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Power Cost and CO₂ Emissions for a Microgrid with Hydrogen Storage and Electric Vehicles

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Abstract: Hydrogen is considered the primary energy source of the future. The best use of hydrogen is in microgrids that have renewable energy sources (RES). These sources have a small impact on the environment when it comes to carbon dioxide (CO₂) emissions and a power generation cost close to that of conventional power plants. Therefore, it is important to study the impact on the environment and the power cost. The proposed microgrid comprises loads, RESs (micro-hydro and photovoltaic power plants), a hydrogen storage tank, an electric battery and fuel cell vehicles. The power cost and CO₂ emissions are calculated and compared for various scenarios, including the four seasons of the year, compared with the work of other researchers. The purpose of this paper is to continuously supply the loads and vehicles. The results show that the microgrid sources and hydrogen storage can supply consumers during the spring and summer. For winter and autumn, the power grid and steam reforming of natural gas must be used to cover the demand. The highest power costs and CO₂ emissions are for winter, while the lowest are for spring. The power cost increases during winter between 20:00 and 21:00 by 336%. The CO₂ emissions increase during winter by 8020%.

Keywords: CO₂ emissions; microgrid; electric vehicles; hydrogen storage; fuel cell; power cost; renewable energy sources; seasons



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1. Introduction

A topic that is currently gaining importance in our lives is the idea of energy. The requirement for energy is growing along with the human population and needs. The rising energy demands, which will rise significantly more in the upcoming years, are met by using both fossil fuels and renewable energy sources (RESs). The main issue with RESs is the fact that they have an intermittent and variable power output [1–5]. One possibility to overcome this issue is to use storage systems [5].

It is possible to improve energy control, dependability, and quality by storing power in batteries, pumped hydro, fuel cells, or supercapacitors. For large-scale export, storage, and transport, hydrogen-based fuel cells and other storage devices are becoming more and more important [2,5–7].

Due to its enormous potential to help create a more liveable and sustainable world for humans, hydrogen is increasingly regarded as the primary energy source of the future. Hydrogen can be produced in a variety of ways, including electrical, thermal, hybrid, and biological [3,8–10]. The cost of hydrogen varies between 0.8 and 6 EUR/kg considering the technology and materials used [11]. The cost is expected to be around 1.8 EUR/kg in 2030 due to developments in the hydrogen production method [11–15]. Also, the carbon dioxide (CO₂) emissions vary considering the production method.

The most desirable use of power and hydrogen is in microgrids, which can achieve low CO₂ emissions [16]. The power supplied by the RESs of a microgrid can be converted into hydrogen through water electrolysis. Also, hydrogen can be used by fuel cell electric vehicles.

The rest of the paper is organized as follows. The work of other researchers is presented in Section 2, the literature review. In Section 3, the algorithm and mathematical model used to calculate the power cost and CO₂ emissions are presented. In Section 4 the results, the discussion and interpretation of the findings are presented, while in Section 5 the conclusions are presented.

2. Literature Review

The dynamic planning of a microgrid, considering uncertainties, was performed by Sun et al. in [16]. The optimal scheduling of a microgrid that comprised wind, photovoltaic (PV) and hydrogen storage was determined by Zhang et al. in [17]. A rural microgrid was investigated by Alluraiah et al. in [18], and its operation cost was minimum, while in [19] study was performed by Zhong et al. on a real microgrid. In [20], the optimal power dispatch of the microgrid sources and hydrogen storage was determined by Ghezlbash et al. in order to maximize the profit of the microgrid. A control strategy was developed by Villa Londono et al. in [21]; power exchange was reduced, and stability of the microgrid was improved. The management of a microgrid using wind, PV, battery, fuel cell and supercapacitor power was studied by Sahri et al. in [22], who found that overcharging was avoided. The recent advances in the field of PV and fuel cells were investigated by Arsalis et al. [23].

The management and optimization of the operation of an islanded microgrid were performed by Abdelsalam et al. in [24], in which RESs provided a high amount of power and the backup diesel generator was used less. The expenditure cost and operational revenues were optimized by Cao et al. for a microgrid in [25], so the costs were reduced by 50%. Day-ahead and intra-day optimization were performed by Wang et al. in [26], so the operation cost of the microgrid which comprised wind, PV and hydrogen storage was reduced. The energy management of a hybrid microgrid was studied by Alzahrani in [27], so the reactive power of the loads was reduced by 90%. The optimal power dispatch was determined by Hou et al. in [28] for a system with power, hydrogen and heat storage, in which efficiency and profit were improved. The use of an electrolyser designed for a quick response in case the power demand was higher than the power supplied in a microgrid was investigated by Ganeshan et al. in [29]. In [30], it was determined by Oliveira et al. that the use of hydrogen for transport, industrial applications and buildings can help reduce CO₂ emissions by 18%. A controller was developed by Behera et al. in [31] for power smoothing in a microgrid with a supercapacitor and redox flow battery. The economic feasibility of a microgrid was investigated by Shanbog et al. in [32] considering the cost of power, investment costs and operational costs.

The optimal management of a residential microgrid, which comprised combined heat and power loads, electric vehicles and charging/discharging behaviour was determined by Gong et al. in [33]. A 100% RES station was developed by Li in [34] in order to supply a microgrid. Fan et al., in [35], minimized the daily operation cost of a microgrid. The performance of a hydrogen storage system in a microgrid was investigated by Serra et al. in [36], in which its annual hydrogen production was optimized. In [37], the optimal management of a microgrid with bidirectional power-hydrogen conversion was determined by Khaligh et al. considering price uncertainties and RES power output. The optimal design of a microgrid was determined by Valverde et al. in [38], while a controller was developed by Cecilia et al. in [39] for the optimal management of a microgrid with short-term storage. The frequency and voltage control were investigated by Naseri et al. in [40] for an islanded microgrid that comprised PV sources. The operation of a hydrogen hub with a microgrid was studied by Hossain et al. in [41], so power balance was respected and power-to-hydrogen and hydrogen-to-power were provided when required.

The efficiency of a hydrogen storage system was studied by Bovo et al. in [42], while in [43] Van et al. reviewed the energy management strategies for microgrids. Califano et al. reduced the size of a hydrogen storage tank by 40% in [44] due to the control strategy. The optimization of a microgrid with electrical and hydrogen loads was performed by Mah et al. in [45], while the participation of the power-to-hydrogen in the power markets in

order to minimize the operation costs was investigated by Mansour-Saatloo in [46]. The modeling and analysis of a direct-current microgrid with hydrogen storage were studied in [47,48]. A self-control algorithm for a microgrid was developed and studied by Yang et al. in [49], while Gugulothu et al. determined in [50] the optimal strategy for the power output of the microgrid sources.

The optimal supply of electric and fuel cell vehicles was studied by Förster et al. in [51], while Abo-Elyousr et al. determined in [52] the optimal configuration and size of the sources of a microgrid. Hybrid power–hydrogen refuelling stations, electric, natural gas and hydrogen stations in microgrids were studied in [53,54], while Navas et al. optimized the investment and operation costs in [55] for a hybrid heat and power residential microgrid. The optimal power management was studied by Yousri et al. in [56] for a microgrid considering battery degradation, discomfort, peak-to-average ratio and consumer discomfort, while Kbidi et al. studied in [57] the unit commitment for the components of a microgrid (PV sources, fuel cell, battery and electrolyser). The dispatch of power and hydrogen in real time was studied by Lin et al. in [58] considering the power markets, which resulted in a reduction in the daily operational costs of 37%. The emissions of a FCEV were studied by Heidary et al. in [59]. The emissions were between 50% and 28% lower compared to gasoline vehicles and BEVs. The use of FCEVs in vehicle-to-grid mode was studied by Robledo in [60]. The use was economically beneficial for the end user if the hydrogen prices were below 8.24 EUR/kg. The techno-economic, environmental and safety assessments of hydrogen microgrids were studied by Mukherjee in [61]. The results showed that the system does not have a positive net present value at the end of its project life. The optimal design of a hybrid charging station for battery electric vehicles and fuel cell electric vehicles was performed by Sánchez-Sáinz in [62].

