

## Article

# Cost-Benefit Analysis of Small-Scale Rooftop PV Systems: The Case of Dragotin, Croatia

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**Citation:** Bošnjaković, M.; Čikić, A.; Zlatunić, B. Cost-Benefit Analysis of Small-Scale Rooftop PV Systems: The Case of Dragotin, Croatia. *Appl. Sci.* **2021**, *11*, 9318. <https://doi.org/10.3390/app11199318>

Academic Editors: Isabel María Moreno García, Rafael López Luque and Isabel Santiago Chiquero

Received: 12 September 2021

Accepted: 30 September 2021

Published: 8 October 2021

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**Abstract:** A large drop in prices of photovoltaic (PV) equipment, an increase in electricity prices, and increasing environmental pressure to use renewable energy sources that pollute the environment significantly less than the use of fossil fuels have led to a large increase in installed roof PV capacity in many parts of the world. In this context, this paper aims to analyze the cost-effectiveness of installing PV systems in the rural continental part of Croatia on existing family houses. A typical example is a house in Dragotin, Croatia with an annual consumption of 4211.70 kWh of electricity on which PV panels are placed facing south under the optimal slope. The calculation of the optimal size of a PV power plant with a capacity of 3.6 kW, without battery energy storage, was performed by the Homer program. The daily load curve was obtained by measuring the electricity consumption at the facility every hour during a characteristic day in the month of June. As most of the activities are related to electricity consumption, repeating during most days of the year, and taking into account seasonal activities, daily load curves were made for a characteristic day in each month of the year. Taking into account the insolation for the specified location, using the Internet platform Solargis Prospect, hourly data on the electricity production of selected PV modules for a characteristic day in each month were obtained. Based on the previous data, the electricity injected into the grid and taken from the grid was calculated. Taking into account the current tariffs for the sale and purchase of electricity, investment prices, and maintenance of equipment, the analysis shows that such a PV system can pay off in 10.5 years without government incentives.

**Keywords:** residential photovoltaic; self-consumption; self-sufficiency; cost-effectiveness analysis

## 1. Introduction

The use of renewable energy sources for electricity generation is in trend all over the world. However, this is not only on a large scale, with large companies for the production and distribution of electricity, but also on a small or consumer scale. In this sense, rooftop photovoltaic power plants (PVs) take a significant place.

Environmental and climate change require action in all key sectors of the economy and strongly encourages the use of renewable energy sources. The European Building Fund currently emits approximately 36% of EU greenhouse gas emissions, and it is key to effectively decarbonizing the atmosphere. Emissions from the construction sector are still higher than in 2014, and the annual rate of energy renovation of buildings in the EU is only about 1%. The EU is trying to overcome these bottlenecks, and there is a new impetus towards rooftop solar installations, with a proven impact on achieving decarbonization and reducing energy demand from the electricity grid.

If 90% of Europe's roof space is known to be unused, using it to install PV systems could make a significant contribution to Europe's energy transition. Under the moderate scenario, it is possible to install up to 570 GW roof photovoltaic capacity by 2030, which is

a big step forward since installed 137 GW in 2020 [1]. Solar PV power plants on buildings in the EU could produce between 680 TWh and 1300 TWh. This represents a significant untapped potential for the growth of the solar energy market and job creation.

In order to exploit this potential of solar roofs, EU Member States need to design support programs for citizens and businesses wishing to install solar energy [1].

Studies specifically focused on rooftop photovoltaic power plants claim that almost 25% of Europe's electricity consumption could be generated from these facilities. Of course, the results depend on various factors, such as investment costs, electricity tariffs, subsidies, and government policies. [2,3].

In 2019, Germany had the most installed PV capacity per capita in the EU (651 W/capita), followed by the Netherlands (539 W/capita) and Belgium (466 W/capita).

Croatia has set a goal of reaching 300 MW of installed PV capacity by small consumers-producers of electricity by 2030 with a tax exemption for self-consumed electricity. Most of the capacity is planned for photovoltaic systems in buildings. This is only 198 W/capita, which is the lowest of all countries in the region and far lower than the EU average planned at 758 W/capita [1].

The cumulative installed capacity of solar power plants in 2020 in Croatia is 166 MW, so we estimate that the planned increase in capacity by 2030 is very modest, and this means a further lagging of Croatia behind neighboring countries.

The decline in the cost of solar photovoltaic systems, combined with the increase in electricity costs, has increased the use of roof PV systems for their consumption in many parts of the world in recent years. Own consumption, which is a completely different system of production and consumption of electricity compared to the traditional system of production of electricity in large power plants, allows consumers to produce and consume their electricity. The main advantages of this system are increased energy autonomy and reduced energy costs.

Production of electricity from renewable sources for own consumption creates immediate positive effects, such as a reduction of grid energy losses and reduced need for modernization of electricity infrastructure by integrating renewable distributed generation into the electricity system. Green energy, thanks to the growing success of its own consumption, plays a strategic role in the energy transition model aimed at combining technological innovation with health, environmental, and economic benefits as well as job creation [4].

It can also be said that self-consumption of photovoltaic (PV) energy is an economic model in which the building uses the produced PV electricity for its own needs, acting at the same time as a producer and a consumer, or as a "prosumer". The neologism "prosumer" refers to a user of electricity who produces electricity to support his own consumption (and perhaps to inject into the grid). The word was built on the association of "producer" and "consumer" and is widely used today. Two ratios are important for own consumption: self-consumption (SC) and self-sufficiency (SS).

SC is defined as the amount of locally produced and consumed electricity ( $E_{lgc}$ ) with respect to total local electricity production ( $E_{gen}$ ) [4]:

$$SC_x = \frac{E_{lgc,x}}{E_{gen,x}}, \quad (1)$$

where  $x$  is the reference time interval for which the ratio is calculated. The interval can be one day, month, or year.

SS is the amount of consumption delivered by local production ( $E_{lgc}$ ), given the total consumption ( $E_{load}$ ). Thus, it quantifies the independence of users from the grid [4] and is calculated according to:

$$SS_x = \frac{E_{lgc,x}}{E_{load,x}}, \quad (2)$$

In practice, SC and SS can be from a few percent to theoretically 100%, depending on the capacity of the photovoltaic system and the user load profile.

The question of the ratio of own consumption is deeply connected with the question of whether to invest in the installation of a roof PV system or not. The higher the SC, the higher the profitability of the whole system, since the retail prices of electricity are significantly higher than the purchase prices of electricity. However, in the household sector, the amount of PV energy produced and the amount of consumption in certain time intervals rarely coincide, which implies that only a limited part of PV-produced electricity can be used for own consumption. For example, Luthander et al. [5] state that the average share of direct own consumption is about 30%. In this context, battery-powered energy storage systems allow for increases in SC levels by storing excess solar energy produced that will be used later (i.e., indirect own consumption). Luthander et al. also state that it is possible to increase your own consumption between 13% and 24% by using a battery system with a capacity of 0.5–1 kWh per installed kW PV system.

