

## Article

# Analysis of Selected Service Industries in Terms of the Use of Photovoltaics before and during the COVID-19 Pandemic

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**Abstract:** Previous analyses of the PV market (and the impact of the pandemic on it) have focused on the market as a whole. The literature does not contain analyses of selected services sectors (e.g., catering, hotel services) in terms of the use of photovoltaics. There are no studies that would show in which segments the demand profile for electricity most closely matches the production from photovoltaic installations (not to mention the impact of the pandemic). The authors analyzed selected service sectors (catering and hotel) in terms of the use of photovoltaics before and during the COVID-19 pandemic. The paper proposes a comparative methodology for the use of photovoltaics for self-consumption, including statistical analyses and calculations of the self-consumption index for representatives of various selected services sectors. The highest value of the self-consumption ratio at the level of 52% was shown for cafes and restaurants (during the pandemic). Surprisingly, in the pandemic, the self-consumption rate increased for restaurants and cafes for the same size of installations (compared to pre-pandemic times).

**Keywords:** photovoltaic (PV); renewable energy source (RES); solar photovoltaic; self-consumption; COVID-19; Poland; energy consumption



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## 1. Introduction

The rapid economic and population development causes that the demand for electricity in the world is growing year by year [1]. The International Energy Agency (IEA) provides forecasts in which the increase in electricity demand is estimated at 30% in 2040 compared to the base year 2016 [2]. At the same time, the challenges of climate change and global warming are led to the energy sector transformation. There is a large shift from fossil fuel-based systems to clean technologies and an economy based on sustainable resources [3,4]. Even though more and more countries in the world are promoting policies based mainly on the use of sustainable energy sources as factors mitigating climate change, ensuring energy security and sustainable economic development [5–8], the cost of producing electricity from renewable sources is still higher than from fossil fuels [9,10]. As a result, it is consumers who pay the highest price for green electricity [11]. There are more and more proposals on the market aimed at better management of energy and lowering its prices—especially the one from renewable sources, these include, among others, initiatives such as the creation of energy cooperatives on the capacity market, which would use the potential of renewable energy sources in rural areas [12], the idea of unlimited use of the low voltage grid by electricity consumers, producers prosumers [13], energy storage systems from renewable energy sources [14,15] or even properly designed subsidy support systems for RES [16]. At the same time, solar (as well as wind) technologies are largely favored among other technologies that use renewable energy sources, which significantly affects the development

of installations supplied from these sources [17,18]. The use of solar technologies for the production of electricity is associated with their undoubted advantages, including scalability, no need for heavy support infrastructure and availability in remote locations, etc. [19]. It is also important that these systems do not have any moving parts, they do not require significant maintenance with relatively long service lives and, during use, do not pollute the air or water [20,21]. Research shows that among individual customers, solar energy is valued higher than electricity generated from other sources [22], while the very idea of self-sufficiency and the possibility of active participation in the energy transformation positively influences investments in solar technologies [23,24]. Taking into account the growing prices of electricity for end-users, with the simultaneous decline in the prices of photovoltaic systems, a significant increase in interest in this type of technology is observed [25]. Despite these undoubted advantages of solar technologies and strong pressure from the European Union to eliminate units fired by coal and switch to clean, renewable sources [26,27], it should be realized that solar technologies are sensitive not only to the solar radiation level but also to average air temperatures, seasonal and weather changes [28]. These factors can significantly affect the power grids [29]. With the observed significant increase in installed solar power not only in Europe but also in the world [30,31], there is more and more discussion about the problems (such as the duck curve) that accompany this increase [32,33]. The imbalance between the intermittent supply, sensitivity to weather conditions and the volatile profile of demand for electricity begins to raise serious concerns about the load and, consequently, the reliability of the power grid [34]. There was the idea of using traditional backup generators (powered by fossil fuels) to prevent the threat of imbalance risks, but it runs counter to the goal of a clean energy transition and has been criticized for polluting the environment [35]. Alternatively, attention is paid to the energy demand response (DR) as a way of balancing the power grid [36,37] or increasing the auto-consumption ratio, which would largely (or fully) cover the demand, depending on the PV load and production level [38]. The COVID pandemic also had a significant impact on the entire energy industry [39]—including the PV industry, which was not resistant to these perturbations and the entire industrial chain felt the effects of the pandemic, which resulted in a short-term increase in production costs [40]. At the same time, Zhang H. et al. [41] show that the risk of slowdown in solar PV deployment due to COVID-19 can be mitigated through comprehensive incentive strategies.

As shown in the literature, there are many analyses of these problems related to PV installations, however, the authors see a large gap regarding the lack of analyses of selected segments in terms of the use of photovoltaics. There are no studies that clearly show that the demand profile for electricity in the selected segment corresponds to the production from PV installations, thus making the self-consumption rate very high. There are no indications of this type of behavior in research papers, not to mention the impact of the COVID-19 pandemic on these phenomena. As shown in Figures 1 and 2, the literature can find the amount of new PV capacity installed in individual segments and forecasts regarding their growth, however, the authors see a lack of in-depth analyses of individual segments. For this reason, the authors decided to analyze selected service industries for their use before and during the COVID-19 pandemic.

Figure 1 shows shares of solar PV net capacity additions by application segment in 2013–2022 (however, until May 2021, this estimate is based on the reported data, and after May 2021 on the forecast). IEA estimated that global solar PV capacity additions are expected to reach nearly 117 GW in 2021 in the main case. In the years 2020–2022, an increase in new installed capacity is expected in all application segments, with the largest share of new installed capacity still being observed for utility-scale projects [42]. Interestingly, comparing this data with [43], where it was stated that in 2020 138 gigawatts of new PV capacity was installed, it can be assumed that these values are underestimated.

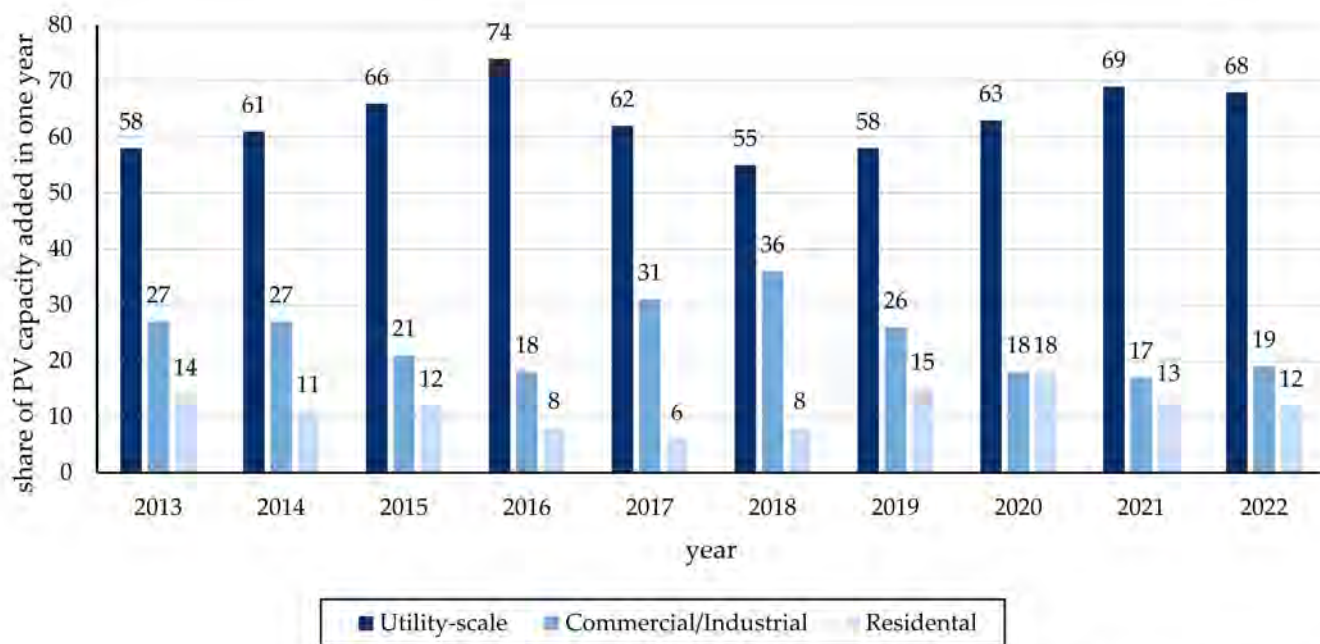


Figure 1. Shares of PV net capacity additions by application segment, 2013–2022. Based on [38].

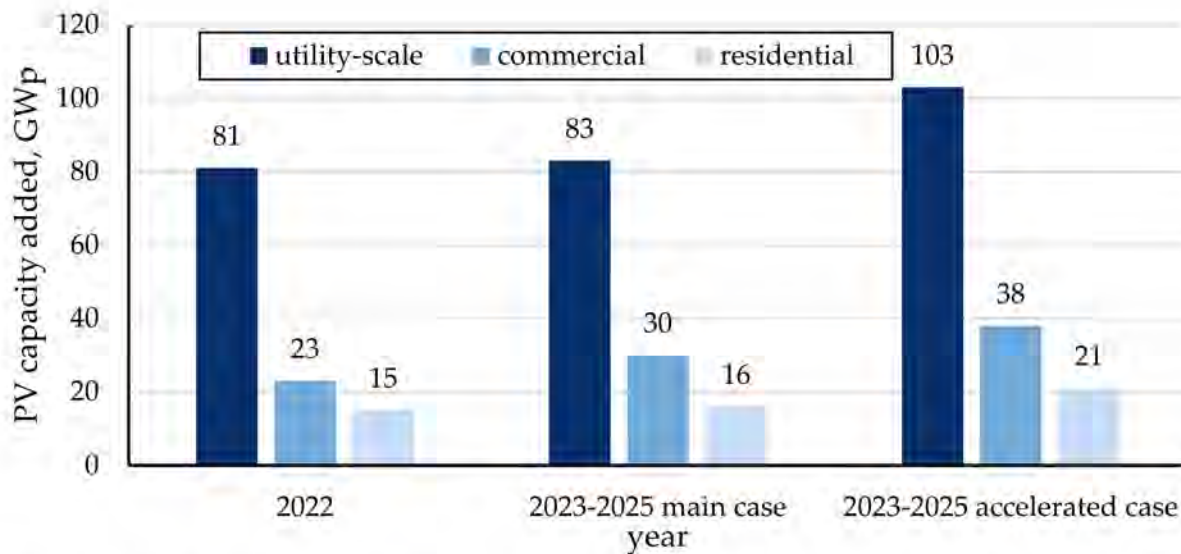


Figure 2. Average global annual capacity additions in main and accelerated cases, 2023–2025. Based on [38].

Figure 2 shows the average global annual capacity additions in main and accelerated cases, 2023–2025. Continued political support and cost reduction are projected to drive further solar expansion beyond 2022. The distributed solar segment is expected to grow in 2023–2025 as a result of the global economic recovery, which will positively impact the faster adoption of commercial and residential systems. The potential for total PV in the accelerated case compared with the main case is significantly higher—it is estimated that in the years 2023–2025 the annual capacity increase may reach 165 GW on average [42]. There are many studies on the impact of self-consumption from PV installations in the literature. McKenna et al. [44] analyzed the self-consumption of photovoltaic systems in a smart grid demonstration project in the residential sector in the United Kingdom. Tongsovit S. et al. [38] analyzed the feasibility of self-consumption chemists for four customer groups from an economic point of view in Thailand. Mateo C. et al. [45] analyzed the impact of shaping the consumption policy on the distribution networks with which the

prosumers are connected. Pedrero J. et al. [46] analyzed the economics of self-consumption from PV installations for an industrial park and showed that greater economic benefits come from shared self-consumption. Fachrizal R. and Munkhammar J. [47] reported an increase in self-consumption from PV systems installed in apartment buildings thanks to the use of an intelligent charging system for electric vehicles.

