdot \lambda_t^{greenElec} - \sum_t buy_t^{H_2O} \cdot \lambda_t^{H_2O} \\
 & - CRF_{ELY} \cdot P_{ELY} - \sum_r CRF_r \cdot P_r - O\&M
 \end{aligned} \quad (1)$$

Problem (1) represents the net income of product sales and cost savings from the self-consumption of gas and electricity, including the annualized investment costs of the renewable technologies (wind and PV) and electrolyser. The decision variables are the installed capacity of wind, PV, and the electrolyser that maximizes the total net income.

The first term is the revenue from the sale of the hydrogen produced, where  $V_{SellGrid_t}^{H_2}$  is the volume of hydrogen produced for sale to the gas grid and  $\lambda_t^{H_2}$  its price. The second term refers to revenues from the sale of oxygen, where  $V_t^{O_2}$  corresponds to the total volume of oxygen produced and  $\lambda_t^{O_2}$  to its sale price. The last revenue term is the profit related to the surplus renewable electricity to be injected into the grid, where  $V_{SellGrid_t}^{Elec}$  represents the surplus renewable electricity and  $\lambda_{Surplus_t}^{Elec}$  represents its selling price. In addition, the fourth and fifth terms of the equation are related to the costs of purchasing electricity and gas from the grid, respectively, by the industrial units. Thus,  $buyGrid_t^{Elec}$  represents electricity,  $buyGrid_t^{Gas}$  corresponds to gas,  $\lambda_t^{Elec}$  corresponds to the electricity tariff, and  $\lambda_t^{Gas}$  corresponds to the gas tariff. The sixth term is the costs of purchasing renewable energy that might be needed to supply the electrolyser. Therefore,  $buy_t^{greenElec}$  is the renewable

energy purchased and  $\lambda_t^{greenElec}$  is its tariff. Similarly, term seven is the expenditure used for the purchase of water for electrolysis, where  $buy_t^{H_2O}$  is the volume of water and  $\lambda_t^{H_2O}$  the tariff for water. Finally, terms eight and nine are the investment costs of the electrolyser and renewable technologies. The capital recovery factor of the electrolyser is  $CRF_{ELY}$ , the capital recovery factor of the renewable technologies (PV and wind) is  $CRF_r$ , the capacity of the electrolyser is  $P_{ELY}$ , and the installed capacity of the renewable technologies is  $P_r$ . The last term corresponds to the operation and maintenance costs (O&M). Index  $r$  refers to the renewable technologies PV and wind, and  $t$  is the time period index that runs from hour 1 to 8760 of the year.

The capital recovery factors for renewable technologies ( $CRF_r$ ) and the electrolyser ( $CRF_{ELY}$ ) are calculated as shown in expressions (2) and (3), respectively.

$$CRF_r = \frac{\alpha (1 + \alpha)^{\tau_r}}{(1 + \alpha)^{\tau_r} - 1} \cdot CAPEX_r \quad (2)$$

$$CRF_{ELY} = \frac{\alpha (1 + \alpha)^{\tau_{ELY}}}{(1 + \alpha)^{\tau_{ELY}} - 1} \cdot CAPEX_{ELY} \quad (3)$$

where  $\alpha$  corresponds to the intertemporal discount rate,  $\tau_r$  is the lifetime of the renewable technology in years, and  $\tau_{ELY}$  is the lifetime of the electrolyser in years.

The electricity consumption in period  $t$  ( $D_t^{Elec}$ ) can be supplied by renewable self-consumption or by the grid, as expressed by (4). Equation (5) establishes that gas consumed in period  $t$  ( $D_t^{Gas}$ ) can be either sourced from the grid or replaced by the hydrogen produced on site.

$$D_t^{Elec} = Renew_t^{SC} + buyGrid_t^{Elec} \quad (4)$$

$$D_t^{Gas} = PCS^{H_2} \cdot V_{SC_t}^{H_2} + buyGrid_t^{Gas} \quad (5)$$

where  $Renew_t^{SC}$  is the renewable energy produced that is used for self-consumption, and  $buyGrid_t^{Elec}$  is the electricity consumption from the grid.  $PCS^{H_2}$  is the higher calorific value of hydrogen (equal to 39.41 kWh/kg<sup>H<sub>2</sub></sup> at a temperature of 25 °C and a pressure of 1 atmosphere).  $V_{SC_t}^{H_2}$  is the quantity of hydrogen for self-consumption, and  $buyGrid_t^{Gas}$  is the consumption of gas from the grid.