Similar to battery electric vehicles, it is anticipated that sales of fuel cell electric vehicles will increase in the upcoming years. Due to the large hydrogen demand that will result from this increase, it is necessary to research any potential effects on power costs and CO₂ emissions. The main contributions of this paper are as follows:

- The microgrid comprises PV power plants and micro-hydro sources in comparison to other studies, where wind turbines and PV power plants were used;
- The analysis is presented for different scenarios (electric and fuel cell vehicles are connected or not to the system) and seasons (spring, summer, autumn and winter);
- It is determined how much hydrogen can be produced and later used to cover power demand and if it is enough, considering the variable power demand during the seasons; three energy carriers are present (power, hydrogen and natural gas);
- The power cost and CO₂ emissions are analysed.

3. Materials and Methods

The microgrid studied is presented in Figure 1. It has several consumers with an installed power of 160 kW, various supply units (two PV power plants—PV1 with an installed power of 200 kW, and PV2 with an installed power of 160 kW—and three micro-hydro sources—MH1 with an installed power of 70 kW, MH2 with an installed power of 90 kW and MH3 with an installed power of 100 kW), a hydrogen storage tank (60 kg), a fuel cell (600 kW proton exchange membrane electrolyser), battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs).

A PV power plant consists of PV panels and an inverter. Photovoltaic panels transform solar radiation into direct current, while the inverter converts direct current into alternating current. The main components of a photovoltaic panel are the solar cells. A solar cell consists of two or more layers of semiconductor material. When the silicon layer is exposed to light, then the electrons from the material agitate and an electric current will be generated. The current generated by a single cell is small, but series and parallel combinations of these cells can produce currents high enough so they can be used in practice. In order to produce electric current, solar cells are joined together. Photovoltaic modules consist of photovoltaic

circuits sealed in a protective laminate environment. Photovoltaic panels include one or more photovoltaic modules [63].

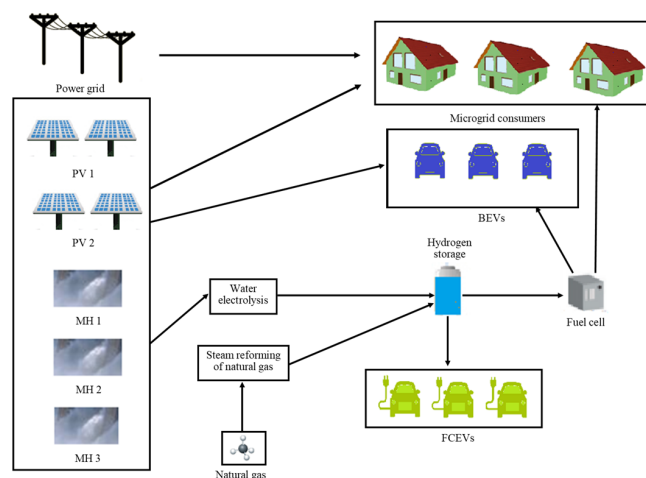


Figure 1. Microgrid with hydrogen storage, BEVs and FCEVs.

Hydropower systems use the energy in flowing water to produce electricity or mechanical energy. For run-of-the-river micro-hydro power systems, a portion of a river's water is diverted to a water conveyance—channel, pipeline, or pressurized pipeline (penstock)—that delivers it to a turbine or waterwheel. The moving water rotates the wheel or turbine, which spins a shaft. The motion of the shaft can be used for mechanical processes, such as pumping water, or it can be used to power an alternator or generator to generate electricity [63].

BEVs comprise an electric motor and a battery that powers the electric motor. The BEVs can be charged at home (outlet) or at a charging station. FCEVs are powered by the chemical reaction of oxygen and hydrogen in the fuel cell, storing electricity and driving the motor with this energy. The FCEVs can be charged at a charging station [17,22].

Water that is supplied to the PEM electrolyser is split into hydrogen and oxygen at the electrodes. At the anode, oxygen is produced by the oxidation of water, while at the cathode, hydrogen is produced by the reduction in protons from the proton exchange membrane [64].

Natural gas comprises methane (CH_4) that can be used to produce hydrogen. In the steam reforming of natural gas, methane reacts with steam under 3–25 bar pressure in the presence of a catalyst to produce hydrogen [64].

The hydrogen produced through water electrolysis or the reforming of natural gas can be stored in a tank. The fuel cell uses the chemical energy of hydrogen in order to generate power [64].

The power demand of the microgrid loads during the seasons is presented in Table 1. This power demand is for Răstolița, a village located in Mureș County, Romania.

An additional power demand from the BEVs was added to the demand in Table 1. Twelve BEVs and two FCEVs were connected to the microgrid. The BEVs were represented by ten Dacia Springs with a battery capacity of 26.8 kW and two Volkswagen ID.4s with a battery capacity of 55 kW. The FCEVs were represented by one Hyundai Nexo with a tank capacity of 6.33 kg and one Toyota Mirai with a tank capacity of 5.6 kg. The BEVs and FCEVs were considered to be charged during the afternoon after the users come back from work. The BEVs were charged at fast charging stations, so the charging took less than one hour. The BEV demand is 134 kW between 18:00 and 19:00 (five Dacia Spring), 55 kW between 19:00 and 20:00 (one Volkswagen ID.4) and 189 kW between 20:00 and 21:00 (five Dacia Spring and one Volkswagen ID.4). The FCEV demand is 11.93 kg of H_2 between 18:00 and 19:00.

The power supplied by the microgrid sources is presented in Table 2 (spring), Table 3 (summer), Table 4 (autumn) and Table 5 (winter).

Table 1. Power demand of the microgrid loads.

Hour (h)	Power Demand [kw]			
	Spring	Summer	Autumn	Winter
1	90.59	86.52	91.33	105.5
2	91.74	85.99	93.66	106.38
3	94.43	87.25	99.28	109.86
4	102.11	93.48	109.28	119.44
5	109.87	100.65	117.79	131.54
6	113.62	103.73	121.98	140.23
7	113.66	105.18	122.27	144.08
8	112.08	105.77	120.8	144.23
9	111.43	107.12	119.89	142.5
10	111.37	108.42	119.57	141.43
11	110.23	107.28	118.65	140.76
12	109.27	106.75	117.5	138.35
13	109.48	106.83	117.18	137.52
14	109.58	106.92	118.18	139.25
15	110.89	106.56	122.27	145.27
16	115	106.78	129.03	147.42
17	122.61	108.34	131.07	146.1
18	123.96	112.55	126.05	141.28
19	115.23	107.5	116.42	132.6
20	104.68	98.87	106.83	116.06
21	97.39	92.15	99.73	117.45
22	93.95	88.38	96.31	111.17
23	91.62	85.94	93.93	107.87
24	90.3	86.13	91.24	105.33

Table 2. Power supplied (spring).