As shown in Figures 1 and 2 in the literature, there are estimates of the increase in installed power in given application segments, however, there are no in-depth analyses of PV installations within a given sector, for example, in which order and in which industries it is best to invest in PV systems (e.g., whether it is better to invest in PV first in the hotel industry, or maybe in the catering industry, etc.) so that the profits and the self-consumption rate are as high as possible. From the point of view of the policy of supporting PV installations, as well as business decisions for investors, this gap seems to be a significant problem, so far not noticeable in research. The novelty of this publication is a proposed comparative methodology of various segments in the service industry in terms of the use of photovoltaics for the production of electricity for own use. In addition, it was analyzed how these factors are changing due to the impact of the COVID-19 pandemic.

The paper is structured as follows: Section 2 describes research objects, data sources and scope of work; Section 3 provides the rationale for the selected research methodology along with its description; Section 4 describes the results of the analyses and discussion and finally, the conclusions can be found in Section 5.

## 2. Research Objects, Data Sources and Scope of Work

The article analyzes anonymized data on the electricity consumption of customers from the C12 group running a business in the gastronomy and hotel industry. Hourly resolution data were provided by one of the Distribution Network Operators.

The research objects were in the south-west of Poland and were:

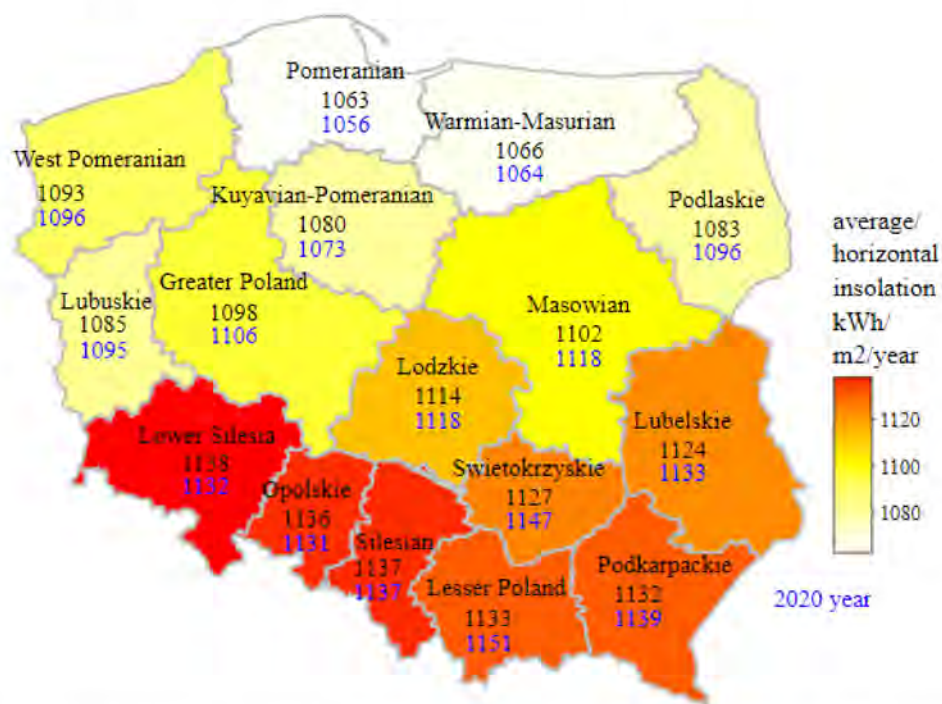
- Three cafes, conventionally marked with the symbols “C1”, “C2” and “C3”;
- Four hotels, conventionally marked with the symbols “H1”, “H2”, “H3”, “H4”;
- Seven restaurants marked with the symbols “R1”, “R2”, “R3”, “R4”, “R5”, “R6” and “R7”.

For the purposes of analyzing the insolation conditions in terms of the productivity of potential photovoltaic installations, the conditions in the vicinity of the capital of the Opolskie Voivodeship were assumed as the geometric center of gravity of the analyzed enterprises’ distribution. The location of the Opolskie Voivodeship and the value of available solar radiation in relation to other regions of Poland are shown in Figure 3. The insolation data in the analyzed period were a set of hourly data of horizontal radiation values downloaded from the website [48]. Horizontal radiation is the sum of direct and diffused solar radiation. The above-mentioned data were extracted from the ERA5 database on an hourly basis.

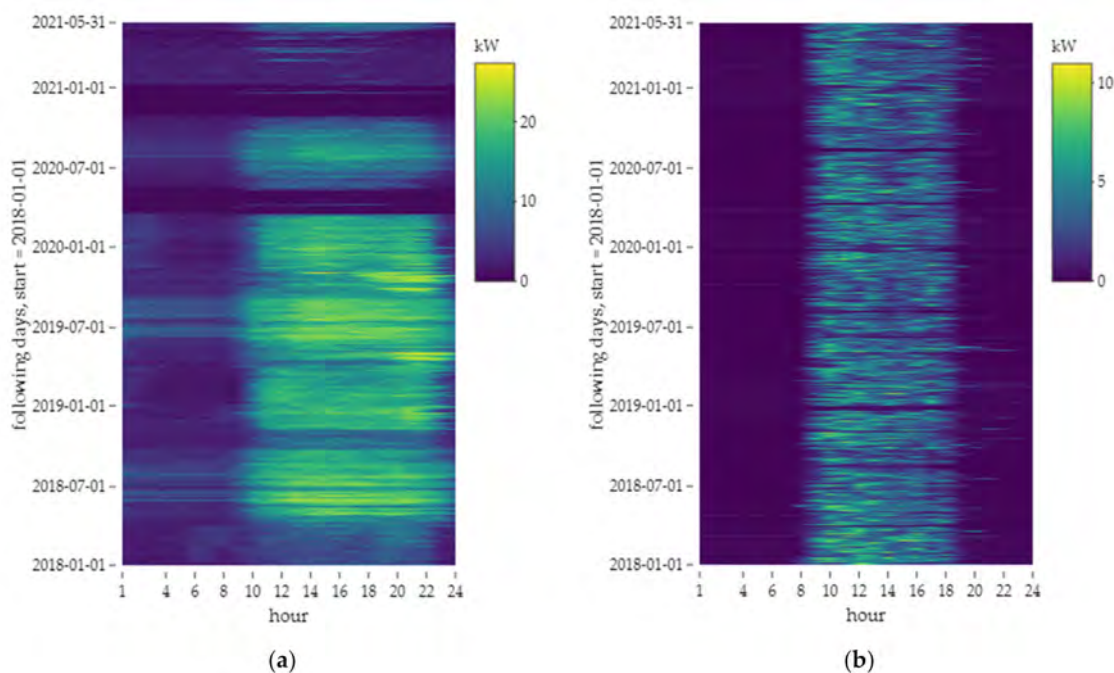
Using statistical methods, the degree of similarity of the electricity consumption profiles in the analyzed enterprises was determined according to:

- The profile of power demand in the National Power System,
- The value of horizontal insolation and (as a derivative) of electricity production profiles from potential photovoltaic installations in the analyzed cases of enterprises, with the degree of self-consumption of the produced energy.

The calculation process was carried out in the RStudio environment (RStudio: Boston, MA, USA) on the hourly data of energy consumption in enterprises (Figures 4–10), hourly power demand in the National Power System (Figure 11a) and solar radiation conditions (Figure 11b).



**Figure 3.** Horizontal insolation in Poland (for horizontal surfaces) for years: 2010–2019 (numbers in black) and 2020 (numbers in blue). Source: own study based on references [48].



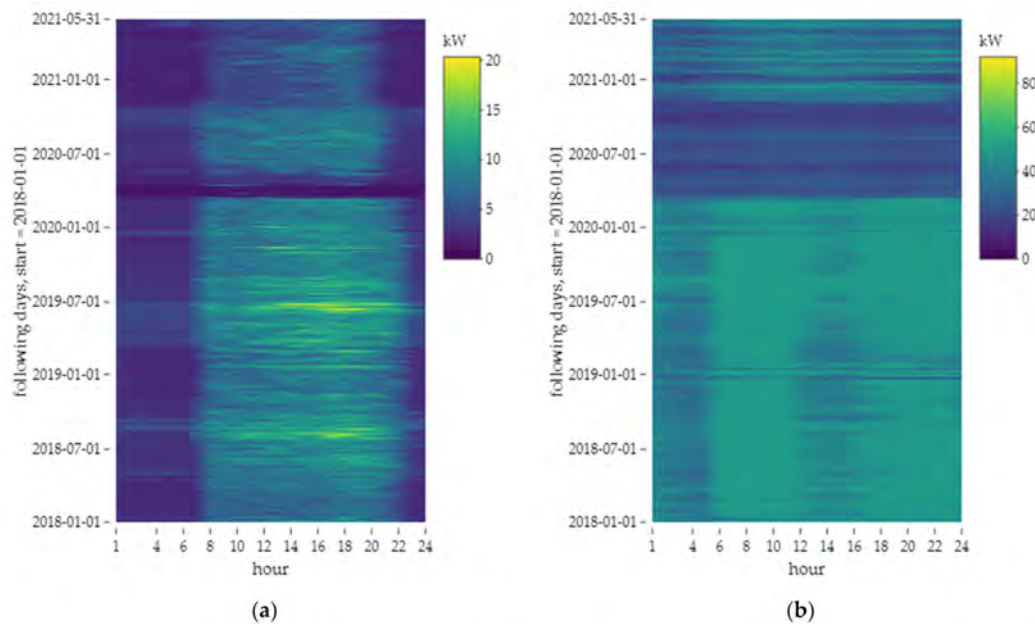
**Figure 4.** Course of hourly electricity consumption for the analyzed case study: (a) C1, (b) C2. Source: own study.

The analysis in Figures 4–10 shows the existence of certain differences in the course of the variability of hourly electricity consumption also within individual industries. These differences result, among others, from the characteristics and working hours of individual enterprises.