Expressions (6) and (7) present the total amount of hydrogen produced ( $V_t^{H_2}$ ).

$$V_t^{H_2} = V_{SC_t}^{H_2} + V_{SellGrid_t}^{H_2} \quad (6)$$

$$V_t^{H_2} = \frac{1}{\gamma} \cdot (Renew_t^{ELY} + buy_t^{greenElec}) \quad (7)$$

where  $V_{SellGrid_t}^{H_2}$  is the quantity of hydrogen for sale to the grid,  $\gamma$  is the energy consumption by the electrolyser (53.33 kWh/kg<sup>H<sub>2</sub></sup>),  $Renew_t^{ELY}$  is the renewable energy produced that is used for electrolysis, and  $buy_t^{greenElec}$  is the consumption of renewable electricity from the grid.

The total renewable production in period  $t$  is expressed in (8).

$$\sum_{pv} R_{pv,t} \cdot P_{pv} \cdot \eta_{inverter} \cdot \eta_{pv} + \sum_{wind} R_{wind,t} \cdot P_{wind} = Renew_t^{SC} + Renew_t^{ELY} + V_{SellGrid_t}^{Elec} \quad (8)$$

where  $R_{pv,t}$  is the normalized hourly production of the PV and  $R_{wind,t}$  is the normalized hourly production of the wind resource,  $P_{pv}$  corresponds to the installed capacity of the photovoltaic technology, and  $P_{wind}$  is the installed capacity of the wind technology. It should also be noted that  $\eta_{inverter}$  refers to the efficiency of the inverters and  $\eta_{pv}$  refers to the efficiency of the PV panels.

The amount of oxygen produced ( $V_t^{O_2}$ ) can be expressed by (9).

$$V_t^{O_2} = \omega \cdot V_t^{H_2} \quad (9)$$

where  $\omega$  is the ratio between the oxygen and hydrogen weight, which equals  $8 \text{ kg}^{O_2} / \text{kg}^{H_2}$ .

In order to calculate the amount of water needed to be consumed by electrolysis, Expression (10) is applied.

$$buy_t^{H_2O} = V_t^{H_2} \cdot (\omega + 1) \quad (10)$$

Additional constraints in capacity and volume are expressed by (11) to (18).

$$P_{r_{min}} \leq P_r \leq P_{r_{max}} \quad (11)$$

$$P_{ELY_{min}} \leq P_{ELY} \leq P_{ELY_{max}} \quad (12)$$

$$V_{SC_t}^{H_2} \leq V_{SC_{max_t}}^{H_2} \quad (13)$$

$$V_{SellGrid_t}^{H_2} \leq V_{SellGrid_{max_t}}^{H_2} \quad (14)$$

$$V_{SC_t}^{H_2} \leq \beta \frac{buy_{Grid_t}^{Gas}}{PCS^{H_2}} \quad (15)$$

$$Renew_t^{ELY} + buy_t^{greenElec} \leq P_{ELY} \quad (16)$$

$$\sum_{pv} P_{pv} \leq P_{PV_{max}} \quad (17)$$

$$\sum_{wind} P_{wind} \leq P_{wind_{max}} \quad (18)$$

Expression (11) sets the minimum and maximum limits for the capacity to be installed in renewable technology  $r$ , (12) sets the minimum and maximum limits of the electrolyser capacity to be installed, and (13) and (14) establish the maximum limits for hydrogen for self-consumption and for sale to the grid, respectively. In addition, (15) limits the share of hydrogen that can be used as a substitute for gas at  $\beta$ . This limit results from the immediate impossibility of certain industries fully replacing gas with hydrogen. Expression (16) sets the amount of hydrogen that the electrolyser can produce. Moreover, Expression (17) establishes the limit for the installed capacity of PV and (18) establishes it for the wind capacity.

Expression (19) converts the hydrogen produced in kg to MWh using the higher calorific value.

$$V_t^{H_2} [\text{MWh}] = V_t^{H_2} [\text{kg}] \cdot PCS^{H_2} \quad (19)$$

Equations (20)–(24) are intended to find out how much renewable electricity is produced by each of the technologies used to power the electrolyser.