Hour (h)	Power Supplied [kw]				
	PV1	MH1	PV2	MH2	MH3
1	0	50	0	70	80
2	0	50	0	70	80
3	0	50	0	70	80
4	0	50	0	70	80
5	0	50	0	70	80
6	0	50	0	70	80
7	14	50	12	70	80
8	24	50	20	70	80
9	36	50	30	70	80
10	50	50	40	70	80
11	70	50	52	70	80
12	84	50	66	70	80
13	66	50	48	70	80
14	56	50	40	70	80
15	42	50	32	70	80
16	28	50	22	70	80
17	16	50	10	70	80
18	0	50	0	70	80
19	0	50	0	70	80
20	0	50	0	70	80
21	0	50	0	70	80
22	0	50	0	70	80
23	0	50	0	70	80
24	0	50	0	70	80

Table 3. Power supplied (summer).

Hour (h)	Power Supplied [kw]				
	PV1	MH1	PV2	MH2	MH3
1	0	25	0	35	45
2	0	25	0	35	45
3	0	25	0	35	45
4	0	25	0	35	45
5	0	25	0	35	45
6	10	25	6	35	45
7	22	25	16	35	45
8	38	25	24	35	45
9	54	25	36	35	45
10	68	25	50	35	45
11	82	25	64	35	45
12	100	25	80	35	45
13	84	25	66	35	45
14	72	25	52	35	45
15	58	25	38	35	45
16	42	25	30	35	45
17	26	25	20	35	45
18	14	25	8	35	45
19	0	25	0	35	45
20	0	25	0	35	45
21	0	25	0	35	45
22	0	25	0	35	45
23	0	25	0	35	45
24	0	25	0	35	45

Table 4. Power supplied (autumn).

Hour (h)	Power Supplied [kw]				
	PV1	MH1	PV2	MH2	MH3
1	0	28	0	38	48
2	0	28	0	38	48
3	0	28	0	38	48
4	0	28	0	38	48
5	0	28	0	38	48
6	0	28	0	38	48
7	10	28	6	38	48
8	18	28	10	38	48
9	32	28	16	38	48
10	42	28	24	38	48
11	56	28	34	38	48
12	68	28	46	38	48
13	58	28	36	38	48
14	44	28	26	38	48
15	36	28	18	38	48
16	22	28	12	38	48
17	12	28	8	38	48
18	0	28	0	38	48
19	0	28	0	38	48
20	0	28	0	38	48
21	0	28	0	38	48
22	0	28	0	38	48
23	0	28	0	38	48
24	0	28	0	38	48

Table 5. Power supplied (winter).

Hour (h)	Power Supplied [kw]				
	PV1	MH1	PV2	MH2	MH3
1	0	30	0	40	50
2	0	30	0	40	50
3	0	30	0	40	50
4	0	30	0	40	50
5	0	30	0	40	50
6	0	30	0	40	50
7	0	30	0	40	50
8	10	30	6	40	50
9	24	30	14	40	50
10	32	30	22	40	50
11	42	30	28	40	50
12	50	30	34	40	50
13	38	30	30	40	50
14	26	30	24	40	50
15	16	30	12	40	50
16	0	30	0	40	50
17	0	30	0	40	50
18	0	30	0	40	50
19	0	30	0	40	50
20	0	30	0	40	50
21	0	30	0	40	50
22	0	30	0	40	50
23	0	30	0	40	50
24	0	30	0	40	50

The power supplied by the microgrid sources is used to cover the power demand of the loads and BEVs. If there is an excess power, then this power is converted by means of water electrolysis into hydrogen and stored in the tank. The hydrogen stored in the tank can be used to charge the FCEVs or it can also be converted into power by means of a fuel cell. The power grid is used only as a backup to cover the power demand in case the power supplied by the microgrid sources is not enough or the sources have a technical problem. Also, a backup source for hydrogen demand is natural gas, which can be converted by steam reforming, which is currently the most used method for hydrogen production.

The power cost is calculated first:

$$\text{Min PC} = \sum g_{ci} \cdot P_{ih} + \sum h \cdot N + \sum n_g \cdot N, \quad (1)$$

where PC represents the power cost for the microgrid in EUR, g_{ci} represents the generation cost in EUR/kWh, P_{ih} represents the energy supplied by the source i at hour h in kWh, h represents the power to hydrogen conversion cost which is 5 EUR/kg for water electrolysis, N is the number of H_2 kilograms obtained in kg and n_g represents the natural-gas-to-hydrogen conversion cost, which is 2.2 EUR/kg for steam reforming.

The microgrid sources and hydrogen fuel cell costs are presented in Table 6.

Table 6. Microgrid sources and hydrogen fuel cell power cost [65–69].

Source	g_c (EUR/kWh)
PV 1	0.047
PV 2	0.0473
MH 1	0.0481
MH 2	0.0478
MH 3	0.0475
Hydrogen fuel cell	3.26
Power grid	0.08

Then, the power supply constraint is verified:

$$\sum PS_i \geq PD, \quad (2)$$

where PS_i represents the total power supplied by the microgrid sources at a specific hour in kW and PD represents the power demand at a specific hour in kW. If this constraint is not respected, then the additional power is supplied by the main power grid. If this constraint is respected and there is a power surplus, then this is converted using water electrolysis into hydrogen. The conversion process requires around 9 L of water and 50 kWh of power for 1 kg of hydrogen. The obtained hydrogen can supply the FCEVs or it can be converted back to power. An amount of 1 kg of hydrogen can produce around 33 kWh. For steam reforming, 4.5 m³ of natural gas are required for 1 kg of hydrogen.

Second, after the power cost is calculated, the CO₂ emissions from the power sources are calculated:

$$COE = \sum (s_i \cdot p_i) + \sum (h_i \cdot c_i) \quad (3)$$

where PSE represents the total emissions in gCO₂ from the power supplied by the sources and power conversion into hydrogen. s_i represents the CO₂ emissions from the power source in gCO₂/kWh, p_i represents the energy supplied by a particular power source during an hour in kWh, h_i represents the CO₂ emissions from the conversion of power or natural gas into hydrogen in gCO₂/kg and c_i represents the number of hydrogen kilograms produced in kg. In Table 7, the CO₂ emissions for the power plants, electrolysis and steam reforming used are presented.

Table 7. CO₂ emissions for the considered sources and for different hydrogen production methods [70–76].

Power Plant Type	Carbon Dioxide Emissions
Hydro	12 gCO ₂ /kWh
Solar	50 gCO ₂ /kWh
Power grid	203 gCO ₂ /kWh
Hydro-powered electrolysis	300 gCO ₂ /kg
Solar-powered electrolysis	1800 gCO ₂ /kg
Steam reforming of natural gas	9000 gCO ₂ /kg

The MATLAB 2023b software [77] was used to perform the analysis.

4. Results and Discussion

The power supplied by the sources in order to cover the power demand, without the BEVs and FCEVs connected, is presented in Table 8 (spring), Table 9 (summer), Table 10 (autumn) and Table 11 (winter).

The power supplied by the sources at 19:00 during summer is not enough to cover the power demand (2.5 kW are required), so the hydrogen storage must be used.

The power supplied by the sources between 5:00 and 6:00, and between 18:00 and 19:00 during autumn is not enough to cover the power demand, so the hydrogen storage must be used. A power of 3.79 kW is required at 5:00, 7.98 kW is required at 6:00, 12.05 kW is required at 18:00 and 2.42 kW is required at 19:00.

The power supplied by the sources between 5:00 and 8:00, and between 16:00 and 19:00 during winter it is not enough to cover the power demand, so the hydrogen storage must be used. A power of 11.54 kW is required at 5:00, 20.23 kW is required at 6:00, 24.08 kW is required at 7:00, 8.23 kW is required at 8:00, 27.42 kW is required at 16:00, 26.1 kW is required at 17:00, 21.28 kW is required at 18:00 and 12.6 kW is required at 19:00.