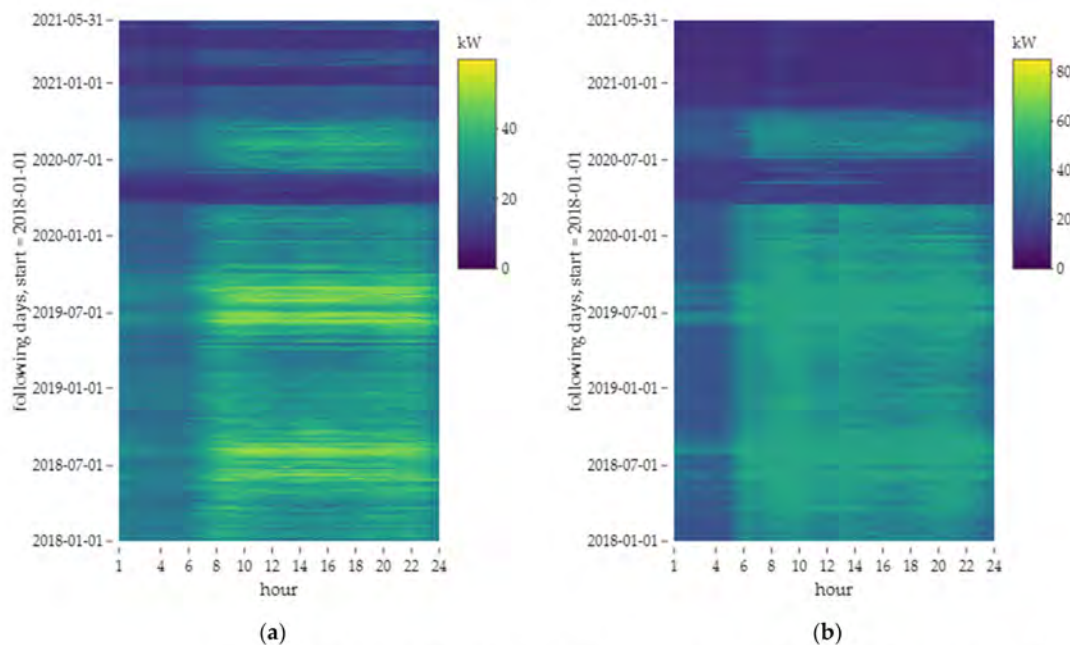
The horizontal blue bars indicate low electricity consumption on off-peak days, which is especially noticeable in C1, H2, R2 and R5. The work pattern adopted in other cases

of enterprises results in the maintenance of a stable level of electricity consumption on a weekly basis, which is particularly visible in the case of C2 and R3.

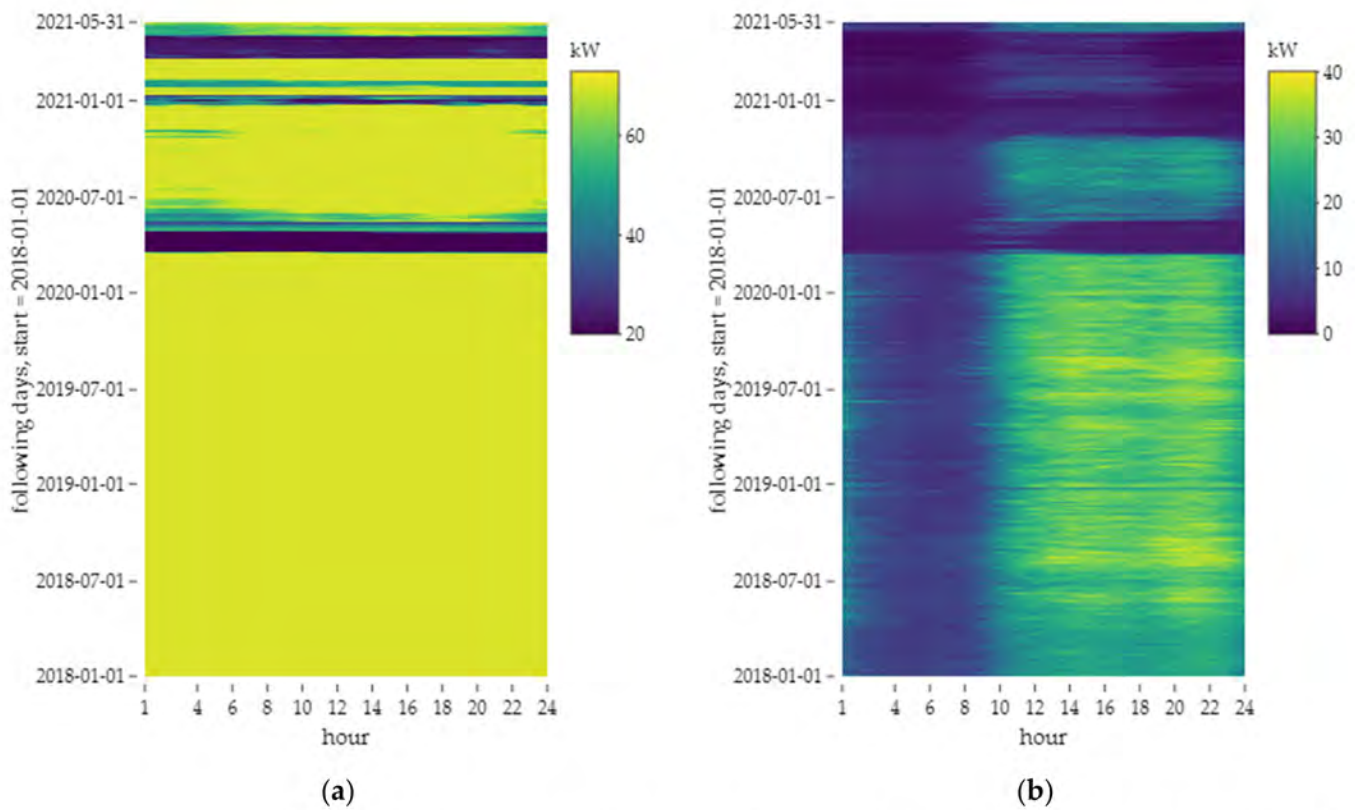
The impact of restrictions introduced during the COVID-19 pandemic waves is particularly interesting. In all cases, except C2, the first lockdown in March 2020 is visible. The impact of the second lockdown in November 2020–January 2021, encompassing the “national quarantine” period, is visible in cases C1, C3, H3, R1–R5. However, in the cases of C1, H2, H3, R1–R5, the devastating effect of restriction is noticeable. A significant reduction in their activities is visible throughout the period from the second to the third wave of the COVID-19 pandemic.



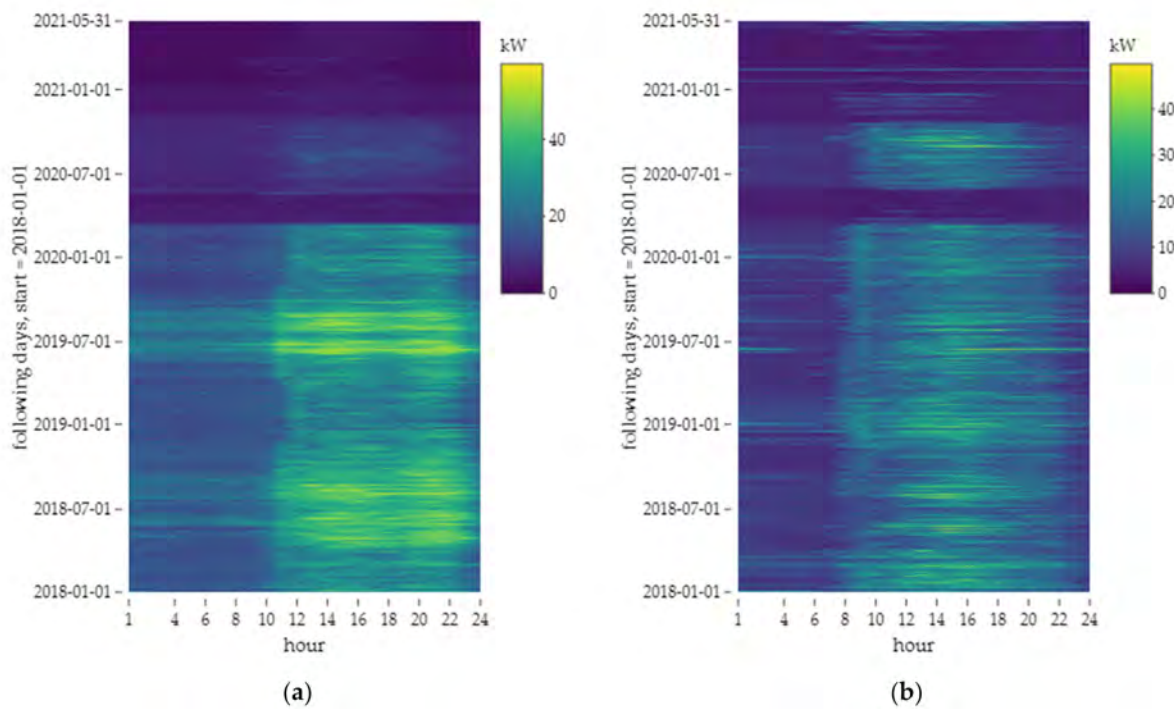
**Figure 5.** Course of hourly electricity consumption for the analyzed case study: (a) C3, (b) H1. Source: own study.



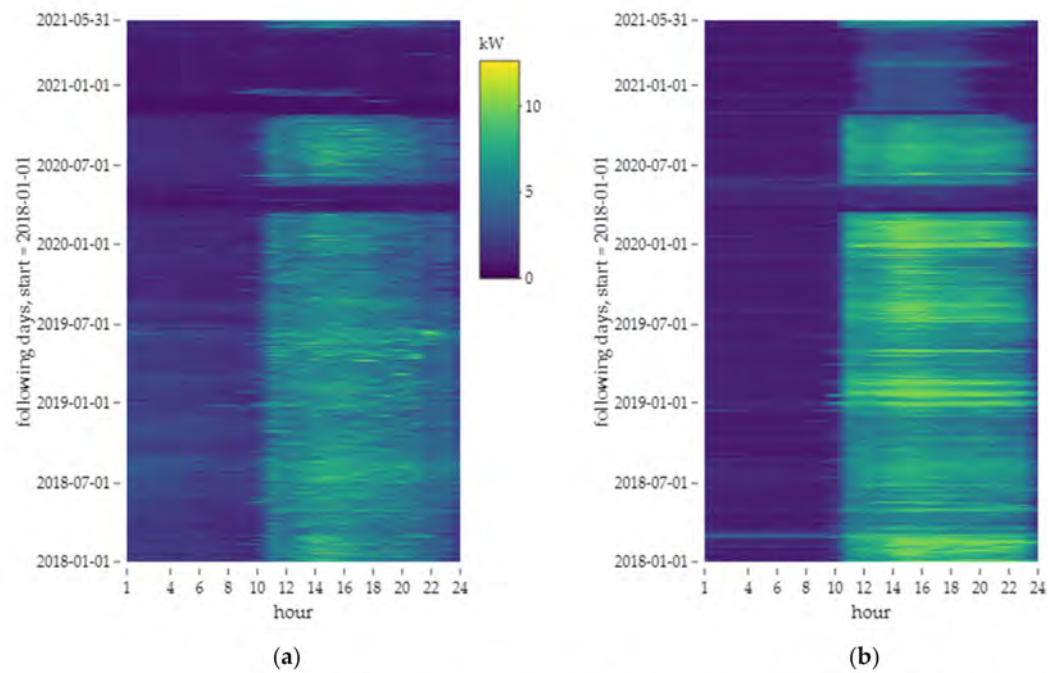
**Figure 6.** Course of hourly electricity consumption for the analyzed case study: (a) H2, (b) H3. Source: own study.