Own consumption of PV electricity assumes that the costs of photovoltaic electricity production are lower (at the time of capital investment or during the lifetime of the rooftop PV plant) than the cost that the consumer pays for electricity from the grid. Without reaching this threshold, own consumption requires state support. The indication that grid parity has been achieved could mean that the production of electricity, rather than its purchase from the grid, is profitable. This is not the case for several reasons, which will be explained below. It can be said that network parity is a milestone but not a guarantee of the competitiveness of roof PV systems.

Grid parity is actually the moment when the levelized cost of energy (LCOE) becomes lower than the retail price of electricity. If certain grid costs and fees cannot be compensated (for example, due to a higher fixed part of the grid excise duty), grid parity is not achieved when the price of electricity from PV becomes lower than the retail price of electricity from the grid. PV electricity prices need to be further reduced to reach this first measure of competitiveness. Moreover, since part of the produced PV electricity is exported to the grid and valued at a lower price than the retail price, PV LCOE must be further reduced to ensure the competitiveness of PV electricity.

Most of the studies conducted were driven by promises of solar PV grid parity [6] and declining battery storage prices [7]. Despite the increase in own consumption and self-sufficiency, most papers claim that PV systems with batteries will not be profitable if battery prices do not fall significantly [8–12] with an increase in the price of electricity from the grid [13]. It should also be taken into account that the lifespan of battery systems is about 10 years, so it is necessary to change the battery system once or twice. According to the authors, taking into account both technological progress and rising electricity prices, battery systems will not be profitable before 2030 without government incentives.

According to Klamka et al. [14], the cost-effectiveness analysis suggests that most of the savings potential comes from direct own consumption of PV, and therefore relates to the cost of electricity. The inclusion of a heat storage system and/or a battery system does not pay off when comparing savings and investment costs, at least at current prices.

An additional impetus to the development of own consumption comes from the increasing production of electric vehicles and support for their charging, which will enable the application of V2G technology (vehicle-to-grid). In this sense, electric vehicles will enable the storage of part of the electricity produced by their own PV system. However, one should be careful here because the working population is at work at a time when the largest production of PV systems and cannot charge cars at that time but only on weekends.

A zero-energy building (ZEB) is a concept that is applied in buildings with a balance between energy production and consumption and close to zero energy or even positive in a typical year. Photovoltaic technology can play a leading role in achieving the goal of ZEB because it is one of the best-positioned technologies for increasing the energy self-sufficiency of buildings.

The integration of PV systems into the electrical grid, in general, increases the complexity of grid management [15]. The variability of solar energy concerning weather conditions (along with variability on the load side) makes it difficult to manage PV production and consumption and requires special procedures to balance the system. These difficulties can be alleviated by the simultaneous development of:

- Energy storage system;
- Smart electrical grids with optimized energy and power management;
- Method of predicting renewable production and consumer consumption.

However, the volatility of energy production and variability of the load can cause an unstable power supply and high peak load [16]. Moreover, the planned mass deployment of electric vehicles can lead to a significant increase in the peak load of electricity demand [17] but can also be considered valuable parts of a smart grid [18].

One solution is to align consumption with solar production, as consumption in the building sector is generally not synchronized with the production of the PV system. Energy storage in this sense can help a lot in solving these problems [19]. The timing of household appliances in smart homes can be applied depending on variations in electricity prices, as well as on consumer loads [20] or external conditions [21]. Samadi et al. [22] proposed a model that schedules the time operation of household appliances in a system with PV production. The authors apply dynamic programming to schedule the operation of household appliances and use game theory to sell excess energy produced. Sheraz et al. [23] proposed a house energy management system in which they incorporated a genetic algorithm, a cuckoo search algorithm, and crow search algorithms. Aslam et al. [24] propose a home energy management system, which implements a load transfer strategy and coordinates the timing of household appliances.

This paper analyzes the cost-effectiveness of using a roof grid-connected PV system without battery storage in the rural continental part of Croatia on an existing family house in Dragotin, Croatia. An analysis of the monthly electricity bills established that the house has an annual consumption of 4210 kWh of electricity.

## 2. Materials and Methods

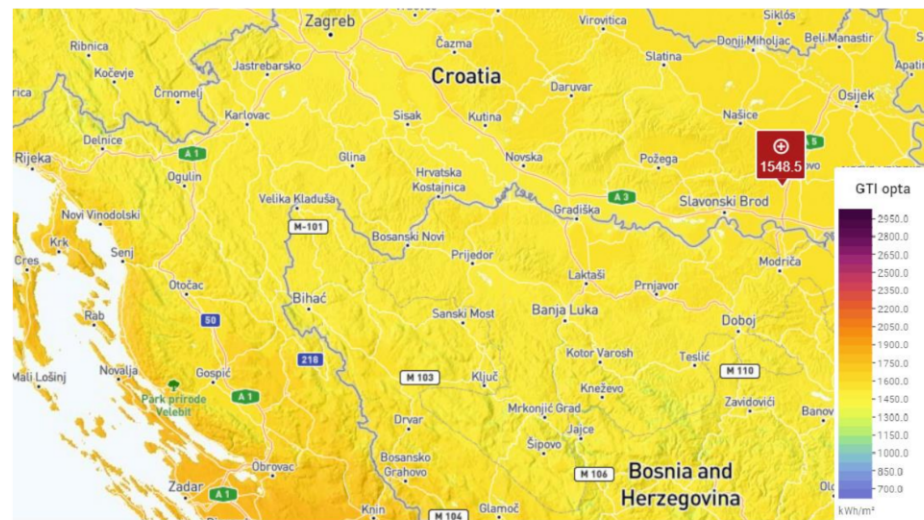
### 2.1. Meteorological Data for the Selected Location

The analyzed photovoltaic system was installed on the sloping roof of a residential building in Dragotin, Croatia. The PV modules are facing south and there is no shading of the modules. The PV modules are mounted on brackets at a roof angle of 35°, thus enabling rear ventilation. The PV system is directly connected to the low voltage network via an inverter. The paper does not consider the storage of electricity using a battery system. Meteorological data were taken using the Solargis Prospect application [24] and are shown in Table 1 and Figures 1–3.