In order to convert power into hydrogen, the following surplus presented in Table 12 (spring), Table 13 (summer), Table 14 (autumn) and Table 15 (winter) is used.

Table 8. Power supplied by the sources in order to cover the power demand (spring).

Hour (h)	Power Supplied [kw]				
	PV1	MH1	PV2	MH2	MH3
1	0	0	0	10.59	80
2	0	0	0	11.74	80
3	0	0	0	14.43	80
4	0	0	0	22.11	80
5	0	0	0	29.87	80
6	0	0	0	33.62	80
7	14	0	12	7.66	80
8	24	0	20	0	68.08
9	36	0	30	0	45.43
10	50	0	40	0	21.37
11	70	0	40.23	0	0
12	84	0	25.27	0	0
13	66	0	43.48	0	0
14	56	0	40	0	13.58
15	42	0	32	0	36.89
16	28	0	22	0	65
17	16	0	10	16.61	80
18	0	0	0	43.96	80
19	0	0	0	35.23	80
20	0	0	0	24.68	80
21	0	0	0	17.39	80
22	0	0	0	13.95	80
23	0	0	0	11.62	80
24	0	0	0	10.3	80

Table 9. Power supplied by the sources in order to cover the power demand (summer).

Hour (h)	Power Supplied [kw]				
	PV1	MH1	PV2	MH2	MH3
1	0	6.52	0	35	45
2	0	5.99	0	35	45
3	0	7.25	0	35	45
4	0	13.48	0	35	45
5	0	20.65	0	35	45
6	10	7.73	6	35	45
7	22	0	16	22.18	45
8	38	0	24	0	43.77
9	54	0	36	0	17.12
10	68	0	40.42	0	0
11	82	0	25.28	0	0
12	100	0	6.75	0	0
13	84	0	22.83	0	0
14	72	0	34.92	0	0
15	58	0	38	0	10.56
16	42	0	30	0	34.78
17	26	0	20	17.34	45
18	14	10.55	8	35	45
19	0	25	0	35	45
20	0	18.87	0	35	45
21	0	12.15	0	35	45
22	0	8.38	0	35	45
23	0	5.94	0	35	45
24	0	6.13	0	35	45

Table 10. Power supplied by the sources in order to cover the power demand (autumn).

Hour (h)	Power Supplied [kw]				
	PV1	MH1	PV2	MH2	MH3
1	0	5.33	0	38	48
2	0	7.66	0	38	48
3	0	13.28	0	38	48
4	0	23.28	0	38	48
5	0	28	0	38	48
6	0	28	0	38	48
7	10	20.27	6	38	48
8	18	6.8	10	38	48
9	32	0	16	23.89	48
10	42	0	24	5.57	48
11	56	0	34	0	28.65
12	68	0	46	0	3.5
13	58	0	36	0	23.18
14	44	0	26	0.18	48
15	36	0	18	20.27	48
16	22	9.03	12	38	48
17	12	25.07	8	38	48
18	0	28	0	38	48
19	0	28	0	38	48
20	0	20.83	0	38	48
21	0	13.73	0	38	48
22	0	10.31	0	38	48
23	0	7.93	0	38	48
24	0	5.24	0	38	48

Table 11. Power supplied by the sources in order to cover the power demand (winter).

Hour (h)	Power Supplied [kw]				
	PV1	MH1	PV2	MH2	MH3
1	0	15.5	0	40	50
2	0	16.38	0	40	50
3	0	19.86	0	40	50
4	0	29.44	0	40	50
5	0	30	0	40	50
6	0	30	0	40	50
7	0	30	0	40	50
8	10	30	6	40	50
9	24	14.5	14	40	50
10	32	0	22	37.43	50
11	42	0	28	20.76	50
12	50	0	34	4.35	50
13	38	0	30	19.52	50
14	26	0	24	39.25	50
15	16	27.27	12	40	50
16	0	30	0	40	50
17	0	30	0	40	50
18	0	30	0	40	50
19	0	30	0	40	50
20	0	26.06	0	40	50
21	0	27.45	0	40	50
22	0	21.17	0	40	50
23	0	17.87	0	40	50
24	0	15.33	0	40	50

Table 12. Power surplus (spring).

Hour (h)	Power Surplus [kw]			
	MH1	PV2	MH2	MH3
1	50	0	59.41	0
2	50	0	58.26	0
3	50	0	55.57	0
4	50	0	47.89	0
5	50	0	40.13	0
6	50	0	36.38	0
7	50	0	62.34	0
8	50	0	70	11.92
9	50	0	70	34.57
10	50	0	70	58.63
11	50	11.77	70	80
12	50	40.73	70	80
13	50	4.52	70	80
14	50	0	70	66.42
15	50	0	70	43.11
16	50	0	70	15
17	50	0	53.39	0
18	50	0	26.04	0
19	50	0	34.77	0
20	50	0	45.32	0
21	50	0	52.61	0
22	50	0	56.05	0
23	50	0	58.38	0
24	50	0	59.7	0

Table 13. Power surplus (summer).

Hour (h)	Power Surplus [kw]			
	MH1	PV2	MH2	MH3
1	18.48	0	0	0
2	19.01	0	0	0
3	17.75	0	0	0
4	11.52	0	0	0
5	4.35	0	0	0
6	17.27	0	0	0
7	25	0	12.82	0
8	25	0	35	1.23
9	25	0	35	27.88
10	25	9.58	35	45
11	25	24.72	35	45
12	25	73.25	35	45
13	25	43.17	35	45
14	25	17.08	35	45
15	25	0	35	34.44
16	25	0	35	10.22
17	25	0	17.66	0
18	14.45	0	0	0
19	0	0	0	0
20	6.13	0	0	0
21	12.85	0	0	0
22	16.62	0	0	0
23	19.06	0	0	0
24	18.87	0	0	0

Table 14. Power surplus (autumn).

Hour (h)	Power Surplus [kw]		
	MH1	MH2	MH3
1	22.67	0	0
2	20.34	0	0
3	14.72	0	0
4	4.72	0	0
5	0	0	0
6	0	0	0
7	7.73	0	0
8	21.2	0	0
9	28	14.11	0
10	28	32.43	0
11	28	38	19.35
12	28	38	44.5
13	28	38	24.82
14	28	37.82	0
15	28	17.73	0
16	18.97	0	0
17	2.93	0	0
18	0	0	0
19	0	0	0
20	7.17	0	0
21	14.27	0	0
22	17.69	0	0
23	20.07	0	0
24	22.76	0	0

Table 15. Power surplus (winter).

Hour (h)	Power Surplus [kw]	
	MH1	MH2
1	14.5	0
2	13.62	0
3	10.14	0
4	0.56	0
5	0	0
6	0	0
7	0	0
8	0	0
9	15.5	0
10	30	2.57
11	30	19.24
12	30	35.65
13	30	20.48
14	30	0.75
15	2.73	0
16	0	0
17	0	0
18	0	0
19	0	0
20	3.94	0
21	2.55	0
22	8.83	0
23	12.13	0
24	14.67	0

The power surplus is converted into hydrogen by means of water electrolysis (Table 16). The total H₂ produced is 57.25 kg (spring), 25.26 kg (summer), 13.92 kg (autumn) and 6.55 kg (winter).

Table 16. Hydrogen production due to power surplus.