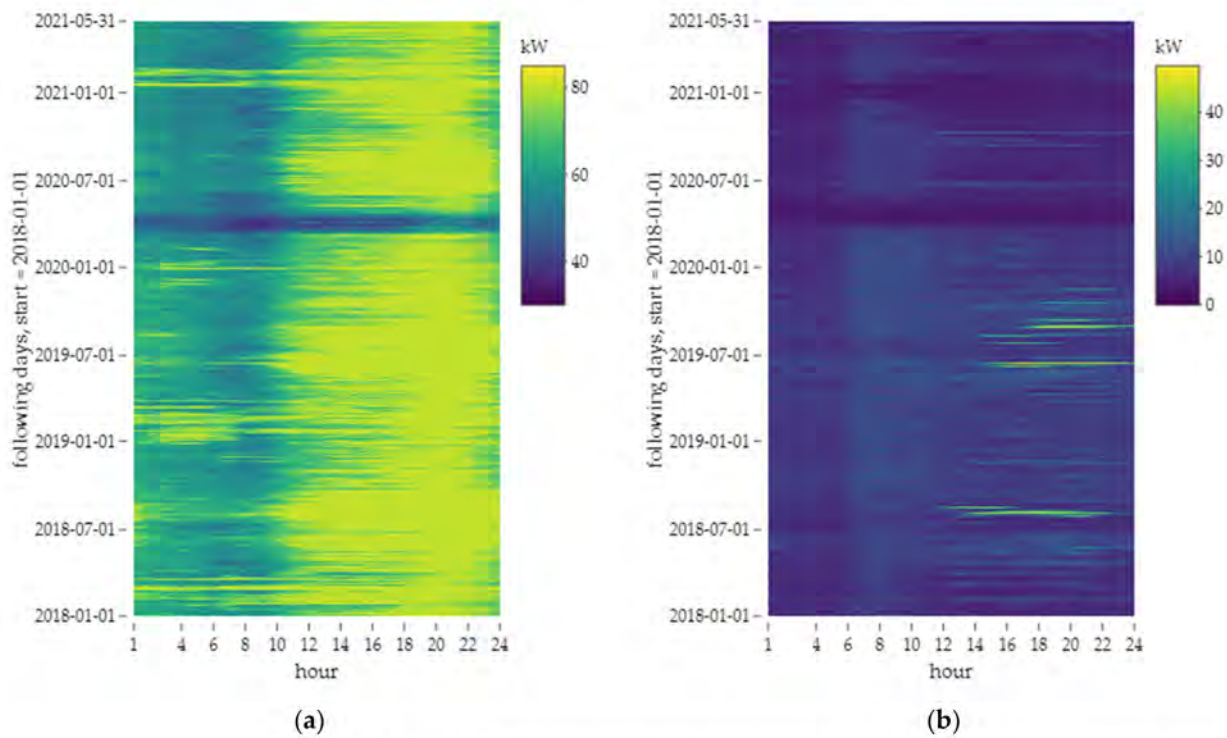
**Figure 7.** Course of hourly electricity consumption for the analyzed case study: (a) H4, (b) R1. Source: own study.



**Figure 8.** Course of hourly electricity consumption for the analyzed case study: (a) R2, (b) R3. Source: own study.

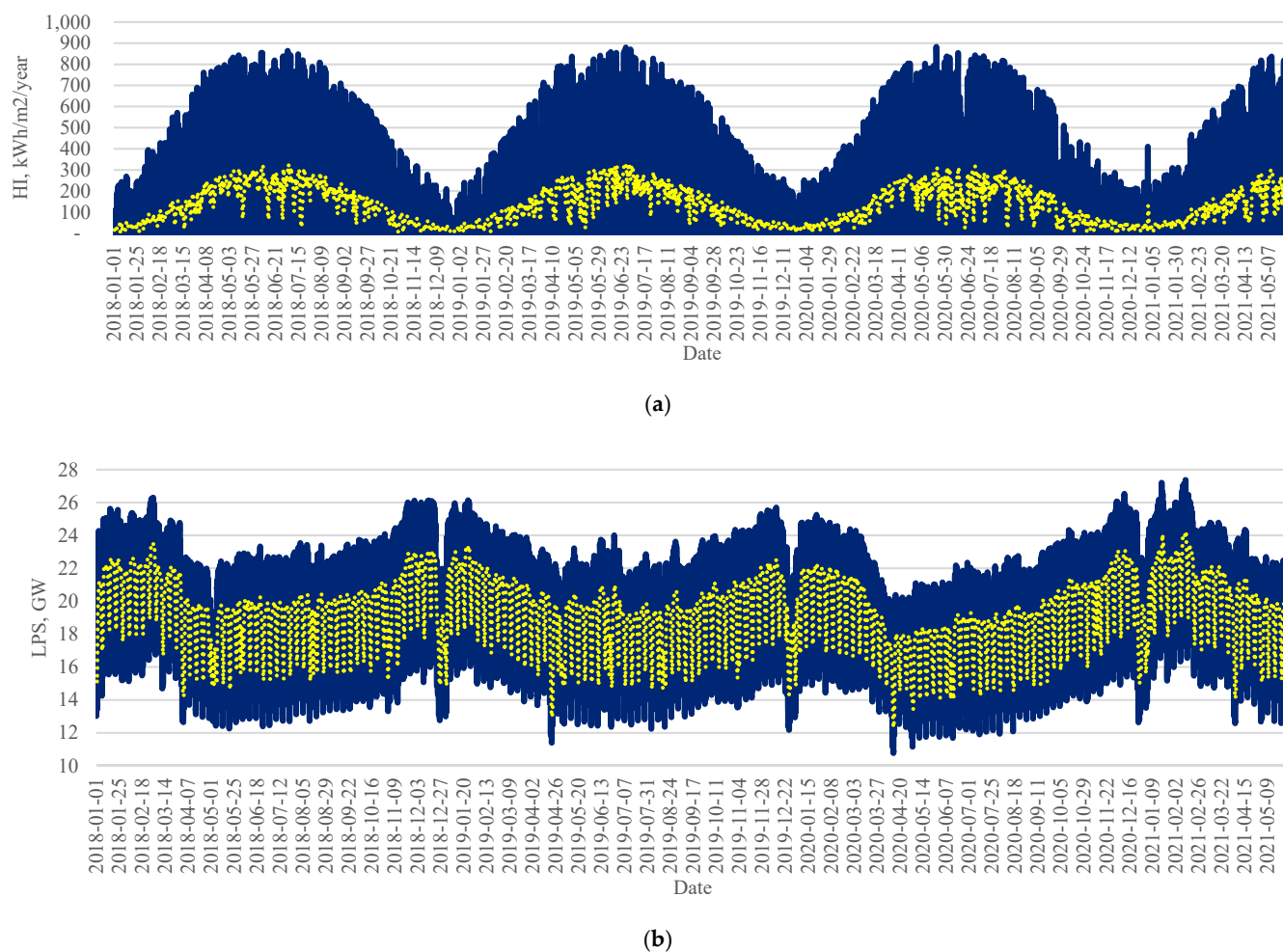


**Figure 9.** Course of hourly electricity consumption for the analyzed case study: (a) R4, (b) R5. Source: own study.



**Figure 10.** Course of hourly electricity consumption for the analyzed case study: (a) R6, (b) R7. Source: own study.





**Figure 11.** Course of hourly electricity consumption for the analyzed case study: (a) Horizontal Insolation, kWh/m<sup>2</sup>/year (b) Load of Power System, GW. Source: own study.

### 3. Research Methods

#### 3.1. Determinants of the Selection of the Research Period

As mentioned in Section 2, electricity consumption data were available for enterprises operating in the catering and hotel industry for the period from 1 January 2018 to 31 May 2021.

However, the authors were particularly interested in the impact of the COVID-19 pandemic on changing the characteristics of electricity consumption in the analyzed sectors of the economy.

The World Health Organization (WHO) on 14 January 2020 issued a warning against the spread of SARS-CoV-2, and then, on 30 January 2020, assessed that the spread of the new pathogen poses a threat to public health of international scope. Ultimately, on 11 March, WHO declared SARS-CoV-2 to be a pandemic [49].

The unprecedented scale of subsequent restrictions imposed by governments as part of counteracting the development of the pandemic in subsequent waves of COVID-19, significantly restricting the freedom to perform previously routine everyday activities, has left its mark, especially on sectors related to people-to-people contacts. The forced change in the behavior of society, especially during the first wave in March and April 2020, from the energy point of view, caused problems in maintaining grid stability and adjusting the volume of energy production to unpredictably fluctuating demand. Thus, the black swan in the form of the new coronavirus pandemic has caused operational and financial difficulties for energy companies [50].

The restrictions regulated by legislation introduced during the pandemic waves, obviously influencing the freedom of everyday activities, influenced the amount of electricity demand in industries related to gastronomy, tourism or broadly understood entertainment (where there was a large concentration of people in closed spaces). However, the impact of behavioral changes in society in the face of growing negative moods is intuitively difficult to determine [51].

Therefore, for a detailed analysis, the time from 5 March 2020 to 31 May 2021 was assumed as a disturbed pandemic period. This is the period starting from the day following 4 March 2020, in which the first case of SARS-COV2 infection was diagnosed in Poland—the so-called “patient zero” [49]. This date was adopted as the limit of the change in the public awareness of the nature of the problem from global to national, which could have caused a spontaneous change in behavior, regardless of the restrictions introduced later.

On the other hand, the reference point was the same period in the previous years, that is, the interval from 5 March 2018 to 31 May 2019.

### 3.2. The Course of the Development of the COVID-19 Pandemic in Poland

- 4 March 2020—the first reported case of COVID-19 in Poland.
- 13 March 2020—announcement of the state of epidemic threat. Restricting the activities of restaurants and cafes only to the fulfillment of take-away or delivery orders.
- 20 March 2020—introduction of an epidemic state.
- 25 March 2020—no movement allowed except in special cases.
- 1 April 2020—hotel operations are limited to serving medical staff, people under quarantine and on business trips.
- 20 April 2020—1st stage of lifting restrictions—permission to travel for recreational purposes.
- 4 May 2020—2nd stage of lifting restrictions—allowing hotels to operate under the sanitary regime while restricting the activities of hotel restaurants to serving meals to rooms. Opening of shopping centers (without opening food court zones).
- 18 May 2020—3rd stage of lifting restrictions—opening restaurants, cafes and gastronomic spaces in shopping centers, maintaining the sanitary regime and the distance between tables.
- 30 May 2020—full opening of hotels along with the stationary operation of hotel restaurants. Admission to the organization of receptions for up to 150 people.
- 6 June 2020—swimming pools and hotel gyms are approved for use.
- 24 June 2020—lifting of restrictions in the event industry (fairs, conferences).
- 8 August 2020—regionalization of restrictions. Division into yellow and red zones (19 poviats, e.g., reducing the number of people in restaurants).
- 17 October 2020—covering part of the area of operation of the analyzed enterprises with the red zone—limiting the stationary activity of gastronomic establishments to 6–21 h and take-out orders after 9 p.m.
- 24 October 2020—the entire country will be restricted in the red zone. Suspension of the restaurant’s stationary activities—only take-away and delivery services are allowed.
- 7 November 2020—hotel operations are limited to receiving guests on business trips. Restriction of the functioning of shopping malls (only stores with basic necessities).
- 27 November 2020—the “responsibility” stage—opening of stores in shopping malls.
- 28 December 2020—“national quarantine”—closure of hotels, including for business purposes. Restricting the functioning of shopping malls to the purchase of basic items.
- 1 February 2021—full opening of shopping malls.
- 12 February 2021—all hotels are allowed to operate in the sanitary regime.
- 13 March 2021—restriction of hotel operations to 50% of places and serving meals only to rooms.
- 20 March 2021—partial lockdown across the country—hotel closure, except for employee hotels and business trips.
- 14 April 2021—closing of shopping malls.
- 4 May 2021—opening of shopping malls and cultural facilities.

- 8 May 2021—opening of hotels with max 50% occupancy.
- 15 May 2021—gastronomy—admission (apart from take-away service) to open restaurant gardens.
- 29 May 2021—opening of the restaurant for indoor service at 50% occupancy, maintaining the distance between the tables and the sanitary regime.
- 13 June 2021—allowing the sale and consumption of meals in cinemas, theaters, events and cultural institutions.
- 26 June 2021—increasing customer limits to 75% in hotels and restaurants. Limits do not apply to vaccinated persons.