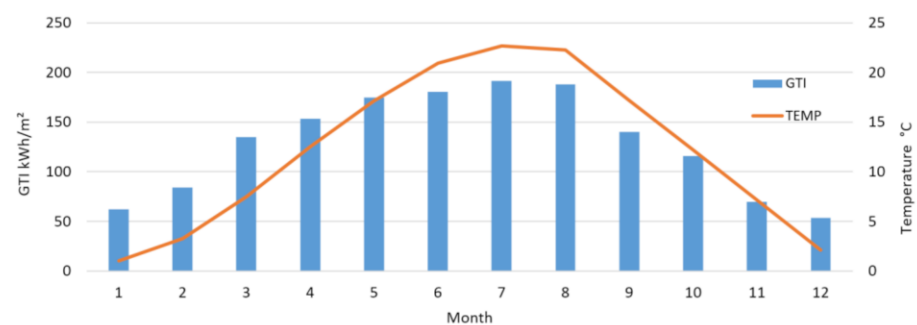
**Table 1.** Long-term annual average data for city Dragotin [24].

Feature	Value	Unit
Direct normal irradiation	1237.6	kWh/m <sup>2</sup>
Global horizontal irradiation	1332.7	kWh/m <sup>2</sup>
Diffuse horizontal irradiation	620.4	kWh/m <sup>2</sup>
Global tilted irradiation at the optimum angle	1549.1	kWh/m <sup>2</sup>
Annual average air temperature at height of 2 m	12.1	°C
The optimum tilt of PV modules	35	°
Terrain elevation	136	m

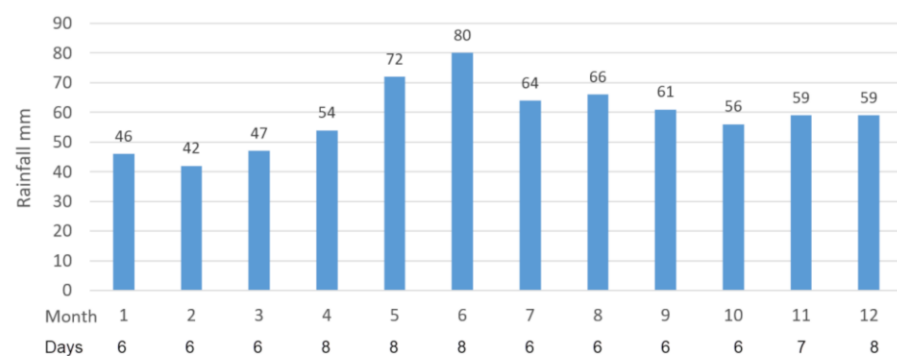




**Figure 1.** Global tilted irradiation at the optimum angle for Dragotin [24].



**Figure 2.** The average GTI and average monthly temperatures for Dragotin [24].



**Figure 3.** The average rainfall for Dragotin [24].

## 2.2. Estimation of Required Power of the PV System

In recent years, many researchers have used the Hybrid Optimization Model Software for Electric Renewables (HOMER) to dimension and simulate micro-grids [25,26]. Hos-sain et al. [27], in their study, tried to determine the optimal size of the roof PV system at an affordable price that will meet the criteria for powering electrical appliances in the house using the above software.

Using the HOMER Grid program based on the given building location, selected load profile “Residential”, “None Peak Month”, average daily consumption of 12.85 kWh for the past 12 months, selected “Simple Tariff”, and the inclination of the PV module in the

amount of  $35^\circ$  and azimuth  $0^\circ$ , the simulation determined that the required power of the PV system for the selected object was 3.58 kW or approximately 3.6 kW.

### 2.3. Facility and Equipment

The PV power plant is placed on the roof of a courtyard building that stands at  $35^\circ$  facing south without deviation. The roof is covered with trapezoidal sheet metal and there is no shading of the building. The courtyard building was chosen because of its south orientation and the ideal angle for placing the PV module, which is not the case with the roof of the house facing east/west. The following equipment was selected for the 3.6 kW power plant:

Solar module Jetion 450 W JT450SGH;

The power converter HUAWEI SUN2000L-3.68KTL;

Installation equipment (roof racks, cables, connectors).

The technical characteristics of the selected equipment are defined in Tables 2 and 3.

**Table 2.** Technical characteristics of the Jetion module 450 W JT450SGH [28].

Feature	Label	Value
Efficiency	$\eta_M$	20.4%
Temperature coefficient of voltage change	$\beta$	$-0.3\%/^\circ\text{C}$
Temperature range of the module application	$t_{min} \sim t_{max}$	$-40^\circ\text{C}$ do $85^\circ\text{C}$
Module area	$A_M$	$2.21\text{ m}^2$

**Table 3.** Technical characteristics of inverters HUAWEI SUN2000L-3.68KTL [29].

Feature	Value
Maximum input power	4968 W
Rated output power	3680 W
Output voltage range	220–240 V
Maximum efficiency	98.6%
European efficiency	97.3%

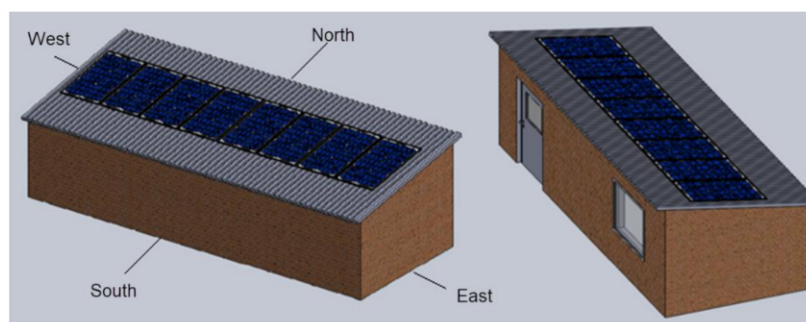
Required number of modules for the 3.58 kW system:

$$n = \frac{P_{PV}}{P_{MPP}} = \frac{3.58}{0.45} = 8 \quad (3)$$

Required surface for mounting the PV module:

$$A_{PV} = A_M \times n = 2.21 \times 8 = 17.68\text{ m}^2 \quad (4)$$

Due to the relatively small number of modules and the shape of the roof, the modules are installed in one row. A compatibility check determined that the selected PV modules are compatible with the selected inverter. The roof area on which the PV modules is installed is  $50\text{ m}^2$  and meets the required area for the installation of the PV module, which is  $17.68\text{ m}^2$ . A 3-D model of the building is shown in Figure 4.



**Figure 4.** Three-dimensional view of the building with installed PV modules.

#### 2.4. Equipment Costs

According to the current market situation in the Republic of Croatia, the price for the JETION 450 W JT450SGH solar module ranges from €218 to €315 depending on the supplier, and the price for the HUAWEI SUN2000L-3.68KTL inverter ranges from €960 to €1143. The costs of the other components are shown in Table 4. The installation of a 3.6 kW PV power plant costs €835. The price includes connection connectors, fuses with a suitable box, and documentation required to submit a request to company HEP for the installation of electricity meters (Table 4).