Hour (h)	Hydrogen Produced (Spring) (kg)	Hydrogen Produced (Summer) (kg)	Hydrogen Produced (Autumn) (kg)	Hydrogen Produced (Winter) (kg)
1	2.1882	0.3696	0.4534	0.29
2	2.1652	0.3802	0.4068	0.2724
3	2.1114	0.355	0.2944	0.2028
4	1.9578	0.2304	0.0944	0.0112
5	1.8026	0.087	0	0
6	1.7276	0.3454	0	0
7	2.2468	0.7564	0.1546	0
8	2.6384	1.2246	0.424	0
9	3.0914	1.7576	0.8422	0.31
10	3.5726	2.2916	1.2086	0.6514
11	4.2354	2.5944	1.707	0.9848
12	4.8146	3.565	2.21	1.313
13	4.0904	2.9634	1.8164	1.0096
14	3.7284	2.4416	1.3164	0.615
15	3.2622	1.8888	0.9146	0.0546
16	2.7	1.4044	0.3794	0
17	2.0678	0.8532	0.0586	0
18	1.5208	0.289	0	0
19	1.6954	0	0	0
20	1.9064	0.1226	0.1434	0.0788
21	2.0522	0.257	0.2854	0.051
22	2.121	0.3324	0.3538	0.1766
23	2.1676	0.3812	0.4014	0.2426
24	2.194	0.3774	0.4552	0.2934

As it can be observed from Table 16, the hydrogen production changes due to the excess power supplied by the microgrid sources. If the excess power is high, then more hydrogen is produced. If the excess power is low, then less hydrogen is produced.

The power cost is presented in Table 17 (spring), Table 18 (summer), Table 19 (autumn) and Table 20 (winter). The CO₂ emissions caused by the power supplied by the microgrid sources, water electrolysis and power grid are presented in Table 21 (spring), Table 22 (summer), Table 23 (autumn) and Table 24 (winter).

The results for the power cost during the seasons are also presented in Figure 2 (spring), Figure 3 (summer), Figure 4 (autumn), and Figure 5 (winter). The results for the CO₂ emissions are also presented in Figure 6 (spring), Figure 7 (summer), Figure 8 (autumn), and Figure 9 (winter).

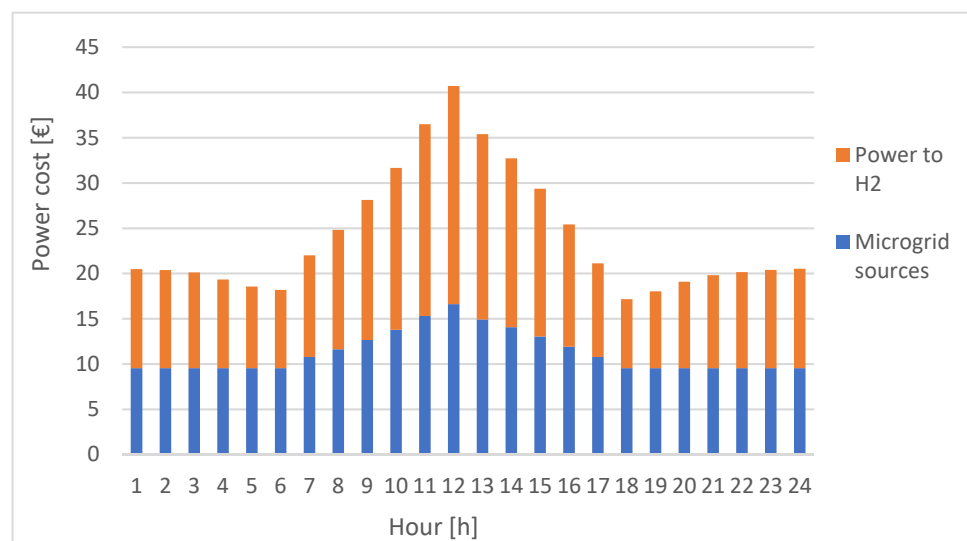


Figure 2. Power cost (spring).

Table 17. Power cost (spring).

Hour (h)	Power Cost [EUR]	
	Microgrid Sources	Power to H ₂
1	9.551	10.941
2	9.551	10.826
3	9.551	10.557
4	9.551	9.789
5	9.551	9.013
6	9.551	8.638
7	10.7766	11.234
8	11.625	13.192
9	12.662	15.457
10	13.793	17.863
11	15.3006	21.177
12	16.6208	24.073
13	14.9234	20.452
14	14.075	18.642
15	13.0386	16.311
16	11.9076	13.5
17	10.776	10.339
18	9.551	7.604
19	9.551	8.477
20	9.551	9.532
21	9.551	10.261
22	9.551	10.605
23	9.551	10.838
24	9.551	10.97

Table 18. Power cost (summer).

Hour (h)	Power Cost [EUR]		
	Microgrid Sources	Power to H ₂	Fuel Cell
1	5.013	1.848	0
2	5.013	1.901	0
3	5.013	1.775	0
4	5.013	1.152	0
5	5.013	0.435	0
6	5.7668	1.727	0
7	6.8038	3.782	0
8	7.9342	6.123	0
9	9.2538	8.788	0
10	10.574	11.458	0
11	11.232	12.972	0
12	13.497	17.825	0
13	12.0828	14.817	0
14	10.8566	12.208	0
15	9.5364	9.444	0
16	8.406	7.022	0
17	7.181	4.266	0
18	6.0494	1.445	0
19	5.013	0	0.24776
20	5.013	0.613	0
21	5.013	1.285	0
22	5.013	1.662	0
23	5.013	1.906	0
24	5.013	1.887	0

Table 19. Power cost (autumn).

Hour (h)	Power Cost [EUR]		
	Microgrid Sources	Power to H ₂	Fuel Cell
1	5.4432	2.267	0
2	5.4432	2.034	0
3	5.4432	1.472	0
4	5.4432	0.472	0
5	5.4432	0	0.374574
6	5.4432	0	0.788594
7	6.197	0.773	0
8	6.7622	2.12	0
9	7.704	4.211	0
10	8.5524	6.043	0
11	9.6834	8.535	0
12	10.815	11.05	0
13	9.872	9.082	0
14	8.741	6.582	0
15	7.9866	4.573	0
16	7.0448	1.897	0
17	6.3856	0.293	0
18	5.4432	0	1.234888
19	5.4432	0	0.239284
20	5.4432	0.717	0
21	5.4432	1.427	0
22	5.4432	1.769	0
23	5.4432	2.007	0
24	5.4432	2.276	0

Table 20. Power cost (winter).

Hour (h)	Power Cost [EUR]			
	Microgrid Sources	Power to H ₂	Fuel Cell	Power Grid
1	5.73	1.45	0	0
2	5.73	1.362	0	0
3	5.73	1.014	0	0
4	5.73	0.056	0	0
5	5.73	0	1.140022	0
6	5.73	0	1.391042	0.492
7	5.73	0	0	1.9264
8	6.4838	0	0	0.6584
9	7.5202	1.55	0	0
10	8.2746	3.257	0	0
11	9.0284	4.924	0	0
12	9.6882	6.565	0	0
13	8.935	5.048	0	0
14	8.0872	3.075	0	0
15	7.0496	0.273	0	0
16	5.73	0	2.70906	0
17	5.73	0	2.57866	0
18	5.73	0	2.102374	0
19	5.73	0	1.244994	0
20	5.73	0.394	0	0
21	5.73	0.255	0	0
22	5.73	0.883	0	0
23	5.73	1.213	0	0
24	5.73	1.467	0	0

Table 21. CO₂ emissions (spring).