### 3.3. A Research Method Choice

The aim of the research was to determine the impact of the electricity consumption profile in the analyzed groups of service enterprises on the cooperation with the National Power System and potential photovoltaic sources. For this reason, the research method was searched for in the group of statistical correlation tests.

Choosing the right statistical test and checking the fulfillment of its assumptions is extremely important from the point of view of the credibility and correctness of the interpretation of the results. The tests of the normality of the distribution are specific tests examining the compliance of a given distribution with the normal distribution—the most frequently used in statistics because many features have a distribution similar to it. The assumption that the distribution is normal is often required in the case of parametric statistical tests. Non-parametric tests, on the other hand, are free from such assumptions [52].

The value of the Pearson's correlation score as a measure of the linear relationship between two variables, however, may be underestimated when there is a dependence between the variables, but the relationship is not linear. It may or may not give erroneous values and lead to a misinterpretation of the results if the assumptions about the normality of the distribution are not met.

After initial identification of the lack of a linear relationship between the analyzed variables, higher values in the Spearman's Rho test were expected as a better measure of the degree of correlation of the analyzed variables. The use of non-parametric methods independent of the distribution of the analyzed variables is more convenient from the point of view of meeting the applicability conditions of parametric statistical procedures. Spearman's Rho can be treated similarly to Pearson's linear correlation coefficient, that is, in terms of the percentage of explained variation, with the difference that Spearman's Rho is calculated based on ranks.

As part of the implementation of this study, tests of interdependencies between the variables were carried out using the most intuitive in interpretation parametric test of Pearson's r-correlation and its non-parametric counterpart based on the ranks of the Spearman, the use of which appears to be more adequate [53].

### 3.4. The Course of the Research Process

#### 3.4.1. Stage "0"

Along with the approximation of the natural conditions (insolation conditions in Poland—Figures 3 and 11a) and market conditions (the course of the variability of power demand in the National Power System—Figure 11b), the general characteristics of electricity consumption in the analyzed enterprises were outlined throughout the entire period of the obtained data. For this purpose, the variability courses of the analyzed variables were determined (Figures 4–11).

The course of the research process is described by a schematic and conceptual flowchart (Figure 12).

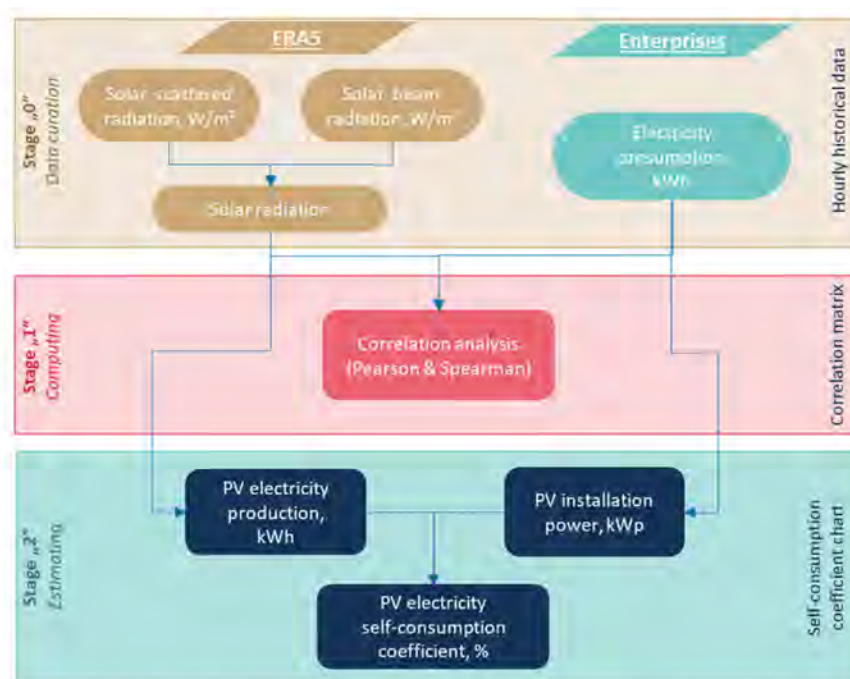


Figure 12. Schematic and conceptual flowchart of the research process. Source: own study.

The analyses in the next part were carried out by dividing them into the period before the outbreak of the COVID-19 pandemic in Poland and in the pandemic period. In the beginning, descriptive statistics of the analyzed variables (in pre-pandemic and pandemic periods) were determined using the “stats” library of the RStudio environment and presented in tabular form (Tables 1 and 2).

Table 1. Descriptive statistics of the analyzed variables for analyzed research objects and insolation and loads of power systems before the COVID-19 pandemic period.

	C1	C2	C3	H1	H2	H3	H4	R1	R2	R3	R4	R5	R6	R7	HI	LPS
Unit	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh/m <sup>2</sup> /year	GW
Min.	0.37	0.01	0.56	20.34	0.96	18.54	17.25	4.40	2.63	4.84	0.47	0.85	11.22	1.64	0	11.40
1st Qu.	3.23	0.06	3.23	37.80	24.15	34.29	118.05	8.94	15.50	8.34	2.27	5.49	60.12	6.57	0	16.68
Median	7.58	0.14	6.23	44.82	28.98	41.72	137.32	21.68	21.49	11.62	3.19	19.91	68.61	7.79	10.53	19.60
Mean	8.81	0.93	6.15	45.64	29.38	40.36	143.87	19.17	23.39	12.95	3.73	18.66	69.89	8.26	143.58	19.38
3rd Qu.	14.22	1.01	8.17	52.56	33.6	47.12	166.51	26.95	29.82	16.17	4.99	29.24	78.28	9.32	238.78	21.88
Max.	27.31	10.27	19.91	91.98	56.10	71.96	285.94	38.40	56.97	43.21	12.63	60.72	115.23	47.72	863.48	26.58
Skewness	0.44	2.46	0.42	0.36	0.51	(0.24)	0.71	-0.16	0.68	1.20	0.78	0.37	0.40	4.41	1.43	-0.06
Kurtosis	1.88	8.95	2.48	2.72	3.09	2.48	3.30	1.54	2.55	4.53	2.83	1.91	3.04	49.62	3.91	2.01
Variance	35.8	2.86	8.41	101.05	45.66	98.61	1223.93	80.96	79.81	33.37	2.95	168.58	150.99	7.39	44,517.58	9892.66
SD	5.98	1.69	2.90	10.05	6.76	9.93	34.98	9.00	8.93	5.78	1.72	12.98	12.29	2.72	210.99	3.14

Source: own study.

Table 2. Descriptive statistics of the analyzed variables for analyzed research objects and insolation and loads of power systems during the COVID-19 pandemic.

	C1	C2	C3	H1	H2	H3	H4	R1	R2	R3	R4	R5	R6	R7	HI	LPS
Unit	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh/m <sup>2</sup> /year	GW
Min.	0.26	0.01	0.98	8.55	3.24	9.99	8.70	0.57	1.66	2.41	0.38	2.50	16.74	1.58	0	10.77
1st Qu.	0.70	0.04	2.17	20.77	10.08	12.06	36.90	2.43	3.13	3.81	0.83	4.38	54.06	4.36	0	16.41
Median	2.12	0.14	3.56	24.12	13.92	14.98	70.20	4.09	4.63	4.84	1.12	6.58	62.04	5.17	10.28	19.07
Mean	3.41	0.85	3.95	26.24	16.01	18.38	67.23	6.51	5.57	6.76	1.75	11.45	64.21	5.53	138.52	19.03
3rd Qu.	4.14	1.01	5.15	31.00	19.86	21.58	94.05	8.68	7.24	7.97	1.80	14.82	74.13	6.29	216.73	21.45
Max.	19.57	8.80	13.57	63.99	43.38	53.15	178.65	32.90	36.38	49.88	10.32	51.11	114.39	18.41	882.83	27.37
Skewness	1.65	2.51	0.93	0.97	1.07	1.35	(0.03)	1.39	1.98	2.29	2.00	1.37	0.36	1.35	1.51	0.08
Kurtosis	5.06	9.22	3.39	3.60	3.44	3.76	2.12	4.01	10.18	10.30	6.74	3.64	2.76	5.98	4.19	2.22
Variance	13.10	2.43	4.48	62.19	51.05	74.09	1172.12	37.66	11.85	20.35	2.23	101.76	181.69	3.08	42,847.07	10,680.73
SD	3.62	1.56	2.12	7.89	7.14	8.61	34.24	6.14	3.44	4.51	1.49	10.09	13.48	1.75	207	3.27

Source: own study.

### 3.4.2. Stage “1”

The article is an attempt to transfer the determined dependencies diagnosed on the basis of a relatively small sample of case studies to the entire industry. Due to the fact that the aim of the study is to obtain knowledge and formulate conclusions about the analyzed groups of service enterprises, despite the relatively small number of their representatives, an analysis of the intergroup correlation was carried out, the product of which is the r-Pearson and non-linear Rho-Spearman correlation matrices for individual general case studies (Figures 13–16).

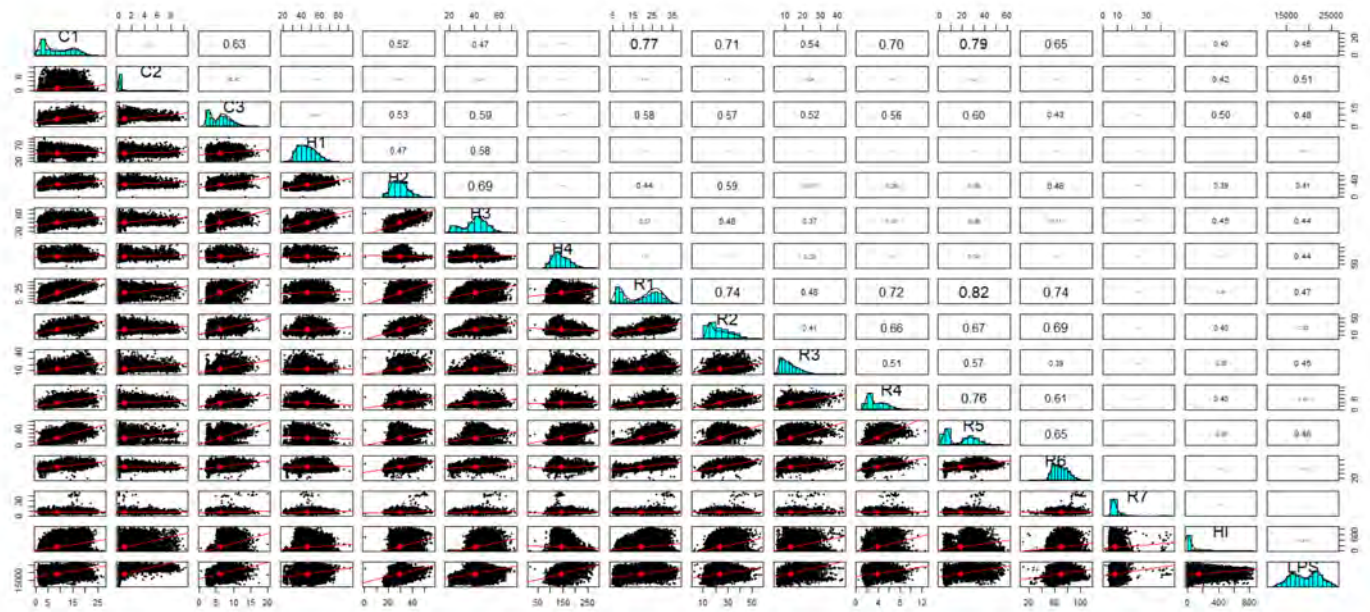


Figure 13. Correlation matrix with Pearson’s correlation coefficients between analyzed case studies for the pre-pandemic period. Source: own study.