Firstly, it is necessary to estimate the production of renewable electricity by technology  $r$ , which is presented in MWh. Thus, Equation (20) shows the renewable production of photovoltaic panels in MWh, (21) the renewable production of wind energy in MWh, and (22) the total renewable production in MWh.

$$Renew_{pv}(pv) = \sum_t R_{pv,t} \cdot P_{pv} \cdot \eta_{inversor} \cdot \eta_{pv} \quad (20)$$

$$Renew_{eol}(wind) = \sum_t R_{wind,t} \cdot P_{wind} \quad (21)$$

$$RenewTotal = \sum_{pv} Renew_{pv}(pv) + \sum_{wind} Renew_{wind}(wind) \quad (22)$$

This is followed by the calculation of renewable electricity production from solar energy to feed the electrolyser in MWh, as shown in Equation (23), and, finally, the calculation of renewable electricity production from wind energy to feed the electrolyser in MWh, as shown in Equation (24).

$$Renew_{ELY_{tec}}(pv) = \left( \frac{Renew_{PV}(pv)}{Renew_{Total_r}} \right) \cdot Renew_{ELY_{Total}} \quad (23)$$

$$Renew_{ELY_{tec}}(wind) = \left( \frac{Renew_{WIND}(wind)}{Renew_{Total_r}} \right) \cdot Renew_{ELY_{Total}} \quad (24)$$

The energy consumed by the electrolyser is calculated in Equation (25), where the sum of the renewable electricity used to power the electrolyser and the renewable energy purchased is calculated.

$$Energy_{ELY_{TOTAL}} = \sum_t Renew_t^{ELY} + \sum_t buy_t^{greenElec} \quad (25)$$

The capacity factor of the electrolyser is computed according to Expression (26).

$$CF_{ELY} = \frac{\sum_t V_t^{H_2}}{P_{ELY} \cdot 8760 \cdot 100} \quad (26)$$

The levelized cost of energy for the renewable technologies is computed by (27).

$$LCOE(r) = \frac{CRF_r \cdot P_r}{\sum_t (R_{r,t} \cdot P_r)} \quad (27)$$

The levelized cost of hydrogen (LCOH) corresponds to the ratio between the present value of the sum of all costs related to hydrogen production during the project's life cycle and the present value of hydrogen production for a period of 1 year.

In the context of the presented model, the LCOH is computed by (28), where each component is developed by (29) to (32).

$$LCOH = LCOH_{CAPEX} + LCOH_{Renew} + LCOH_{greenElec} + LCOH_{H_2O} \quad (28)$$

$$LCOH_{CAPEX} = \frac{CRF_{ELY} \cdot P_{ELY}}{\sum_t (V_{SC_t}^{H_2} + V_{SellGrid_t}^{H_2})} \quad (29)$$

$$LCOH_{Renew} = \frac{\sum_r (Renew_{ELY_{tec}}(r) \cdot LCOE(r))}{\sum_t (V_{SC_t}^{H_2} + V_{SellGrid_t}^{H_2})} \quad (30)$$

$$LCOH_{greenElec} = \frac{\sum_t buy_t^{greenElec} \cdot \lambda_t^{greenElec}}{\sum_t (V_{SC_t}^{H_2} + V_{SellGrid_t}^{H_2})} \quad (31)$$

$$LCOH_{H_2O} = \frac{\sum_t buy_t^{H_2O} \cdot \lambda_t^{H_2O}}{\sum_t (V_{SC_t}^{H_2} + V_{SellGrid_t}^{H_2})} \quad (32)$$

### 3. Results

The model described in the previous section is used to identify the optimal renewable capacity of PV and wind to be installed on site and the electrolyser's optimal capacity

considering the multiple uses of the renewable electricity discussed and the corresponding economic value.

Results are computed and presented regarding the optimal installed capacity of PV, wind and the electrolyser. Hourly energy generation and consumption is also computed for an entire year of operation and presented for an illustrative month (May was chosen). The overall yearly energy flows are also presented for each scenario.

Moreover, the levelized cost of energy (LCOE), for PV and wind, as well as the levelized cost of hydrogen (LCOH), is also presented.

The levelized cost of energy (LCOE) is the average price at which electricity is produced by renewables, in this case PV and wind. The levelized cost of hydrogen (LCOH) is the cost per unit of hydrogen for paying for the project over its life cycle to obtain a zero net present value of the project (NPV). It enables the comparison, on a similar basis, of different hydrogen production scenarios.

Two scenarios for the gas price are used: a low-gas-price scenario of  $\lambda_t^{Gas} = 50$  EUR/MWh (Scenario 1) and a high-gas-price scenario of  $\lambda_t^{Gas} = 150$  EUR/MWh (Scenario 2). Other input data are shown in Table 1.