**Table 4.** Investment costs by purchasing components at the lowest prices on the market.

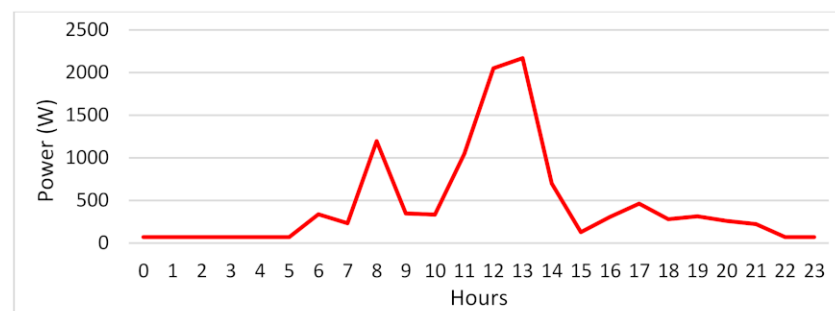
Component/Service	No of Pieces	Length (m)	Price per Piece/m (€)	Total Cost (€)
Solar module, monocrystalline, 450 W	8		218.30	1746.40
Inverter	1		960.00	960.00
Module holders	32		1.41	45.12
DC cables	1	20	1.58	31.60
AC cables	1	50	1.58	79.00
Assembly				835.00
Installation of electricity meters				347.00
Quality control with a report				200.00
Total investment cost €				4243.72
Total investment cost €/kW				1178.81

Total investment costs vary significantly depending on the type of installation, the capacity of the PV system, and the country in which the system is installed, but decline rapidly [30,31]. For example, in 2020, in Switzerland, the cost of investment of roof PV systems was 2125 €/kW, in France 1554 €/kW, in Germany 1360 €/kW, in Italy 1180 €/kW, in India 555 €/kW, in China 630 €/kW, and in Australia 1214 €/kW [32]. The investment costs of large PV systems are significantly lower. In Europe, the cost ranges from € 600/kW in the Czech Republic to € 1040/kW in Ireland.

To determine the payback period, it is necessary to determine the profile of the average daily load for the analyzed facility and the profile of the average daily production of electricity for the selected PV system, which is described below.

#### 2.5. Creating a Daily Grid Load Profile

Daily load profiles were recorded on an existing building, for which a Uni-trend UT-203+ measuring instrument was used, which was used to measure current and voltage in time intervals of 30 min to obtain an hourly load curve. Figure 5 shows a typical average daily load curve for the month of July.



**Figure 5.** Hourly load curve.

The area under the curve shows the daily electricity consumption for a household in Wh. From the picture, it is possible to read the peak power of that day, which is 2169 W.

## 2.6. Insulation and Electricity Produced from PV Systems

Data on insolation and electricity production required for cost-effectiveness analysis were taken from the report prepared using Solargis Prospect [24] for the Dragotin location according to the given parameters. These data are shown in Table 5, taking into account losses in the system. Losses in the PV system that occur during energy conversion are difficult to quantify accurately, but it is important to take them into account when designing and installing the system.

**Table 5.** Average daily electricity production (Wh) [24].

Hours	January	February	March	April	May	June	July	August	September	October	November	December
0–1	0	0	0	0	0	0	0	0	0	0	0	0
1–2	0	0	0	0	0	0	0	0	0	0	0	0
2–3	0	0	0	0	0	0	0	0	0	0	0	0
3–4	0	0	0	0	0	0	0	0	0	0	0	0
4–5	0	0	0	1	14	31	18	0	0	0	0	0
5–6	0	0	1	48	159	188	157	70	12	0	0	0
6–7	0	0	93	325	479	507	466	387	263	98	4	0
7–8	34	181	544	811	957	998	969	910	750	593	221	34
8–9	407	618	1042	1320	1435	1489	1479	1455	1235	1082	679	413
9–10	721	959	1448	1712	1833	1878	1878	1903	1616	1458	996	717
10–11	891	1173	1688	1966	2056	2099	2131	2181	1849	1679	1163	854
11–12	964	1297	1801	2047	2108	2118	2193	2280	1952	1769	1239	914
12–13	1005	1330	1781	2007	2038	2086	2161	2228	1912	1713	1211	898
13–14	897	1250	1623	1787	1823	1897	1967	2026	1668	1453	1029	759
14–15	662	944	1270	1460	1514	1593	1690	1701	1310	1060	700	521
15–16	271	603	882	1048	1118	1210	1290	1258	883	598	244	160
16–17	3	193	452	600	679	774	817	742	428	87	0	0
17–18	0	0	46	173	275	342	363	261	40	0	0	0
18–19	0	0	0	4	49	123	110	20	0	0	0	0
19–20	0	0	0	0	0	7	3	0	0	0	0	0
20–21	0	0	0	0	0	0	0	0	0	0	0	0
21–22	0	0	0	0	0	0	0	0	0	0	0	0
22–23	0	0	0	0	0	0	0	0	0	0	0	0
23–24	0	0	0	0	0	0	0	0	0	0	0	0
Total	5856	8549	12,673	15,310	16,536	17,339	17,691	17,423	13,918	11,590	7486	5268
Days in month	31	28	31	30	31	30	31	31	30	31	30	31
Monthly kWh	181.5	239.4	392.9	459.3	512.6	520.2	548.4	540.1	417.6	359.3	224.6	163.3

The most important losses to be considered are according to [33,34]:

- Losses in the inverter;
- Ohmic losses that occur as a result of resistance to current flow from the AC side of the inverter and in the cables;

- (c) Losses due to dust or snow on the surface of the PV module;
- (d) Losses of auxiliary devices.

For a given PV system and object location, theoretical losses are defined and shown in Figure 6.