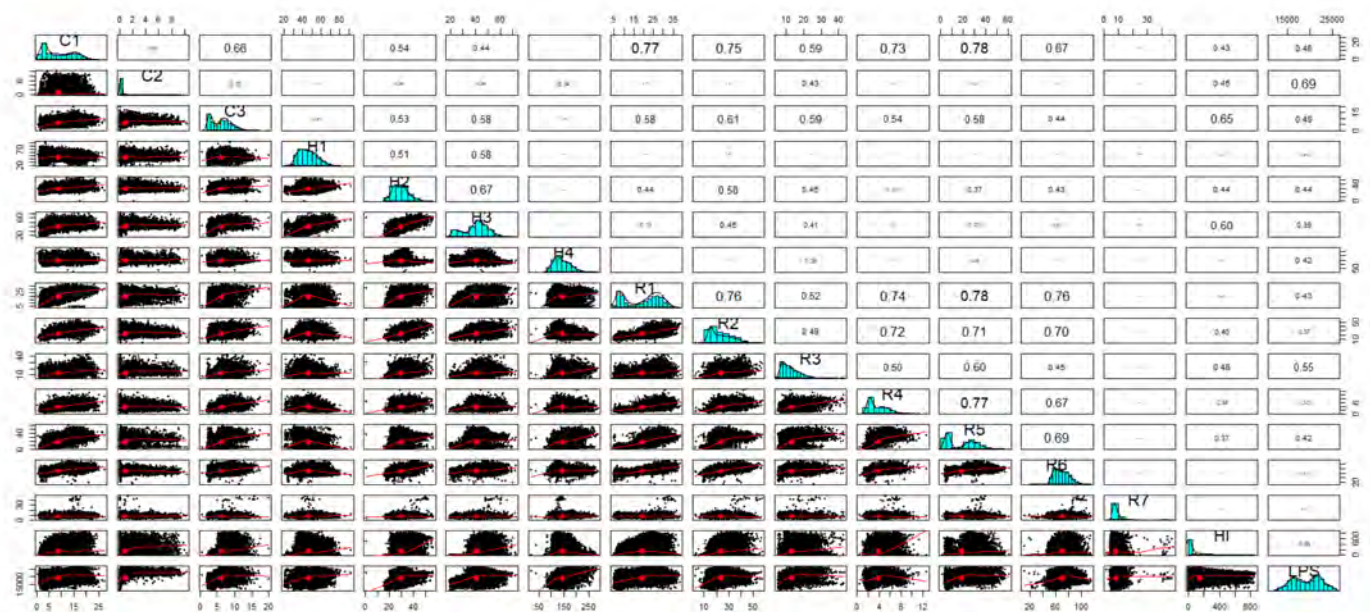
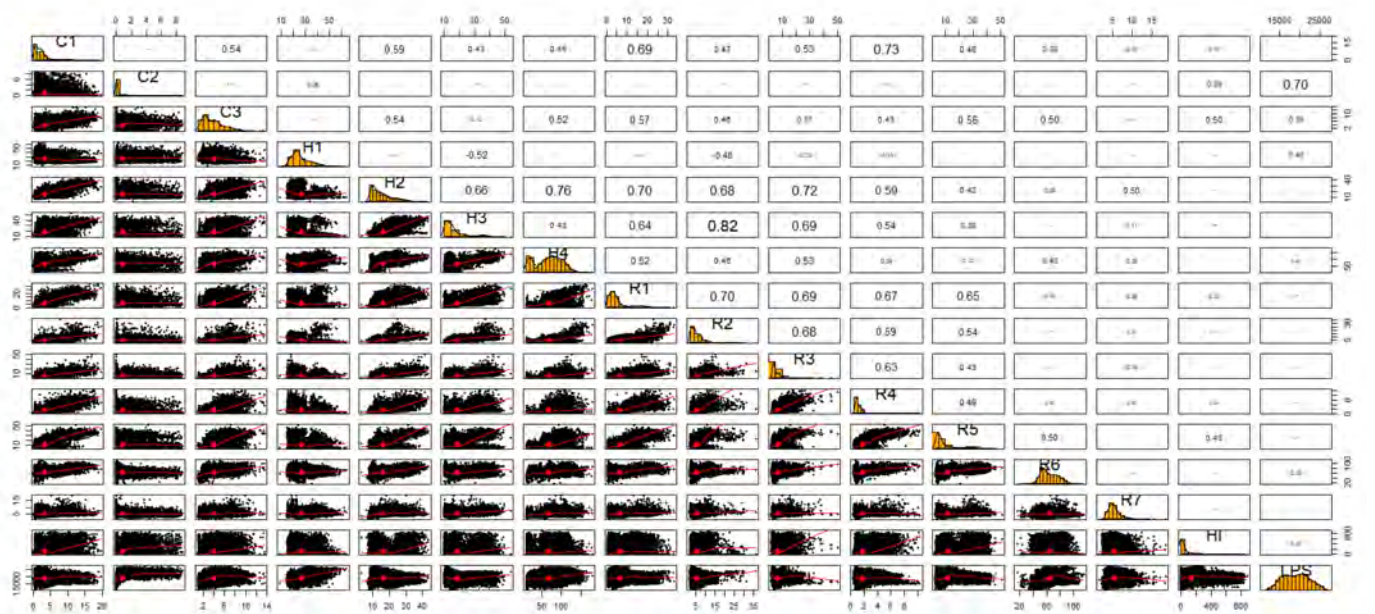


Figure 14. Correlation matrix with Spearman’s correlation coefficients between analyzed case studies for pre-pandemic period. Source: own study.



**Figure 15.** Correlation matrix with Pearson's correlation coefficients between analyzed case studies for pandemic period. Source: own study.



**Figure 16.** Correlation matrix with Spearman's correlation coefficients between analyzed case studies for the pandemic period. Source: own study.

The correlation analysis of the electricity consumption profiles of the analyzed enterprises was carried out in relation to:

- The power demand profile in the National Power System to determine the impact of these groups of enterprises on the power grid stability. The partial aim of the study is to determine whether these economic sectors contribute to the electricity peak demand in the national network, still covered in Polish conditions by high-emission conventional sources. The positive correlation justifies the environmental effectiveness of PV using in case studies.

- The electricity production profiles of potential PV sources with their productivity defined in simplification only on the basis of historical insolation conditions for the considered locations.

Higher correlation coefficients between electricity consumption profiles in enterprises and insolation, and thus also the potential production of electricity from photovoltaics, result in a greater potential self-consumption coefficient of this electricity.

Therefore, in the first stage of the research process, correlation analysis was performed to avoid unnecessary in-depth self-consumption analysis. Only when the correlation analysis reveals the existence of a relationship between the variables, it is reasonable to test the degree of self-consumption of PV electricity.

The correlation matrices were organized in such a way as to investigate how the electricity generation profiles of a potential RES source fit into the electricity consumption profiles in individual research objects to cover their own energy needs. Thus, the study deals with an increase in environmental efficiency as a result of the reduction of the emissions of national energy, based mainly on fossil fuels as a result of the use of own photovoltaic sources to cover their own electricity demand. Then, the correlation matrices between the individual electricity consumption profiles in the relevant case studies at pre-pandemic and pandemic periods were determined using the “pairs.panels” function from the “psych” library of the RStudio environment. The correlation between the case studies was carried out in order to assess their representativeness, including the research results and conclusions drawn on their basis in relation to the industries they represent.

### 3.4.3. Stage “2”

Finally, the degree of self-consumption of electricity produced in potential photovoltaic sources was determined and the averaged values of the degree of auto-consumption in individual enterprises were presented.

Based on hourly historical data:

- Electricity consumption in individual case studies,
- Value of available solar radiation available in these locations in a correspondence hour

We estimated:

1. The size of the PV installation expressed in kWp based on the average annual electricity consumption. The analyzed sub-periods (before and in the pandemic) covered 10,872 h. In consequence, the sum of 10,872 h was multiplied in the research by the quotient (8760/10,872) to specify average yearly electricity consumption (demand) levels in analyzed case studies.
2. Hourly electricity production from PV installations estimated on the basis of Equation (1).

$$Ep_{PV} = \frac{Y_{EC}}{1000} * HI_h * \eta * \frac{1}{1000} \quad (1)$$

where:

$Ep_{PV}$ —electricity produced by the PV installation on an hourly basis, kWh

$Y_{EC}$ —PV installation power, kWp (average annual electricity demand, kWh)

$HI_h$ —horizontal insolation on an hourly basis, kWh/m<sup>2</sup>/year

$\eta$ —efficiency factor of the components of the PV installation, assumed  $\eta = 0.9$

The value of the self-consumption electricity was estimated on an hourly basis based on Equation (2). These values were determined for the period from 5 March to 31 May of the following year (10,872 h).

$$Esc_{PV} = \begin{cases} H_{EC} & \text{if } : H_{EC} < Ep_{PV} \\ Ep_{PV} & \text{if } : H_{EC} \geq Ep_{PV} \end{cases} \quad (2)$$

where:

$Esc_{PV}$ —hourly consumption of PV produced electricity, kWh

$Ep_{PV}$ —hourly PV electricity production, kWh

$H_{EC}$ —hourly electricity consumption, kWh

The averaged value of the self-consumption coefficient was determined (Equation (3)) as the quotient of the sums of self-consumed and potentially produced electricity in 8760 consecutive hours (Equation (4)).

$$HSCc = \frac{E_{scPV}}{E_{pPV}} * 100\% \quad (3)$$

where:

$Hsc_{PV}$ —hourly PV electricity self-consumption coefficient, %

$$SCc = \frac{\sum_1^{8760} E_{scPV}}{\sum_1^{8760} E_{pPV}} * 100\% \quad (4)$$

where:

$SCc$ —annual average PV electricity self-consumption coefficient, %

The specified research sub-periods covered the period from 5 March 2020 to 31 May 2021 (10,872 h) and the corresponding period in 2018/2019. In order not to disturb the analysis on an annual basis, due to the two-stage occurrence of the spring season in the analyzed sub-periods (2112 h), averaged values of the self-consumption coefficient were determined for the next 2112 observations of moving average values from the previous 8760 h. This shift removes the impact of seasonal variability while using the full knowledge of the analyzed sub-periods. The course of the variability of the coefficient is shown in the Section 4.5.

With a low power of the installation, the self-consumption of the produced energy will occur practically always [54] while with the rescaling of the installation, the degree of self-consumption of electricity decreases and, at the same time, the self-sufficiency increases [18,55]. Apart from the power of the installation, the very degree of correlation of the profile course, while maintaining the conditions for which they were determined, remains approximately constant.

## 4. Results of Numerical Analysis of Research Objects

### 4.1. Descriptive Statistics of the Analyzed Variables

The values of descriptive statistics show the character of the empirical distribution of the analyzed variables. Table 1 presents descriptive statistics as well as measures of dispersion and shape of distribution of the analyzed variables in the pre-pandemic period (Table 1) and during the COVID-19 pandemic (Table 2).

In the pre-pandemic period, the variables show a relatively high similarity of empirical distributions to the normal distribution. In the case of variables H2, R4 and R6, the values of descriptive statistics and the parameters of the shape of empirical distributions of these variables prove their significant normality. This is confirmed by the graphical analysis of the histograms (Figures 13–16).