**Table 1.** Input data for the simulations of Scenario 1 and Scenario 2.

	Scenario 1	Scenario 2
<b>ELECTROLYSER</b>		
Capex (EUR/kW)	1750	1750
Min. capacity (MW)	5	5
Max. capacity (MW)	10	10
<b>RENEWABLES</b>		
Capex PV (EUR/kW)	650	650
Capex wind (EUR/kW)	1000	1000
<b>TARIFFS</b>		
Electricity (EUR/MWh)	90	90
Gas (EUR/MWh)	50	150
Green electricity (EUR/MWh)	120	120
Water (EUR/kg)	0.01	0.01
<b>SELLING PRICE</b>		
Hydrogen (EUR/kg)	5.0	5.0
Electricity surplus (EUR/MWh)	0	0
Oxygen (EUR/kg)	0	0

With this input data, the electricity surplus and oxygen will not contribute to the system revenues as the price is taken as 0. The lifetime for the electrolyser is 10 years, and that for the renewable technologies (PV and wind) is 25 years. A 5% discount rate is considered in the financial analysis.

Simulation results concerning the electrolyser, hydrogen production optimal capacity, and hydrogen generation are presented in Table 2.

The optimal capacity for the electrolyser of 5.0 MW is equal to the minimum limit (see Table 1 for input data), which reveals that a lower capacity would be desired for the underlying conditions of the scenarios. For this electrolyser capacity of 5.0 MW, the optimal mix of PV and wind consists of 13.6 MW of PV and 8.4 MW of wind in Scenario 1 and 13.6 MW of PV and 8.9 MW of wind in Scenario 2. This represents a total installed renewable capacity of 22 MW, more than four times the electrolyser's capacity. This results from the low capacity factor of the renewable sources (15.4% for PV and 16% for wind), in comparison to the capacity factor of the electrolyser (46.4% and 46.9% in Scenario 1 and Scenario 2, respectively), needed to make good use of the capital investment in the electrolyser of 1750 EUR/kW in the analysed use case.

**Table 2.** Simulation results for hydrogen and renewable energy capacity and generation.

	Scenario 1	Scenario 2
<b>HYDROGEN</b>		
Capacity (MW)	5.0	5.0
Capacity factor (%)	46.4	46.9
LCOH (EUR/kg)	5.14	5.12
ELY Sourcing (MWh)	20,330	20,554
Renewable (MWh)	20,330	20,554
Grid supply (MWh)	0	0
ELY losses (MWh)	5306	5365
Production (MWh)	15,023	15,189
Self-consumption (MWh)	0	6070
Sell to gas grid (MWh)	15,023	9120
<b>RENEWABLES</b>		
Capacity (MW)	22.0	22.4
PV	13.6	13.6
Wind	8.4	8.9
Energy (MWh)	30,103	30,661
PV	18,340	18,258
Wind	11,763	12,403
Capacity factor (%)	15.6	15.6
PV	15.4	15.4
Wind	16.0	16.0
LCOE (EUR/MWh)	40.7	40.9
PV	34.2	34.7
Wind	50.7	50.7

The annual economic results from the investment in renewable hydrogen are presented in Table 3, with disaggregated results for the annual revenues and annualized investment costs.

**Table 3.** Annual financial results of the investment in renewable hydrogen production in the ceramics factory (EUR).

	Scenario 1	Scenario 2
Profit (EBIT)	39,792	179,584
Revenues	2,397,581	2,567,731
H <sub>2</sub> to gas grid	1,906,019	1,157,028
Renewable surplus to electricity grid	0	0
Oxygen	0	0
H <sub>2</sub> self-consumption (cost reduction in gas)	0	910 452
Renewables self-consumption (cost reduction in electricity)	491,562	500,251
Costs	2,357,789	2,388,147
Electrolyser	1,133,165	1,133,165
Renewables	1,224,281	1,254,635
PV	627,710	625,590
Wind	596,571	629,045
Water	343	347
Green electricity	0	0