Hour (h)	CO ₂ Emissions [gCO ₂]	
	Microgrid Sources	Water Electrolysis
1	2400	656.46
2	2400	649.56
3	2400	633.42
4	2400	587.34
5	2400	540.78
6	2400	518.28
7	3700	674.04
8	4600	791.52
9	5700	927.42
10	6900	1071.78
11	8500	1623.72
12	9900	2666.28
13	8100	1362.72
14	7200	1118.52
15	6100	978.66
16	4900	810
17	3700	620.34
18	2400	456.24
19	2400	508.62
20	2400	571.92
21	2400	615.66
22	2400	636.3
23	2400	650.28
24	2400	658.2

Table 22. CO₂ emissions (summer).

Hour (h)	CO ₂ Emissions [gCO ₂]	
	Microgrid Sources	Water Electrolysis
1	1260	110.88
2	1260	114.06
3	1260	106.5
4	1260	69.12
5	1260	26.1
6	2060	103.62
7	3160	226.92
8	4360	367.38
9	5760	527.28
10	7160	974.88
11	7860	1519.92
12	10,260	3267
13	8760	2184.12
14	7460	1244.88
15	6060	566.64
16	4860	421.32
17	3560	255.96
18	2360	86.7
19	1260	0
20	1260	36.78
21	1260	77.1
22	1260	99.72
23	1260	114.36
24	1260	113.22

Table 23. CO₂ emissions (autumn).

Hour (h)	CO ₂ Emissions [gCO ₂]	
	Microgrid Sources	Water Electrolysis
1	1368	136.02
2	1368	122.04
3	1368	88.32
4	1368	28.32
5	1368	0
6	1368	0
7	2168	46.38
8	2768	127.2
9	3768	252.66
10	4668	362.58
11	5868	512.1
12	7068	663
13	6068	544.92
14	4868	394.92
15	4068	274.38
16	3068	113.82
17	2368	17.58
18	1368	0
19	1368	0
20	1368	43.02
21	1368	85.62
22	1368	106.14
23	1368	120.42
24	1368	136.56

Table 24. CO₂ emissions (winter).

Hour (h)	CO ₂ Emissions [gCO ₂]		
	Microgrid Sources	Water Electrolysis	Power Grid
1	1440	87	0
2	1440	81.72	0
3	1440	60.84	0
4	1440	3.36	0
5	1440	0	0
6	1440	0	1248.45
7	1440	0	4888.24
8	2240	0	1670.69
9	3340	93	0
10	4140	195.42	0
11	4940	295.44	0
12	5640	393.9	0
13	4840	302.88	0
14	3940	184.5	0
15	2840	16.38	0
16	1440	0	0
17	1440	0	0
18	1440	0	0
19	1440	0	0
20	1440	23.64	0
21	1440	15.3	0
22	1440	52.98	0
23	1440	72.78	0
24	1440	88.02	0

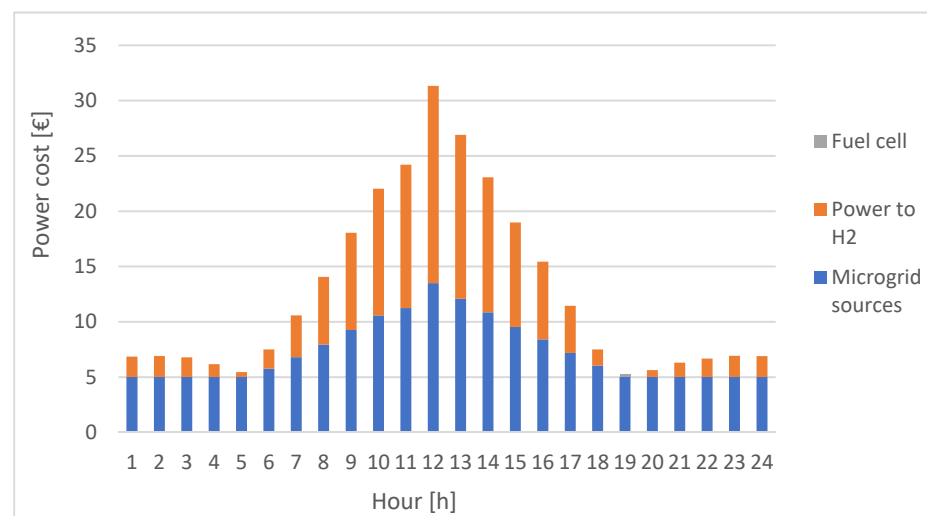


Figure 3. Power cost (summer).

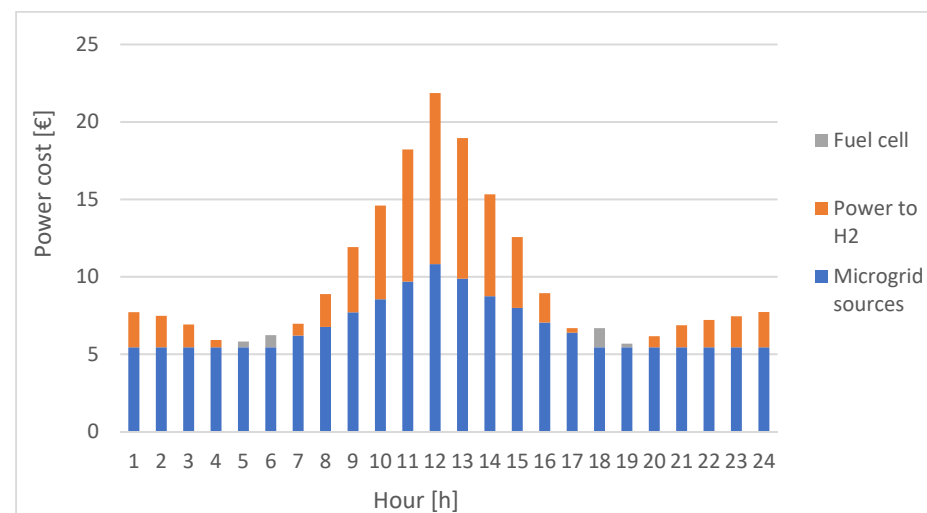


Figure 4. Power cost (autumn).

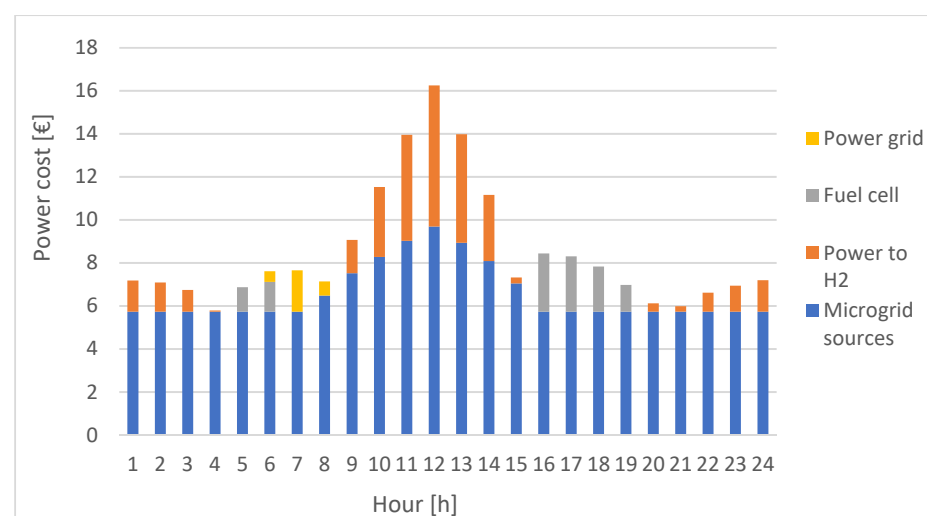


Figure 5. Power cost (winter).