During the pandemic, in research objects of C1, C2, H3, R1, R2, R3, R4 and R5 cases, the average value of hourly electricity consumption is higher than the median, and therefore more observations are on the left-hand side of the average value, which indicates the right-hand value asymmetry of the empirical distribution. The concentration of the empirical distribution (kurtosis) for only three cases of H4, R6 and LPS is below 3, which means that they are platocurtic distributions, and the values of the variable are less concentrated than with the normal distribution. In the case of six variables, it is close to the 3 value typical for the normal distribution. The cases of the H6 and LPS variables show the greatest similarity to the normal distribution, but their empirical distributions, intuitively, do not meet the normality criteria.

In the case of insolation conditions in the location of the analyzed case studies during a pandemic, the distribution of the variable is of course similar to the pre-pandemic period, due to the numerous occurrences of zero and close to zero values, it shows a strong left-



hand asymmetry. Literature sources confirm that the empirical distribution of horizontal insolation does not show similarity to the normal distribution and is best approximated by the beta distribution [56–58]. Sources also indicate that for some seasons and latitudes, the empirical distribution may approximate the Weibull distribution [59,60] commonly used for wind speed analysis, as well as the log-normal [61] or gamma [58,61] distribution.

Therefore, the use of the Pearson linear correlation method for all variables may be associated with the incorrect determination of the value of the correlation coefficient and lead to erroneous conclusions. Therefore, the nonlinear rho-Spearman correlation method was used as an alternative, although less intuitive in interpretation.

#### *4.2. Analysis of the Correlation between the Cases of Enterprises and with Regard to Sunlight Conditions and the Course of Power Demand in the National Power System*

The partial goal of the research was to determine the power and nature of the relationship between the course of electricity demand in the analyzed groups of enterprises and:

- The course of power demand in the National Power System in order to determine the global impact of the considered groups of enterprises on the stability of the distribution network.
- Variability of insolation conditions, and thus determining the potential of cooperation of enterprises from the analyzed sectors with the photovoltaic installation.

The analysis of correlation carried out between the profiles of individual enterprises may turn out to be valuable for determining the degree of similarity and representativeness of the analyzed enterprises, and thus the legitimacy of making a conclusion about the sector on the basis of a relatively small sample.

#### *4.3. Pre-Pandemic Period*

To facilitate the interpretation and readability of the matrix, the functionality of the “pairs.panels” function (“psych” RStudio library) was used, which differentiates the font size of the given values of correlation coefficients depending on their size. For absolute values close to 1 (full correlation), the font has a target size, and for values tending to zero (no correlation) the font is fading out.

When analyzing the results included in the Pearson and Spearman correlation matrices in the pre-pandemic period (Figures 13 and 14) and the values of correlation coefficients collected in tabular form (Tables 3 and 4), it should be stated that the highest degree of similarity (relationships) is shown by the restaurants marked R1 and R5, for which the r-Pearson correlation coefficient was 0.82, which should be interpreted as the existence of a strong linear correlation. Spearman’s rho coefficient was slightly lower, that is, 0.78. Similarly, the cases of R1, R2, R4, R5 and R6 showed a strong almost linear relationship, as the values of both statistics here are over 0.7. Hotels H2 and H4 and cafes C1 and C3 show a slightly lower value, but which can already be interpreted as the average strength of correlation. In the linear Pearson correlation to the power demand profile in the National Power System, only the C2 café case showed a value above 0.5 (average correlation), although most enterprises achieved values above 0.4 (moderate correlation). It is worth noting, however, that Spearman’s rho-statistic showed the existence of a much stronger non-linear relationship in the case of C3 cafes with the Spearman correlation coefficient at the level of 0.69 and 0.55 for the R3 restaurant.

With regard to the insolation conditions, and thus the productivity of a potential PV installation, the highest value of non-linear correlation at the level of 0.65 was achieved by the case of the C3 café. The H3 hotel recorded a slightly worse result (0.60).

**Table 3.** The values of correlation coefficients between hourly electricity consumption and load of Power System. Description of colors: Green = positive. Red = negative. Ascending order: from light (near zero) to dark (near 1) color.

		C1	C2	C3	H1	H2	H3	H4	R1	R2	R3	R4	R5	R6	R7
before	r-Pearson	0.45	0.51	0.48	0.23	0.41	0.44	0.44	0.47	0.32	0.45	0.28	0.46	0.23	0.12
COVID-19	rho-Spearman	0.46	0.69	0.49	0.24	0.44	0.39	0.42	0.43	0.37	0.55	0.3	0.42	0.27	0.16
during	r-Pearson	0.11	0.49	0.33	0.44	0.08	(0.02)	0.27	0.14	0.03	0.04	(0.01)	0.19	0.31	0.09
COVID-19	rho-Spearman	0.09	0.70	0.39	0.4	0.12	(0.12)	0.28	0.17	(0.02)	(0.06)	(0.14)	0.21	0.35	0.13

Source: own study.

**Table 4.** The values of the correlation coefficients between hourly electricity consumption and horizontal insolation. Description of colors: Green = positive. Red = negative. Ascending order: from light (near zero) to dark (near 1) color.

		C1	C2	C3	H1	H2	H3	H4	R1	R2	R3	R4	R5	R6	R7
before	r-Pearson	0.40	0.42	0.50	0.11	0.39	0.45	(0.05)	0.28	0.40	0.35	0.40	0.35	0.16	0.05
COVID-19	rho-Spearman	0.43	0.45	0.65	0.24	0.44	0.60	0.06	0.24	0.40	0.48	0.34	0.37	0.12	0.10
during	r-Pearson	0.37	0.41	0.35	0.01	0.19	0.20	(0.01)	0.31	0.21	0.30	0.35	0.40	0.04	0.04
COVID-19	rho-Spearman	0.29	0.39	0.50	0.05	0.12	0.19	0.05	0.37	0.23	0.11	0.24	0.43	0.05	0.08

Source: own study.

#### 4.4. COVID-19 Pandemic Period

Analyzing the results presented in the Pearson and Spearman correlation matrices for the pandemic period (Figures 15 and 16) and the values of correlation coefficients collected in tabular form (Tables 3 and 4), it should be noted that in relation to the period before the pandemic, a slight increase in the number of significant relationships between the variables was noted. The highest value of the correlation coefficient occurred again in the case of the R1 and R5 restaurants in the Pearson linear correlation (0.82), as well as R4-R5 (0.81) and R1-R4 (0.80). The dependencies identified by the Spearman’s rho test were much weaker—a maximum of 0.70 in the case of the R1-R2 pair. Next in terms of the strength of the relationship is the pair of hotels H2-H3 ( $r = 0.77$ ) and H2-H4 ( $\rho = 0.76$ ). It is worth noting the negative Spearman correlation between H1-H3 at  $-0.52$ . The C1–C3 cafes again showed an average correlation at the level of  $r = 0.61$  and  $\rho = 0.54$ .

In the linear Pearson correlation of electricity consumption profiles in enterprises with the profile of power demand in the National Power System, only the cases of C2 café and H1 hotel showed a value above 0.4 (moderate dependence). It is worth noting, however, that at the same time the Spearman’s rho-statistic showed the existence of a much stronger non-linear relationship in the case of the C2 cafe with the Spearman correlation coefficient at the level of  $\rho = 0.70$ .

With regard to the insolation conditions, that is, the productivity of a potential PV installation, a decrease in the correlation power was noted, and the highest non-linear correlation value at the level of 0.5 was achieved by the C3 café. The R5 hotel reported a slightly worse result (0.43).

However, in the case of the analysis of the correlation with the demand profile in the transmission network, the existence of an average to strong correlation occurring between approx. 70% of the analyzed cases (values of Pearson’s and Spearman’s coefficients ranging from 0.7 to 0.82 in the period before and during the COVID-19 pandemic) entitles one to attempt to draw conclusions about the restaurant industry on a national scale. Similarly, there is a moderate Pearson and Spearman correlation with coefficient values of 0.6–0.7 for 75% of the analyzed hotels and 0.5–0.6 for 66% of the analyzed cafes.

A high positive correlation of the energy consumption profile in relation to the profile of power demand in the pandemic period was observed in cafe C2, although its volume of energy consumed is several times lower than that of other representatives of the sector. Thus, the significance of inference based on its example in the context of the impact on the stability of the power grid may be flawed.

The strength of this dependence in the pandemic period, and thus the destabilizing effect on the distribution network, was increased by the H1 hotel and the R6 restaurant,

which are in an intermediate position among the analyzed cases in terms of the amount of energy demand. The case of the R6 restaurant shows that it is a facility that has successfully recovered from the unprecedented COVID-19 situation. The average consumption during the pandemic decreased in the case of the R6 restaurant by less than 9% compared to the same period 2 years earlier. This may indicate a strong market position and an established brand that previously successfully offered a kitchen for delivery, which thus constituted a market advantage in the new reality.

On the other hand, a decrease in the value of correlation coefficients of 25–50% was recorded by: café C3, hotel H4 or restaurant R5. Other enterprises noticed multiple decreases in the value of the correlation power to the demand profile in the energy system, at the same time showing the average value of energy consumption two or even three times lower than in the corresponding period in previous years. This proves the problems of those entities that encountered difficulties in functioning in the new reality. The gap between restaurants with lower energy consumption and those with a stronger market position is particularly visible. The same applies to cafes. The four analyzed hotel cases recorded a decrease in the volume of electricity consumption of approx 100%.

In the context of the change in the correlation of the electricity demand profiles in the analyzed enterprises in relation to the insolation conditions, it is worth noting that the average value of correlation coefficients during the pandemic decreased compared to the comparative period by 19% in the case of cafes—64% in the case of hotels and 18% in the case of restaurants.