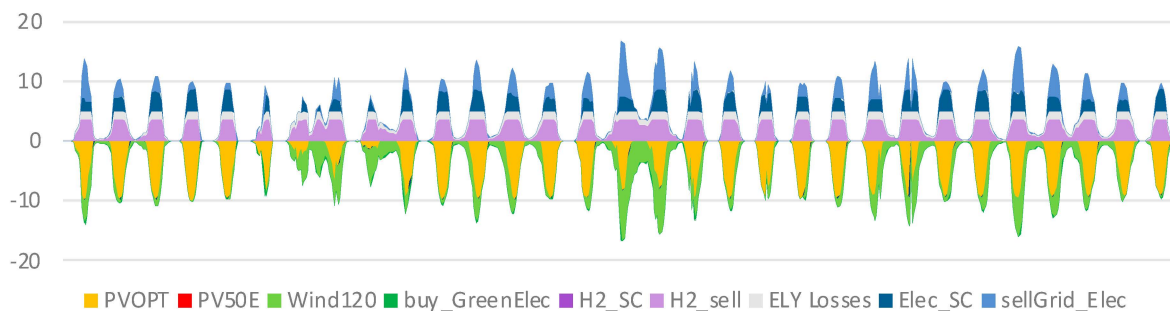
It is seen that the project is profitable for the low-gas-price scenario (Scenario 1) and the high-gas-price scenario (Scenario 2), being much more valuable in the latter scenario (39.8 k/EUR vs. 179.5 k/EUR annually). For the profitability of this project, the added value of the self-consumption of renewable power is key, which accounts for 491.6 kEUR in

Scenario 1 and 500.3 kEUR in Scenario 2, as is the hydrogen self-consumed in Scenario 2, which accounts for 910.5 kEUR. The price of selling hydrogen to the gas grid is 5 EUR/kg, which corresponds to 127 EUR/MWh, explaining why hydrogen is only self-consumed in Scenario 2 as a competitive substitute for gas, at a gas price of 150 EUR/MWh (higher than the 127 EUR/MWh), and not in Scenario 1, which considers a gas price of 50 EUR/MWh (lower than the 127 EUR/MWh).

### 3.1. Low-Gas-Price Scenario (Scenario 1)

For the low-gas-price scenario ( $\lambda_t^{Gas} = 50$  EUR/MWh), the optimal investment decision, using the model described in the previous section, corresponds to 13.6 MW for installed capacity for PV and 8.4 MW for wind capacity to source the electrolyser of 5 MW. In this scenario, the LCOE for PV is 34.2 EUR/MWh, the LCOE for wind is 50.7 EUR/MWh, and the LCOH is 5.14 EUR/kg.

Figure 2 illustrates the generation of renewable power and the corresponding use in one month of simulation (May was chosen). The lower part refers to renewable production (wind and PV) and the upper part refers to the consumption. The series in yellow represents the renewable electricity obtained through PV with the optimal slope ( $36^\circ$  with an azimuth of  $6^\circ$ ) and the renewable wind energy obtained with a wind turbine at a 120 m height.



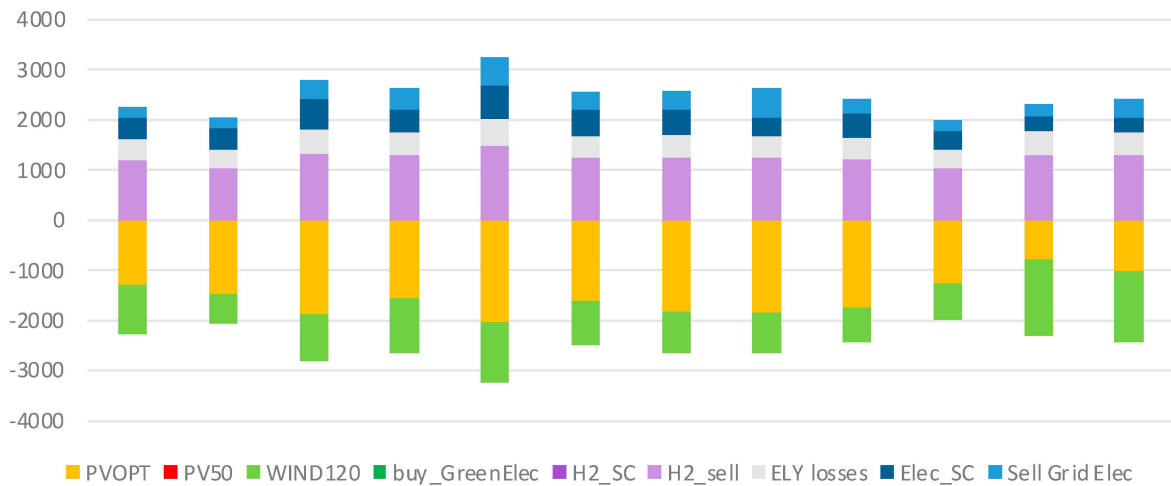
**Figure 2.** Renewable electricity and the corresponding use for one month of simulation in the low-price scenario (MWh).