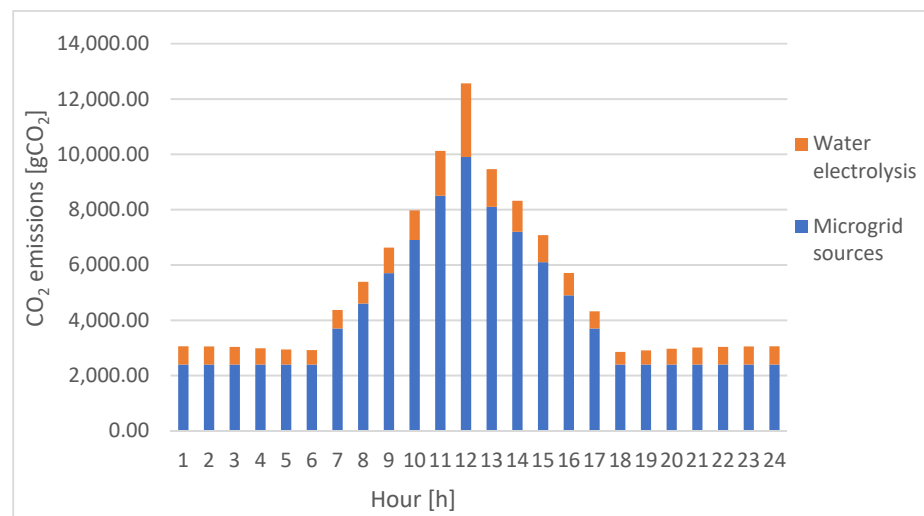


Figure 6. CO₂ emissions (spring).

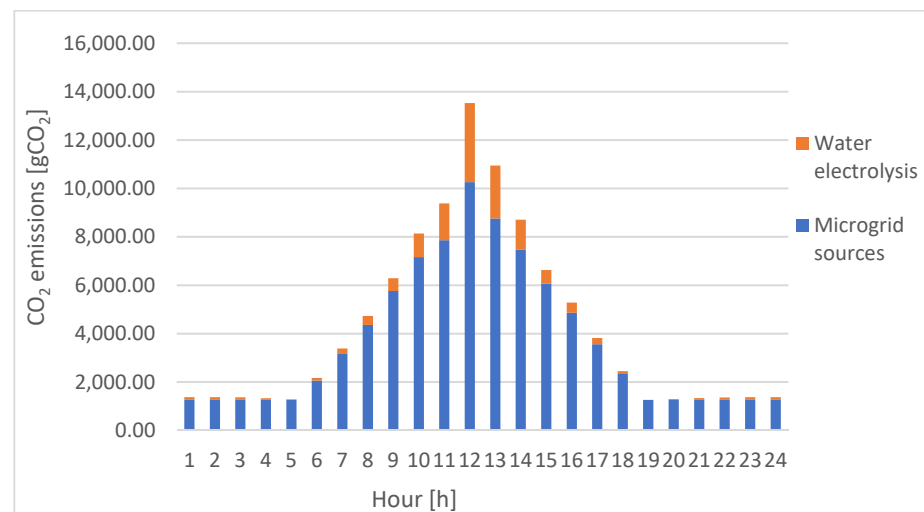


Figure 7. CO₂ emissions (summer).

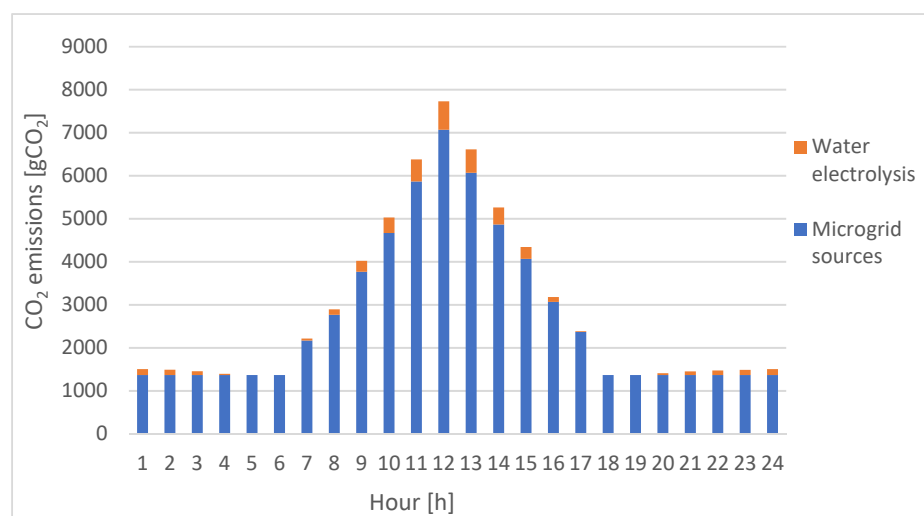


Figure 8. CO₂ emissions (autumn).

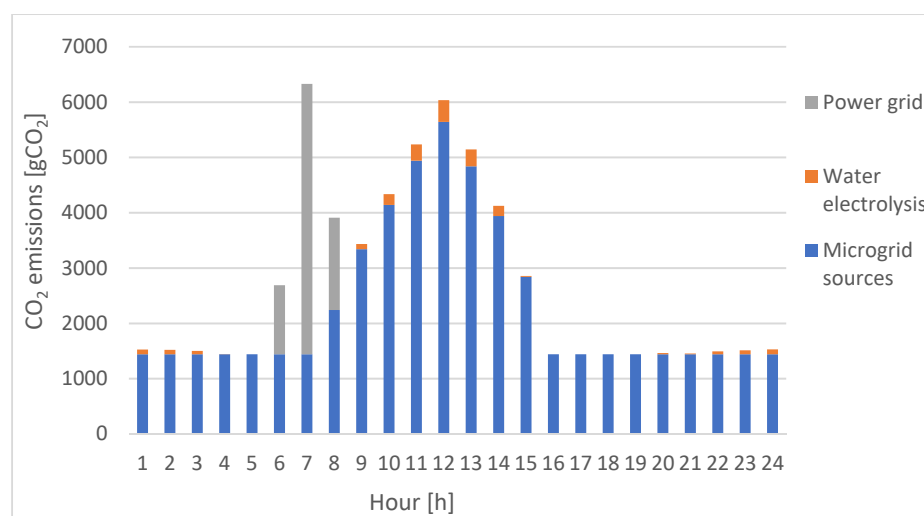


Figure 9. CO₂ emissions (winter).

During autumn, 0.1149 H₂ kg are used at 5:00, 0.2419 H₂ kg are used at 6:00, 0.3788 H₂ kg are used at 18:00 and 0.0734 H₂ kg are used at 19:00.

During winter, 0.3497 H₂ kg are required at 5:00, 20.23 kW are required at 6:00, 24.08 kW are required at 7:00, 8.23 kW are required at 8:00, 27.42 kW are required at 16:00, 26.1 kW are required at 17:00, 21.28 kW are required at 18:00 and 12.6 kW are required at 19:00. The H₂ tank can supply only 0.7764 kg in the morning. This covers the demand at 5:00 and part of the demand at 6:00. At 6:00, there are still 0.1864 H₂ kg or 6.15 kW required. This is taken from the power grid, as well as the extra power required between 7:00 and 8:00. Regarding the power required between 16:00 and 19:00, the hydrogen produced and stored between 9:00 and 15:00 is enough to cover the demand that cannot be covered by the microgrid sources. An amount of 0.831 H₂ kg is used at 16:00, 0.791 H₂ kg is used at 17:00, 0.6449 H₂ kg is used at 18:00 and 0.3819 H₂ kg is used at 19:00.