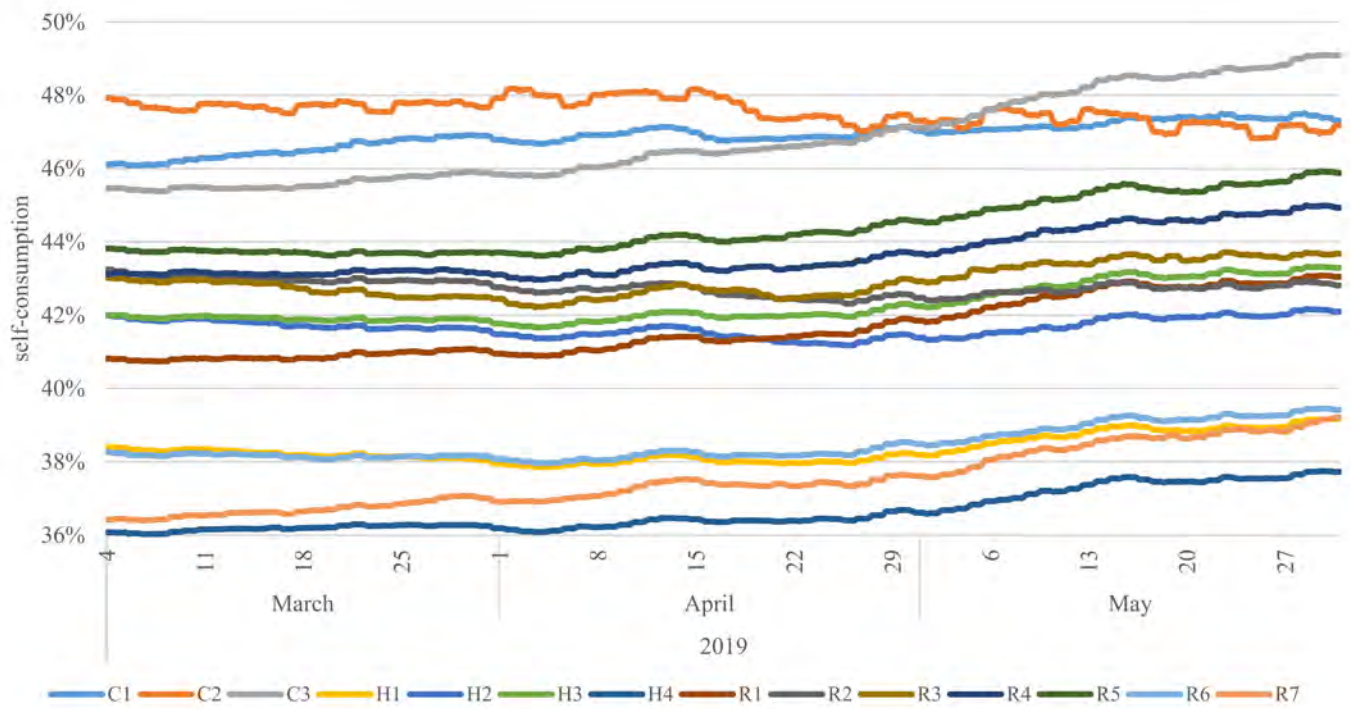
Only in two cases, that is, the R1 and R5 restaurants, an increase in the value of correlation coefficients was recorded in the pandemic period. On the other extreme, however, there is the case of the R6 restaurant whose demand profile is characterized by a peak coinciding with the evening peak of demand in the distribution network and in the hours of the highest availability of solar radiation, the level of electricity consumption is relatively low. The highest, an almost six-fold decrease in value, was recorded in the case of the H1 hotel, the energy demand profile of which results directly from the nature of the accommodation facility—daily peaks occur before checking out and at dinner time.

To sum up, it should be stated that among the analyzed enterprises, the greatest potential for using photovoltaics for the purposes of self-consumption of electricity was retained by entities from the catering industry.

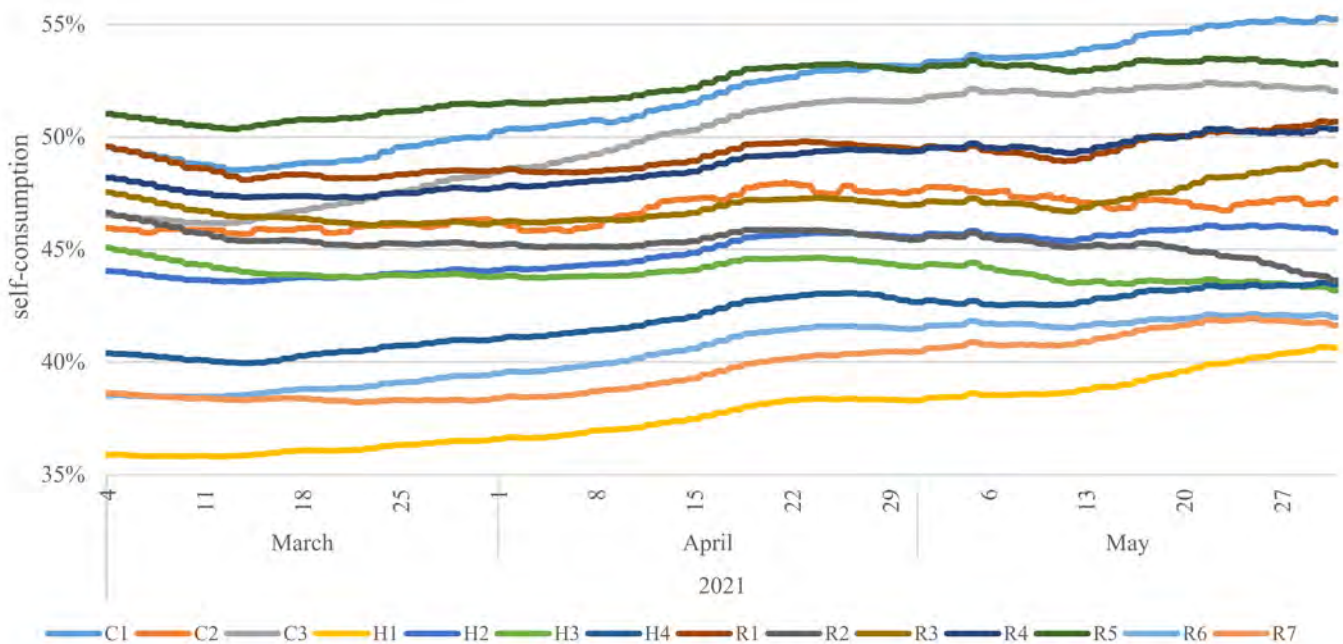
#### *4.5. Analysis of Self-Consumption Levels of Electricity Generated in Potential PV Installations*

The study of the potential degree of self-consumption of electricity from own photovoltaic installation confirms the above observations. Apart from the H1 and C1 cases, in the pandemic period, there is a higher value of the degree of electric energy self-consumption compared to the comparative period. The course of the variability of the coefficient is shown in Figures 17–19.

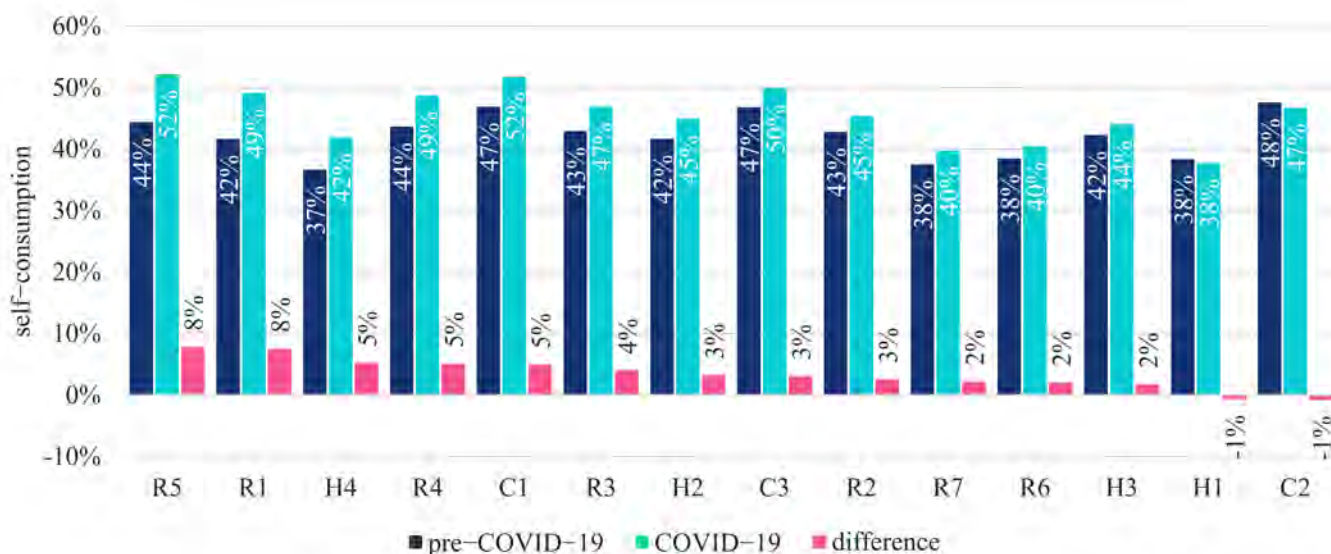
The highest value of the self-consumption coefficient, at the level of 52%, is for the C1 cafe and the R5 restaurant. The next ones are the cases of C3 (50%), R1 and R4 (49%), R3 and C2 (47%) and R2 and H2 (45%).



**Figure 17.** Variability of the percentage of self-consumption of electricity produced in the potential photovoltaic installation for the previous 8.760 h in the pre-pandemic period. Source: own study.



**Figure 18.** Variability of the percentage of self-consumption of electricity produced in the potential photovoltaic installation for the previous 8.760 h during the pandemic period. Source: own study.



**Figure 19.** Average indicator of self-consumption of energy from PV and its difference in the pre-COVID-19 and COVID-19 periods in the analyzed case studies. Source: own study.

## 5. Conclusions

The occurrence of the black swan in December 2019, which is undoubtedly the emergence of the SARS-CoV-2 coronavirus epidemic in the Chinese province of Hubei and its spread throughout the world by the end of the first quarter of 2020, triggered a series of events that changed the face of the known so far in the world. Some of the industries most affected by the scale of unprecedented restrictions in individual waves of the pandemic consist of those areas of activity where people-to-people contact is on the agenda so far, such as the catering and hotel industries.

The picture of the world affected by the pandemic in the context of the energy demand of these sectors is quite different from its previously known form. The high correlations between the profiles of electricity demand in restaurants, cafes and hotels and the profile of power demand in the national power grid or production profiles of photovoltaic sources reaching the Pearson or Spearman correlation coefficients of 0.6–0.7 for the pre-pandemic period a significant change. Especially in the case of the hotel industry, there is a noticeable decrease in the volumes of electricity demand as well as their daily variability that is different from the demand profile in the network.

In the case of restaurants and cafes, these dependencies still remain at a moderate level, which is tantamount to a destabilizing impact on the parameters of the distribution network. At the same time, these industries appear to be potentially effective entities to install photovoltaics for the self-consumption of more expensive electricity. This is confirmed by the relatively high determined index of the hypothetical self-consumption of energy from own PV sources in the analyzed enterprises.

A positive correlation with a moderate value of the coefficient of the order of 0.5 means that these enterprises currently consume relatively expensive energy which in the context of the introduction of dynamic tariffs in 2027 justifies the interest in investing in their own PV source. Proper selection and flattening of the resultant profile of energy demand from the grid may also reduce costs and create preferential conditions for DSOs.

It is worth noting that the self-consumption coefficient, unlike the industries initially associated with the energy transformation, in the case of broadly understood services, has a justified potential to increase due to the increase in EV popularization. Especially in the case of restaurants located on busy thoroughfares car chargers could be an interesting supplement to the PV installation subject to preferential conditions. Such a service would be an additional incentive to stop at this specific place, which would translate into an

increase in the competitiveness of the company's offer. The economic efficiency of such a solution seems to be a natural development step for the research presented in this article.

In the case of hotels, with the indicated values of correlation, the justification for such solutions could be found by entities focused on business customers and conferences. Intelligent energy management system could be integrated into the Vehicle-2-Grid and/or Grid-2-Vehicle model. In this way, the hotel could obtain preferential conditions and/or create an additional level of relationship with the customer by offering him a financial advantage in return for providing a vehicle for the V2G/G2V model.

The directions of the further development of research problem presented in this article may be:

1. Taking into account the application of concentrated (CPV) or bi-facial PV panels,
2. Taking into account the change of the prosumer support model to the net metering model,
3. Actions that can be taken to increase the matching of the consumption and generation profile of PV electricity due to the reorganization of key processes such as water heating in hotels at noon,
4. Transferring the research process to other, potentially sensitive to pandemic restrictions, economic sectors,
5. Correlation of the level and profile of energy demand with data on business bankruptcy statistics and the assumption of new ones reported by the Central Statistical Office.

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## Abbreviations

EV	Electric Vehicle
HI	Horizontal Insolation, kWh/m <sup>2</sup> /year
LPS	Load of Powers System, GW
PV	Photovoltaics
V2G	Vehicle-2-Grid
G2V	Grid-2-Vehicle

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