The upper part of the graph shows three colors. Dark blue refers to the renewable electricity used for self-consumption by the factory, and light blue is the surplus of renewable electricity that can be sold to the electricity grid. Purple refers to the renewable electricity used to power the electrolyser. Light purple represents the hydrogen sold to the grid, and dark purple (which has no value in this scenario) is the hydrogen used for self-consumption by the factories. Finally, in grey, it is possible to see the losses from the electrolyser.

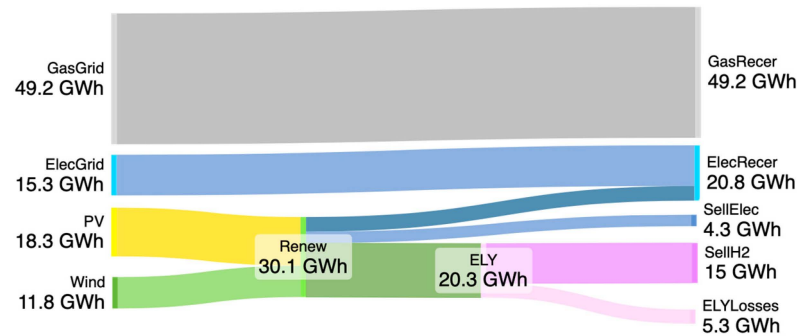
Figure 3 presents renewable energy production and its respective use for one year on a monthly basis.

Figure 4 shows the annual energy flows in Scenario 1. It is important to note that GasGrid is the gas purchased from the grid by the factories, and GasRecer is the gas consumption by the ceramics factory. Similarly, ElecGrid refers to electricity purchased from the grid to power the industrial units, and ElecRecer is the electricity consumed by the industrial units.

PV is the electricity produced by photovoltaics, Wind is the electricity generated from wind, and Renew is the renewable combined generation. Finally, ELY corresponds to the energy input of the electrolyser, SellH2 represents the hydrogen sold to the gas grid, and SellElec is the surplus electricity sold to the electricity grid. ELYLosses represents the losses from the electrolyser.



**Figure 3.** Renewable electricity and its corresponding use for one year of simulation in the low-price scenario (MWh).

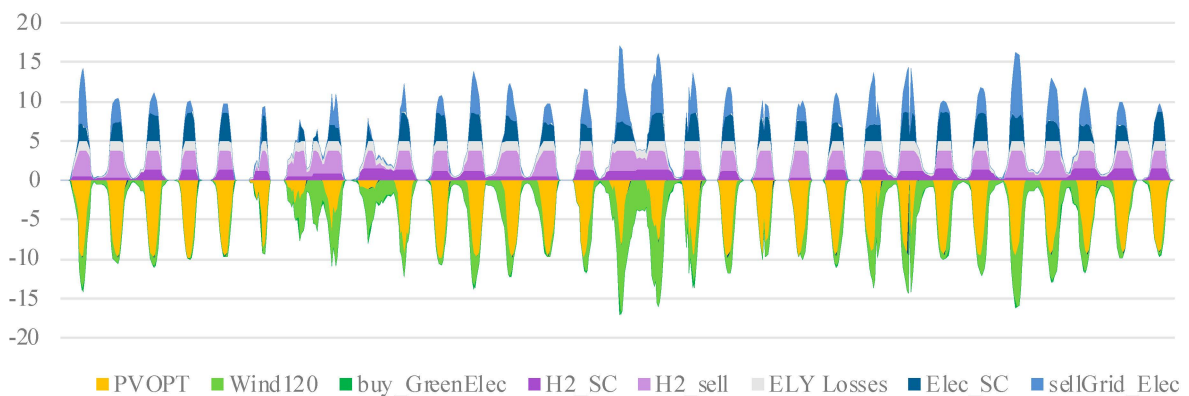


**Figure 4.** Energy flow diagram for the low-gas-price scenario.

**3.2. High-Gas-Price Scenario (Scenario 2)**

For the high-gas-price scenario ( $\lambda_t^{Gas} = 150$  EUR/MWh), which represents the price of gas in periods of the 2022 energy crisis, the optimal installed capacity is 13.6 MW for the PV, 8.9 MW for wind, and 5 MW for the electrolyser’s installed capacity. In this scenario, the LCOE for PV is 34.7 EUR/MWh, and for wind, it is 50.7 EUR/MWh. Finally, the LCOH is 5.12 EUR/kg.