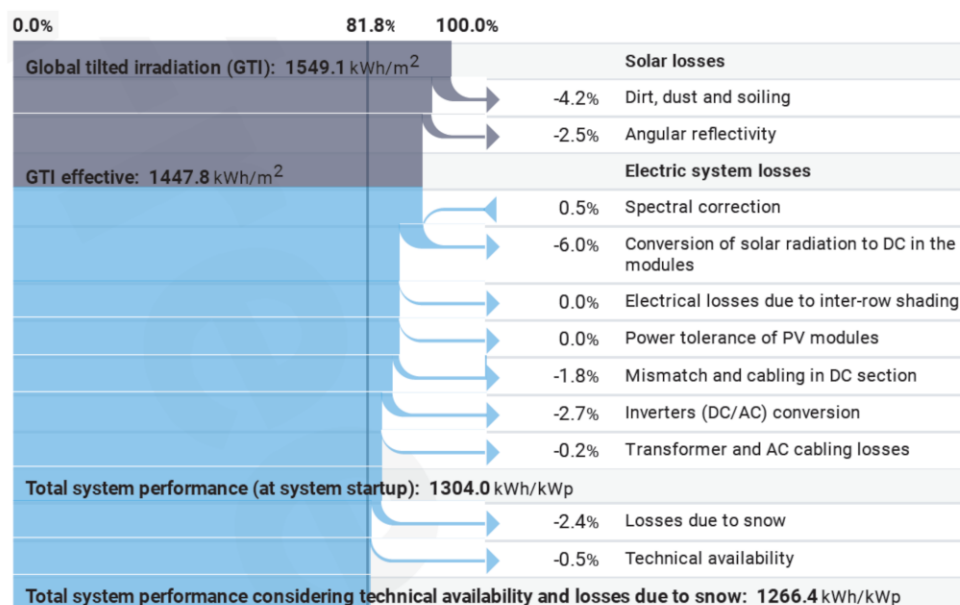


Figure 6. Theoretical losses in a given PV system [24].

The average daily production and consumption of electricity for each month is calculated based on the measured hourly electricity consumption and hourly electricity production (according to Table 5). The profile with 1-h time steps is most often applied [35,36]. Figure 7 shows an example of the electricity consumption and production profile for the month of January.

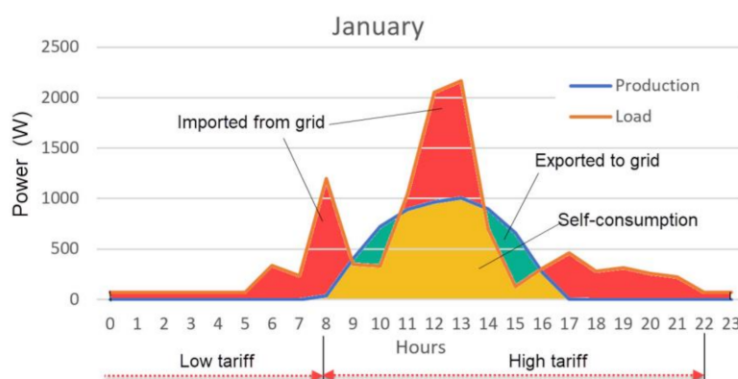


Figure 7. Average hourly profile of electricity consumption and production for July.

The choice of the measurement time interval has an impact on the appearance of the electricity consumption profile, i.e., on the results of the analysis. Steps of 5 min, 15 min, and 1 h are mentioned in the literature. The longer the time step, the higher the amounts for (SC) and (SS). The difference between (SC) for a step of 5 min and 1 h on an annual basis can be 3.2%, while daily it can be more than 5% [4]. Accordingly, for our case of selecting a time step of 1 h, it can be assumed that the error in the analysis results does not exceed 5%.

In general, production and consumption profiles rarely match, leading to a low SS or SC value. In the case of excess electricity (production greater than consumption), unused



electricity can be injected into the electricity grid or dissipated, resulting in low SC. In case of insufficient production of electricity from the PV system, energy is taken from the electricity grid, which leads to low SS. Maximizing SC along with SS is the goal of the user.

In Croatia, self-production is associated with renewable production and high-efficiency cogeneration for facilities with a capacity of <500 kW. The Renewable Energy Act obliges suppliers to purchase surplus electricity injected into the grid. In doing so, prosumers can have one of the following two statuses:

*Self-supply plant user:* a final customer of electricity of the household category who has a self-supply plant from renewable energy sources or high-efficiency cogeneration connected within his installations, whose surplus energy within the billing period can be taken over by a supplier or market participant with a contract, provided that within the calendar year, the amount of electricity that he delivered to the grid is less than or equal to the electricity taken from the grid.

*End customer with own production:* the end customer of electricity to whose installation the production plant for the production of electricity from renewable energy sources or high-efficiency cogeneration is connected, which meets the needs of the end customer and with the possibility of delivering surplus electricity to the distribution grid. In this case, within a calendar year, the amount of electricity injected into the grid is usually higher than the electricity taken from the grid.

In our case, the purchase price of electricity is determined according to the principle of the customer with its own production and is calculated by the term given by the company HEP Ltd., i.e., according to the Renewable Energy Sources and High-Efficiency Cogeneration Act. According to the same law, the billing period is one month. In the case where more energy is taken from the grid than sent to the grid, expression (5) applies:

$$C_i = 0.9 \times PKC_i \quad (5)$$

In the case where more energy is injected into the grid than taken from the grid, expression (6) applies:

$$C_i = 0.9 \times PKC_i \times \frac{E_{pi}}{E_{ii}} \quad (6)$$

where:

$C_i$	Purchase price of electricity;
$PKC_i$	The average unit price of electricity without excise duties;
$E_{pi}$	Electricity is taken from the grid;
$E_{ii}$	Electricity delivered to the grid.

The cost-effectiveness of PV systems is to a lesser extent affected by the decline in the efficiency of the PV module that occurs throughout the life of the system. The amount of efficiency drop is shown in Figure 8. For the first year of operation of the system, the degradation of module properties is 0.8%, and for other years 0.5%.

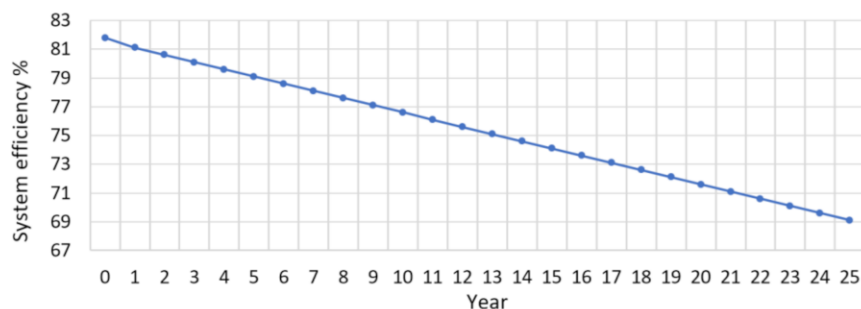
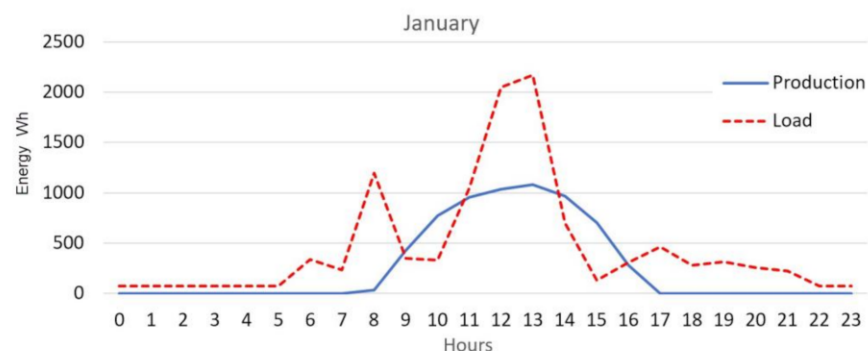


Figure 8. Decrease in efficiency over the life of the PV system (%) [24].