The power supplied by the sources at 19:00 during the summer is not enough and hydrogen storage must be used (0.076 kg). This results in a higher cost at 19:00.

The connection of BEVs and FCEVs changes the results, so the conversion of the stored hydrogen into power for BEVs and fuelling the FCEVs with hydrogen is required.

During spring, from the 48.4 kg of H₂ stored until 18:00, 11.93 kg must be used to fuel the FCEVs and 11.46 kg must be converted by the fuel cell into power in order to charge the BEVs.

During summer, the 23.5 kg of H₂ stored until 18:00 are enough to cover the power demand at 19:00 (0.076 kg) and the total 23.39 kg required by the BEVs and FCEVs.

During autumn, there are 11.47 kg of H₂ stored until 18:00. All of these kilograms are used by the FCEVs, which require an additional 0.46 kg. These additional kilograms are produced by means of steam reforming of natural gas, so there is a 1.012 EUR increase in the cost. The power (189 kW) required by the BEVs between 18:00 and 19:00 is supplied by the power grid. Between 20:00 and 21:00, there is a 7.17 kW surplus, which is no longer converted into hydrogen due to the high cost, but supplied to the BEVs with an additional 181.83 kW from the power grid. Considering the fact that extra power is required from the grid, the power cost and CO₂ emissions increase. As a result, the power cost increases between 18:00 and 19:00 from 6.67 EUR to 16.16 EUR, which is added to the hydrogen cost from natural gas. The result is 17.172 EUR. The power cost also increases between 19:00 and 20:00 from 5.68 EUR to 9.84 EUR and between 20:00 and 21:00 from 5.44 EUR to 19.86 EUR. The CO₂ emissions are higher due to the steam reforming of natural gas and power supplied by the grid. They increase between 18:00 and 19:00 from 1368 gCO₂ to 32,710 gCO₂, between 19:00 and 20:00 from 1368 gCO₂ to 12,533 gCO₂ and between 20:00 and 21:00 from 1411.02 gCO₂ to 38,193.45 gCO₂.

During winter, there are only 2.28 kg of H₂ stored until 18:00, which are used by the FCEVs with an additional 9.65 kg from steam reforming of natural gas, so the cost is 21.23 EUR. As in the case for autumn, the power required by the BEVs is supplied by the power grid. Between 20:00 and 21:00, there is a 3.94 kW surplus, which is supplied to the BEVs alongside 185.06 kW from the power grid. As a result, the power cost increases between 18:00 and 19:00 from 7.83 EUR to 16.45 EUR, which is added to the hydrogen cost from natural gas. The result is 37.68 EUR. The power cost also increases between 19:00 and 20:00 from 6.97 EUR to 10.13 EUR and between 20:00 and 21:00 from 6.12 EUR to 20.59 EUR. The CO₂ emissions are also higher in the winter. They increase between 18:00 and 19:00 from 1440 gCO₂ to 115,492 gCO₂, between 19:00 and 20:00 from 1440 gCO₂ to 12,605 gCO₂ and between 20:00 and 21:00 from 1463.64 gCO₂ to 38,959.9 gCO₂.

The power supplied by the microgrid sources and hydrogen stored was enough to cover the demand during spring and summer for the cases when the BEVs and FCEVs were connected or not to the microgrid. During the autumn, the hydrogen stored was enough to cover the demand in case the BEVs and FCEVs were not connected to the microgrid. In case the BEVs and FCEVs were connected to the microgrid, the hydrogen stored was enough to cover the demand, so the BEVs were supplied by the main grid and part of the FCEVs were supplied by the hydrogen obtained as steam reforming of natural gas. The same situation happened during the winter, with the difference that the demand of the loads being higher and the hydrogen stored being lower. Therefore, a higher amount was supplied by the power grid. Also, a higher amount of hydrogen obtained by steam reforming was supplied in order to cover the demand.

The power cost was higher during autumn and winter when the BEVs and FCEVs were connected due to the extra power and hydrogen that had to be supplied. The CO₂ emissions were also higher during autumn and winter when the BEVs and FCEVs were connected due to the extra power and hydrogen that had to be supplied.

The power cost and CO₂ emissions were lower compared to the use of the power grid and steam reforming of natural gas. The power cost of the grid was 100% higher compared with the cost of the RES. A disadvantage was the cost of hydrogen, which was higher than the cost of the power grid, but is expected to decrease to at least half during the next few years due to the advances in the field, as was the case with the power cost of RESs. The CO₂ emissions of the power grid were between 400% and 1600% higher compared with the emissions of the RES. An advantage of the hydrogen obtained using water electrolysis is represented by the CO₂ emissions. The CO₂ emissions of the hydrogen obtained by water electrolysis were between 500% and 3000% lower compared to steam reforming of natural gas. So, the use of hydrogen obtained by water electrolysis decreases the CO₂ emissions and increases the power cost.

The power cost and CO₂ emission values obtained by other researchers were also lower when renewable energy sources were used in microgrids with hydrogen storage. The CO₂ emissions were 72.44% lower during a year in [24] due to the use of microgrid sources and hydrogen storage instead of the power grid, while in [25] the cost of power was 26.3% lower. In [45], it was found that the power cost for the microgrid increased between 5% and 158% due to the use of hydrogen. In [51], it was found that the CO₂ emissions are higher in a microgrid if BEVs are used compared to FCEVs.

5. Conclusions

In this paper, hydrogen was obtained from water electrolysis based on the power supplied by photovoltaic and micro-hydro sources. This type of method has low CO₂ emissions and high production costs. The hydrogen was also obtained using the steam reforming of natural gas, which has high CO₂ emissions and a lower production cost compared to water electrolysis. The hydrogen obtained by steam reforming was used only to cover the hydrogen demand of FCEVs. The hydrogen obtained by water electrolysis was used to cover the power demand of the loads of the microgrid and to supply the

FCEVs. The microgrid comprised loads, RESs, BEVs and FCEVs. The power grid and steam reforming of natural gas were used as back-up in case the demand could not be covered.

Considering the seasons and whether the BEVs and FCEVs were connected or not, the hydrogen stored had to be used. The power supplied by the power sources and hydrogen stored was enough to cover the demand during spring and summer, while during autumn and winter the power grid and steam reforming had to be used. Therefore, a back-up is required to ensure the continuous supply of consumers.

The connection of BEVs and FCEVs resulted in a higher power cost and CO₂ emissions during autumn and winter due to the extra power and hydrogen that were needed. The power cost increased during the winter between 20:00 and 21:00 by 336%. The CO₂ emissions increased during the winter by 8020%. The use of hydrogen obtained from conventional sources has a greater impact on the environment, but the use of hydrogen obtained from renewable energy sources has a smaller impact on the environment, as will be the case in the next decades.

If the power generation cost of the sources is compared with the generation cost of power to hydrogen, it can be observed that during summer, autumn and winter the H₂ generation cost is in most cases lower due to the low excess power supplied by the microgrid sources. During spring, the H₂ generation cost is in most cases higher, even by 40%, due to the high excess power supplied by the microgrid sources. This means that the H₂ generation cost represents a barrier for the adoption of the large-scale use of hydrogen, so this cost must be lower. One way of achieving a lower H₂ production cost, around 3 EUR/kg, is to use the hydrogen obtained from ammonia if there are any industrial facilities nearby that use this product, so this is worth further investigation.

In a future study, natural gas can be considered to supply some consumer appliances as well as more FCEVs. Also, the power cost of hydrogen obtained by water electrolysis is expected to decrease, so this will make hydrogen more attractive, especially considering the expected rise in the number of FCEVs.

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