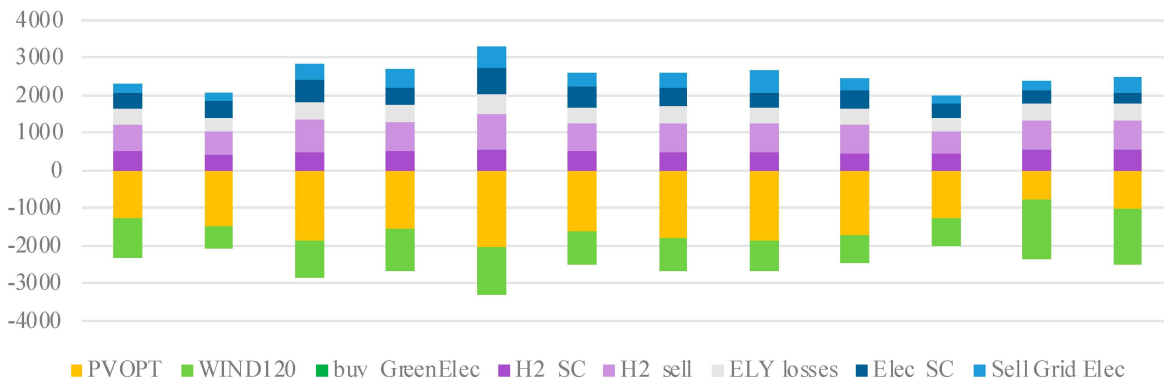
Figure 5 presents the generation of renewable power and the corresponding use in one month of simulation (May was chosen).



**Figure 5.** Renewable electricity and its corresponding use for one month of simulation in the high-price scenario (MWh).

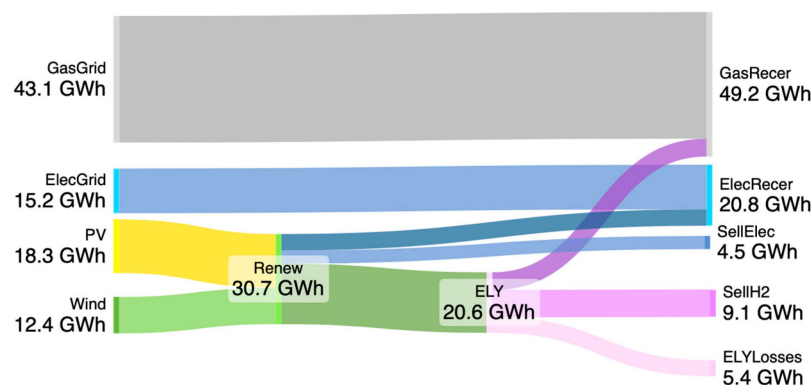
In this case, it is possible to verify that a large share of hydrogen is used for self-consumption (dark purple) as a substitute for natural gas in the ceramics factory. The remaining (light purple) is sold to the gas grid.

The Figure 6 presents renewable electricity and its corresponding use for one year.



**Figure 6.** Renewable electricity and its corresponding use for one year of simulation in the high-price scenario (MWh).

Figure 7 presents the annual energy flow diagram for this high-gas-price scenario with the variables described above in the Scenario 1 description.



**Figure 7.** Energy flow diagram for the high-gas-price scenario.

Compared to the previous case (low gas price), it is important to notice that the value of GasGrid is lower because, in this case, some of the hydrogen produced is used for self-consumption, as can be seen in dark purple, reducing the amount of gas needed.

#### 4. Discussion

The model presented in this work and its application to the real case of a ceramics factory put in evidence the multiple value streams of a project of this kind. The renewable electricity generation from solar PV and wind can directly supply the electricity demand in the factory (electricity self-consumption), and the electricity surplus can be sold to the electricity grid. Additionally, following the main goal of the project, the renewable electricity can be converted into renewable hydrogen in the electrolyser, which, in turn, is used to replace natural gas in the factory (gas self-consumption) and inject hydrogen into the gas grid.

The results presented in the previous section put in evidence the conditions under which the hydrogen would be used for self-consumption, based on the economic merit of the renewable hydrogen over natural gas. In this regard, as the renewable hydrogen can be injected into the gas grid at a price of 5 EUR/kg, there would be an economic advantage to use hydrogen to replace gas in the ceramics factory only at natural gas prices exceeding

127 EUR/MWh, the equivalent of 5 EUR/kg. This was exemplified by Scenario 1, with a gas price of 50 EUR/MWh, where no hydrogen was used for self-consumption, and Scenario 2, with a gas price of 150 EUR/MWh, where hydrogen was used for self-consumption as a substitute for natural gas in the ceramics factory.