### 3. Results and Discussion

The average daily data of insolation and electricity production were calculated for each month of the year using Solargis Prospect [24]. Global tilted irradiation is 1549 kWh/m<sup>2</sup> per year and total photovoltaic power output is 4559 kWh per year.

Average load values are approximately the same for each month due to routine household activities that are the same almost every day. Even differences in electricity consumption on Sundays and other days of the week can be ignored. Only in September, there are additional seasonal activities that affect electricity consumption and that are taken into account. Figure 9 and Table 6 show the production and load at the average daily level for January for 24 h.



**Figure 9.** Load and energy production at the average daily level for January.

**Table 6.** Energy production and load at the average daily level for January.

Time h	Production Wh	Load Wh	From Grid Wh	Injection to Grid Wh
0–1	0.00	70.00	70.00	0.00
1–2	0.00	70.00	70.00	0.00
2–3	0.00	70.00	70.00	0.00
3–4	0.00	70.00	70.00	0.00
4–5	0.00	70.00	70.00	0.00
5–6	0.00	70.00	70.00	0.00
6–7	0.00	337.76	337.76	0.00
7–8	0.00	233.65	233.65	0.00
8–9	34.07	1196.55	1162.48	0.00
9–10	407.27	347.94	0.00	59.33
10–11	721.39	333.32	0.00	388.07
11–12	890.83	1046.32	155.49	0.00
12–13	963.72	2051.42	1087.70	0.00
13–14	1004.94	2169.17	1164.23	0.00
14–15	897.39	698.89	0.00	198.50
15–16	661.95	127.34	0.00	534.61
16–17	271.23	307.60	36.37	0.00
17–18	3.47	461.38	457.91	0.00
18–19	0.00	280.36	280.36	0.00
19–20	0.00	315.26	315.26	0.00
20–21	0.00	258.62	258.62	0.00
21–22	0.00	221.56	221.56	0.00
22–23	0.00	70.00	70.00	0.00
23–24	0.00	70.00	70.00	0.00
Total	5856.26	10,947.14	6271.39	1180.51

Analogously, data can be obtained on an average daily basis for all 12 months of the year. Below are graphical representations of data for the months of July and the month of September (Figures 10 and 11) as characteristic months.

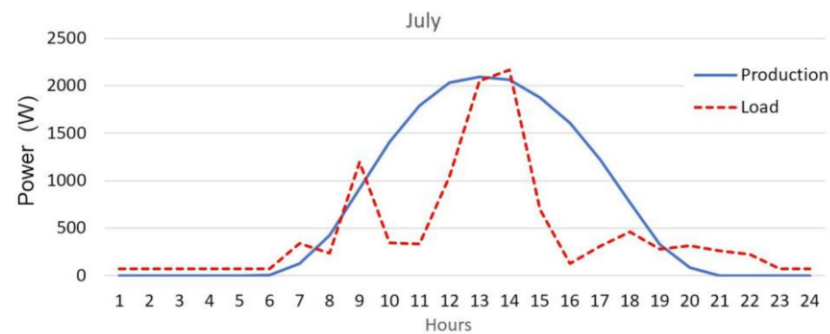


Figure 10. Load and energy production at the average daily level for July.

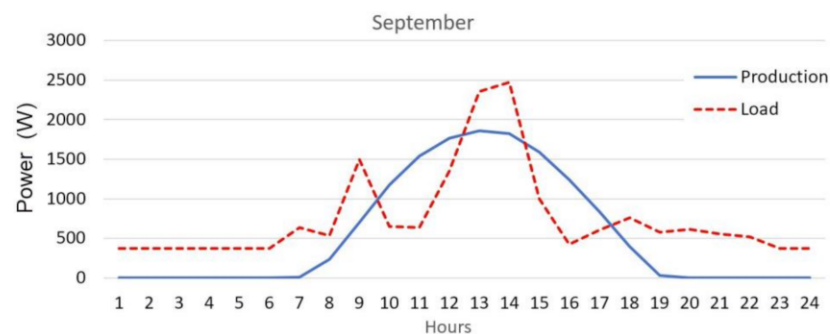


Figure 11. Load and energy production at the average daily level for September.

Based on the calculated data for all months of the year and taking into account the duration of the higher and lower tariff, summary data can be obtained for all months (Table 7) and the whole year (Table 8). Electricity meters register energy delivered to the grid and energy taken from the grid. The amount of electricity taken from the grid or delivered to the grid is calculated for each hour as the difference between load and electricity production. The values of daily energy generated by photovoltaic installation, daily energy imported and exported to the network (assuming current net metering), self-sufficiency (SS), and own consumption (SC) can be defined using Table 7 and Figure 7.

Table 7. Average monthly values of energy.

Month	Load kWh	Production kWh	From Grid kWh		To Grid kWh	Consumption from PV kWh	SC %	SS %
			Higher Tariff	Lower Tariff				
January	339.36	181.54	159.71	34.70	36.60	144.95	79.8	42.7
February	306.52	239.36	111.04	31.34	75.23	164.14	68.6	53.5
March	339.36	392.85	69.68	34.67	157.84	235.01	59.8	69.3
April	328.41	459.29	36.88	32.12	199.87	259.42	56.5	79.0
May	339.36	512.62	34.79	22.49	230.53	282.09	55.0	83.1
June	328.41	520.16	28.42	20.36	240.53	279.63	53.8	85.1
July	339.36	548.42	28.48	22.40	259.94	288.48	52.6	85.0
August	339.36	540.11	33.51	25.67	259.93	280.18	51.9	82.6
September	544.41	417.55	128.15	115.69	116.98	300.57	72.0	55.2
October	339.36	359.30	86.56	32.03	138.54	220.77	61.4	65.1
November	328.41	224.57	130.64	33.58	60.38	164.20	73.1	50.0
December	339.36	163.32	169.30	34.70	27.96	135.36	82.9	39.9
Total	4211.70	4559.11	1017.16	439.75	1804.32	2754.79	60.4	65.4

**Table 8.** Data on energy consumption and production on an annual basis.

Electricity	With PV System	No PV System
Higher tariff (kWh)	1017.16	3710.92
Lower tariff (kWh)	439.75	500.13
Total	1456.91	4211.05
To grid (kWh)	1804.32	—

The traditional definition of self-consumption says that photovoltaic energy is consumed instantly or within 15 min. Instead, net metering can be applied to dispose of surplus PV energy in the grid over a longer period of time (“store” in the grid), and use in periods of insufficient PV production, thus increasing self-consumption.

The most general definition of net metering policy is the permission given to utility-related consumers to compensate for their consumption by injecting their own surplus electricity into the grid and creating loans that can be used later. Although the general definition is clear, net metering policy varies from country to country. For example, the policymaker should decide on elements, such as the policy objective (promote the adoption of a distributed grid system or guarantee the financial sustainability of utilities), compensation scheme (in energy or money), minimum technical requirements of the plant to guarantee distribution generation quality, financial mechanisms (if any) and the way it is financed, and the like. The net metering/net billing policy is essential for the cost-effectiveness of PV roofing systems.

Various net metering/net billing schemes have been analyzed in the literature, ranging from instantaneously net metering to 1-year net metering [37–39]. According to [37], significant compensation of electricity taken from the grid can be achieved for a period of 1 day or more. If net metering is used annually, excess PV production during the summer can be injected into the grid and used in the winter months. For the object analyzed in this paper, the results for different net measurement schemes are shown in Table 9.

**Table 9.** Energy injection to grid and energy consumption from grid for different net metering schemes.

Net Metering Scheme	Grid Injection (kWh)	Grid Consumption (kWh)
1 h	1804	1457
1 month	1048	554
1 year	347	0

As can be seen, the longer the net metering/net billing period, the lower the values of energy consumed from the grid to be paid to the electricity supplier. In the case of the application of annual net metering, the energy consumed from the grid can be equal to zero, and this incentive scheme allows compensation of production and consumption during the year. This value increases as the time frame decreases, but in any case, the total energy injected into the grid is greater than that consumed from the grid. These results suggest that depending on the legislation of each country, adjusting demand to production may be more or less critical. In the worst case, when it is not possible to compensate for the energy produced (instantaneously balances), the percentages of self-consumption and self-sufficiency can only be improved by some kind of consumption management. At best, the grid acts as a system for storing all the excess energy produced from the PV system [37].

#### *Payback Time*

The investment for a 3.6 kW PV power plant totals €4243.72. The PV system is connected to the electricity grid via a home installation without incentives. From the network 1456.92 kWh of energy is taken and 2754.14 kWh of energy is taken from the PV system. Into the network is injected 1804.32 kWh from the PV system. The price of electricity with VAT 13% [40] for a higher tariff is 0.139 €/kWh, and for a lower tariff 0.076 €/kWh. The annual cost of energy in case without a PV system (acc. Table 8) is:

Higher tariff	$3710.92 \times 0.139 = €515.24$	(88.12%)
Lower tariff	$500.13 \times 0.076 = €38.05$	(11.88%)
Total:	$= €553.29$	

The annual cost of energy in case with a PV system (acc. Table 8) is:

Higher tariff	$1017.16 \times 0.139 = €141.23$	(69.82%)
Lower tariff	$439.75 \times 0.076 = €33.47$	(30.18%)
Total:	$= €174.70$	

The time of return on investment can be significantly affected by the price of electricity throughout the life of the PV system. Compared to the other EU Member States, the price of electricity in Croatia is currently quite low, as can be seen from Figure 12. This implies that it is possible to increase prices over time, which shortens the payback time. The share of taxes and VAT in the price of electricity (Figure 13), i.e., their changes, may also have a certain impact on the return on investment.

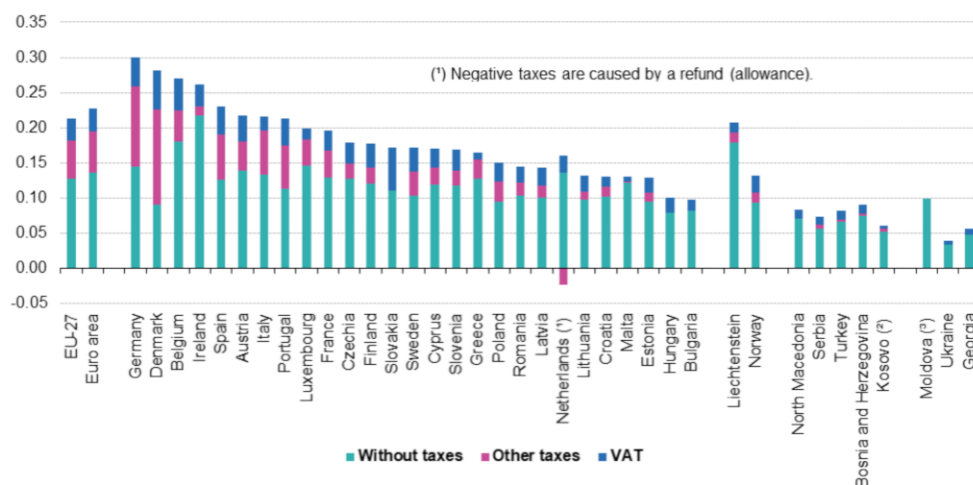


Figure 12. Electricity prices for household consumers, second half 2020 (EUR/kWh) [41].

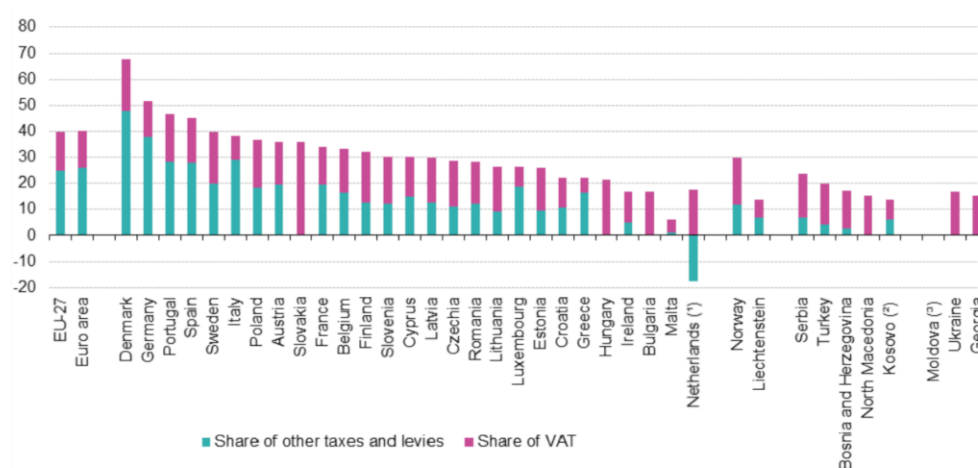


Figure 13. Share of taxes and levies paid by household consumers for electricity, second half 2019 [41].