The environmental impact of the project regarding GHG emissions reduction is also to be discussed, taking into account the multiple destinations of the renewable generation. Accordingly, the impact is partially system-dependent. In fact, the impact of the renewable generation used as electricity surplus to be supplied the electricity grid depends on the existing electricity mix in the grid. In this case, the GHG reduction should be accounted for as the difference in the specific emissions of the grid electricity mix multiplied by the volume of electricity surplus in each period. The impact on the GHG mitigation by hydrogen is more straightforward as it substitutes natural gas, either when used in the ceramics factory or in the injection to the gas grid. In this case, the GHG reductions are the avoided emissions that would have been put in place by burning the natural gas. In the studied scenarios, this would represent annual CO<sub>2</sub> emission reductions of 3017 Mg in Scenario 1 and 3050 Mg in Scenario 2 (using natural gas-specific emissions of 200.8 g CO<sub>2</sub>/kWh).

As an evolving technology, electrolysers are expected to develop in scale, cost and efficiency, which means that the presented results would be changed by these technological developments. To evaluate the impact of the electrolyser costs and efficiency, additional simulations were carried out to assess the LCOH under different conditions of Capex and efficiency, considering that the electrical efficiency of alkaline electrolysers is presently 63%–73% and the goal is to achieve 70–80% [30]. Figure 8 presents the LCOH forecasts for the case study of the ceramics factory using four electrolyser efficiencies (65%, 70%, 75%, 80%) for three levels of Capex (500 EUR/kW, 1000 EUR/Kw, and 1750 EUR/kW).



**Figure 8.** LCOH as a function of the electrolyser efficiency for three levels of Capex: 500 EUR/kW, 1000 EUR/Kw, and 1750 EUR/kW (EUR/kg).

## 5. Conclusions

This paper presents a multipurpose renewable hydrogen production planning model with an application to a real-case ceramics industry scenario, which demonstrates how renewable hydrogen projects can add and optimize economic value in hard-to-abate sectors.

The renewable electricity generation from solar PV and wind can directly supply electricity demand in the factory (electricity self-consumption), and the electricity surplus can be sold to the electricity grid. Additionally, following the main goal of the project, the renewable electricity can be converted into renewable hydrogen in the electrolyser which, in turn, is used to replace natural gas in the factory (gas self-consumption) and inject hydrogen into the gas grid. The model is also able to value the oxygen generated in the electrolysis process, in case an off taker exists for this good.

This multiple-purpose complex model was developed and implemented as a profit maximization constrained problem using the General Algebraic Modelling System (GAMS). Our results show the different tradeoffs in applications of renewable hydrogen and re-

newable electricity generation in the ceramics industry, highlighting the capacity to meet demand through self-consumption (electricity and gas) and sell surplus to the grids (electricity and gas).

Two scenarios of hydrogen production from renewable energy sources are studied with a selling price of hydrogen to the gas grid of 5 EUR/kg—a low-gas-price scenario of 50 EUR/MWh and a high-gas-price scenario of 150 EUR/MWh. In the first scenario (Scenario 1), with the gas price at 50 EUR/MWh, hydrogen is only sold to the grid because hydrogen injected to the gas grid is valued at 5 EUR/kg, which equals 127 EUR/MWh. On the other hand, when the gas price increases to 150 EUR/MWh (Scenario 2), its value is higher than the hydrogen price and, therefore, hydrogen self-consumption is prioritized to reduce the cost of the gas supply in the factory.

As a result, it is found to be beneficial to sell all the hydrogen produced to the gas grid rather than using it for self-consumption in the factory when the price of gas is low. On the other hand, when the price of gas is significantly high, it is more effective to use as much hydrogen as possible for self-consumption to supply the factory and reduce the use of natural gas.

The role of electricity self-consumption has proven to be key for the application use case in the ceramics industry as, without this revenue stream, the project would not be profitable in any analysed scenario.

Furthermore, this study shows that hydrogen can reduce GHG emissions by replacing natural gas, either in the ceramics factory or in the gas grid. In the studied scenarios, substituting natural gas with hydrogen would result in an annual CO<sub>2</sub> emissions reduction of over 3000 Mg.

Developments in electrolyser technology were also assessed for improvements due to the scaling-up capacity that is expected to bring efficiency improvements and cost reductions. In this regard, in the presented ceramics use case, the LCOH undergoes a decrease from 6.67 EUR/kg, for the base case with 65% efficiency and an electrolyser Capex of 1750 EUR/kW, to 2.86 EUR/kg, for an improved efficiency of 80% and an electrolyser Capex of 500 EUR/kW.

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