The calculation of the purchase price according to the accounting period of 1 month for the whole year was performed according to expressions (5) or (6), and is shown in Table 10. The average unit price of electricity without excise duties ( $PKC_i$ ) is 0.0627 €/kWh [40]).



**Table 10.** Calculation of profit for sold surplus electricity.

Month	From Grid kWh	To Grid kWh	Expression	The Purchase Price €/kWh	Profit €
January	194.41	36.60	5	0.056	2.07
February	142.38	75.23	5	0.056	4.25
March	104.35	157.84	6	0.0374	5.89
April	69.00	199.87	6	0.020	3.90
May	57.28	230.53	6	0.0147	3.23
June	48.78	240.53	6	0.012	2.75
July	50.88	259.94	6	0.0107	2.87
August	59.19	259.93	6	0.0133	3.34
September	243.84	116.98	5	0.056	6.61
October	118.59	138.54	6	0.048	6.70
November	164.22	60.38	5	0.056	3.41
December	204.00	27.96	5	0.056	1.58
Total	1456.91	1804.32			46.60

Profit for surplus electricity delivered to the grid: €46.60

Annual system maintenance €20.

Total annual profit:  $378.60 + 46.60 - 20 = €405.20$

Return on investment time is calculated as the simple payback period (*SPP*):

$$SPP = \frac{\text{Cost of investment (€)}}{\text{Annual profit (€/year)}} \quad (7)$$

$SPP = 4243.72 / 405.20 = 10.47$  years (no incentive)

In case of exercising the right to incentives based on the Law on the Fund for Environmental Protection and Energy Efficiency and the Statute of the Fund for Family Homes, it is possible to exercise the right to incentives up to 40% for the investment amount not exceeding €5006. The simple payback time with incentives is:

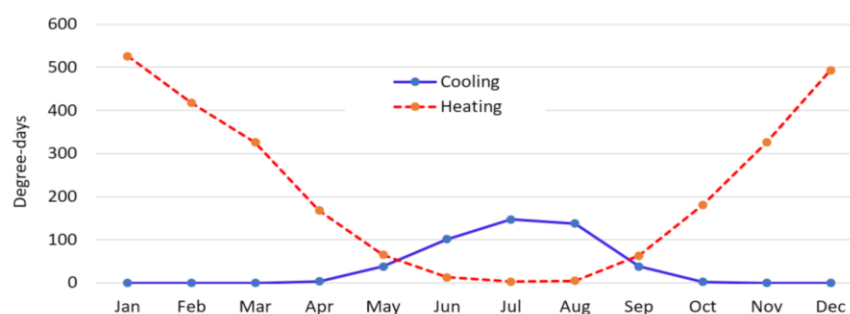
$$SPP_i = \frac{(100 - \text{incentives } (\%))}{100} \cdot \frac{\text{Cost of investment}}{\text{Annual profit}} \quad (8)$$

$SPP_i = (100 - 40) / 100 \times 4243.72 / 405.20 = 6.3$  years

The main way to increase the cost-effectiveness of PV systems is to increase self-consumption. There are two ways to improve your own consumption, namely load management and energy storage. These methods can be applied separately or in combination.

There are several definitions of load management, and common to all is the improvement of the energy system on the consumption side [42]. In this research, the term is used to time-shift the load in the household, for example, the use of washing machines, heating, ventilation, and air conditioning, from periods with lower energy production from PV systems to periods with higher production from PV systems. In this way, the periods of interaction with the distribution grid can be reduced. Timeshift of the load can be achieved manually, where people turn on electrical appliances when there is excess PV production, or automatically, which requires microprocessor control, and for more advanced systems, ambient temperature, and insolation weather forecasts [43,44].

As an additional measure to improve the consumption profile, air conditioning can be installed, which would use the excess electricity for cooling in the summer, while it would be used for space heating in spring and autumn during colder days (see Figure 14). In this way, the cost of heating would be somewhat reduced.



**Figure 14.** Degree-days of heating/cooling for Dragotin [24].

There are several different techniques for load management, such as direct load control, load limits, and smart metering and devices [45]. Most of the papers studied the PV-battery system with a storage capacity of 0.5–1 kWh times the installed PV capacity in kW [46–50]. This means that battery systems are applied for short-term storage, usually shorter than one day. Although battery prices are falling, PV systems with batteries are still not cost-effective, as stated in the introduction [8–12].

Dynamic power control controllers can also be purchased on the market, which constantly matches the amount of electricity produced by photovoltaic panels with the amount of energy consumed in the building. They do this by changing the MPPT (maximum power point tracker) of the inverter according to the power consumption of the user. This guarantees that no excess energy is injected into the grid or that only a certain amount is injected in accordance with the legislation of each country.

#### 4. Conclusions

The paper analyzed the cost-effectiveness of applying the PV roof system on a family house in the continental rural part of Croatia. For this purpose, a daily curve of electricity consumption was recorded with a step of 1 h for the observed object and the production of electricity from the PV system for a given location of the object was calculated. Due to routine daily activities that are repeated throughout the year, it was possible to apply the curves of the average daily electricity consumption for the whole month.

In general, the daily load profile and the electricity generation profile do not match, so it is necessary to calculate the SS and SC factors. For the observed object, the SC factor is in the range of 51.9% to 82.9%, which can be assessed as satisfactory. However, as the purchase price of surplus electricity produced (in case more energy is injected into the network than is taken from it) is low, the load profile needs to be further improved by using electricity consumers at a time when there is surplus electricity produced. However, it is not realistic to expect that the consumption profile could be significantly improved by manual regulation and changes in inhabitants. An in-house energy management system, mentioned in the introductory part, can yield much better results related to self-consumption. The amount of SS and SC can be significantly affected by the use of battery systems for energy storage. However, such systems are still not cost-effective. The increasing use of air conditioners due to climate change has a positive effect on the daily load profile in summer but also in spring and autumn when there are certain needs for less heating of the building, and there is surplus electricity produced in the PV system.

For the analyzed facility, with the existing electricity prices, which are among the lowest in the EU and with the existing legislation related to net metering, the roof PV system can be paid for in 10.5 years without government incentives.

In addition to reducing electricity bills, installing PV roofing systems provides benefits, such as energy autonomy, reduced carbon emissions, and the creation of new, local jobs.

As a continuation of this research, it would be interesting to analyze PV systems of different capacities (for example, in the range of 2 to 5 kW) for current legislation and

determine the optimal system not only by the criterion of the payback period but also by the total profit over the life of the PV system.

**Author Contributions:** M.B.: conceptualization, methodology, writing—original draft preparation, visualization; A.Č.: validation, supervision; B.Z.: software, data curation. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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