Università degli studi di Milano-Bicocca

Data Science Lab for Smart Cities

Final Essay

Illuminating the Past, Powering the Future

A Data-Driven Approach to Photovoltaic Integration in Amsterdam's Heritage Buildings

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Abstract

This study explores the potential for integrating photovoltaic (PV) systems in the historic city center of Amsterdam, focusing on postcode 1012. Amsterdam's smart city initiatives aim to reduce CO2 emissions and promote renewable energy. However, heritage buildings, which constitute a significant portion of Amsterdam's infrastructure, face challenges in adopting modern energy solutions due to aesthetic and legal constraints. Using data analytics and spatial analysis, the research assesses the energy consumption patterns of Amsterdam and the untapped potential for solar energy production in its historic center. The findings indicate that while current PV installations in postcode 1012 cover only 1% of its energy consumption, maximizing the feasible PV installations could produce over 11 GWh/year, significantly offsetting conventional energy use. Financial analysis suggests that expanding PV systems can reduce annual energy costs by 23%, although initial installation costs must be considered. The study concludes with policy recommendations to facilitate PV integration in heritage sites, emphasizing economic incentives, streamlined regulations, and innovative design solutions to balance conservation with sustainability goals. These efforts could enhance Amsterdam's renewable energy capacity and set a precedent for other smart cities globally.

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1 Introduction and Problem Description

Amsterdam is often cited as an exemplary smart city globally, largely due to its proactive smart city strategy known as the "Amsterdam Smart City Programme." Initiated in 2007, this programme was a collaborative effort by Amsterdam Innovation Motor (AIM), energy-network operator Liander, and the municipal administration. The primary objective was to leverage ICTs to address environmental challenges and create a sustainable urban environment. Central to this initiative is the New Amsterdam Climate Programme, which aims to significantly reduce carbon dioxide (CO_2) emissions by 40%, making Amsterdam one of the most sustainable cities in the world by 2025. A key component of the Amsterdam Smart City Programme is the promotion of renewable energy to combat climate change [1].

Renewable energy sources, offer a sustainable solution to reduce dependency on fossil fuels and decrease greenhouse gas emissions. The residential building sector within the European Union is responsible for one-third of the overall energy consumption, thereby playing a pivotal role in CO_2 emissions [2]. The high levels of CO_2 emissions from this sector underscore the urgent need to increase reliance on renewable energy sources, especially PV panells which can be directly installed on rooftops to enhance household self-sufficiency.

Household energy consumption is influenced by several factors, including building characteristics and the socio-economic status of the occupants. Studies have shown that the age and size of dwellings significantly impact energy performance. Additionally, there is a linear positive correlation between overall household expenditure and energy use. Occupant behavior, including the presence at home, environmental motivation, and awareness of resource use, also affects energy consumption, almost as much as physical factors [2].

Amsterdam has already implemented various initiatives to promote renewable energy and energy efficiency. For example, the city has invested in smart grid technologies, energy-efficient buildings, and incentives for renewable energy installations [1]. Despite these efforts which mainly focus on new building projects, there remains significant untapped potential in the historic city center where many older buildings are located. These buildings typically have higher energy needs due to less efficient insulation and older energy systems, and their cultural-historical value can result in restrictions on the installation of renewable energy technologies [3] [4] [5].

Creating citizen awareness and engagement, along with incentivizing self-production of energy through renewable sources such as solar panels, is crucial for achieving emission reduction targets. Engaging citizens not only helps in reducing energy consumption but also promotes a culture of sustainability and environmental responsibility. By focusing on older buildings, which are identified as the most energy-intensive, we can maximize the impact of PV installations. Due to their design and construction period, older buildings generally consume more energy for heating, cooling, and lighting. Retrofitting these buildings with modern PV systems can significantly enhance their energy autonomy and reduce the carbon footprint of their electricity usage. However, to achieve actual reductions in energy consumption, it is essential to also insulate the buildings, improve energy efficiency, or encourage behavioral changes that lead to lower energy use. [3][4] [5].

Given these premises, our study aims to analyze energy consumption trends in Amsterdam and adopt a data-driven approach to evaluate the untapped potential for renewable energy production from PV panels in the city center, while considering restrictions related to heritage conservation. By leveraging data analytics and spatial analysis tools, we aim to estimate the potential penetration rates of PV panels in the city's energy mix. This approach will help in formulating targeted strategies to enhance Amsterdam's renewable energy capacity, thereby contributing to its sustainability goals and setting a precedent for other smart cities worldwide.

1.1 Renewable Energy Sources on Heritage Buildings

Historical buildings, defined as those constructed before 1945, make up nearly 30–40% of the building stock in European countries [5]. These structures play a fundamental role in preserving cultural heritage, contributing to the townscape character and community identity, and creating urban spaces enjoyed by residents and attracting tourists, which in turn brings economic benefits.

While these heritage buildings hold immense cultural and historical value and are often legally protected, they are generally low performers in terms of energy efficiency, primarily due to low degrees of insulation of the buildings themselves and inefficient systems. Buildings account for 40% of total energy consumption in Europe, with about 75% being energy inefficient, highlighting the need for energy interventions in the European landscape [3].

Despite not constituting the majority of buildings, heritage structures significantly impact greenhouse gas emissions due to their high energy consumption. Heating and cooling these buildings requires a significant amount of energy, whether electrical or thermal. Currently, energy is predominantly sourced from conventional thermoelectric power plants, resulting in the consumption of fossil fuels and contributing to greenhouse gas emissions. However, if this energy were instead generated by PV panels, it would constitute clean energy with a low carbon footprint, offering a more sustainable solution for meeting the buildings' energy needs while reducing environmental impact.

Energy efficiency improvements in historical buildings have been hindered by underinvestment and numerous obstacles. Legal protections often limit alterations to their visual appearance, materials, and construction techniques. The Venice Charter [1] emphasizes the duty to preserve historic monuments as a common heritage, safeguarding them for future generations in their authentic form [3][5].

Integrating historical heritage into energy transition policies is essential. Requalification and renovation are crucial for avoiding the abandonment of these buildings, ensuring they meet modern living standards and improving the quality of life, health, and well-being for residents, as emphasized by EU initiatives like the NextGenerationEU program [3].

To conserve this heritage for future generations, conservation-compatible energy retrofit approaches are needed. These should preserve historical and aesthetic values while enhancing comfort, energy consumption, and minimizing environmental impact. Energy-retrofit interventions aimed at reusing such spaces help prevent deterioration of a building's fabric by meeting higher energy efficiency targets and providing occupant comfort [3][5].

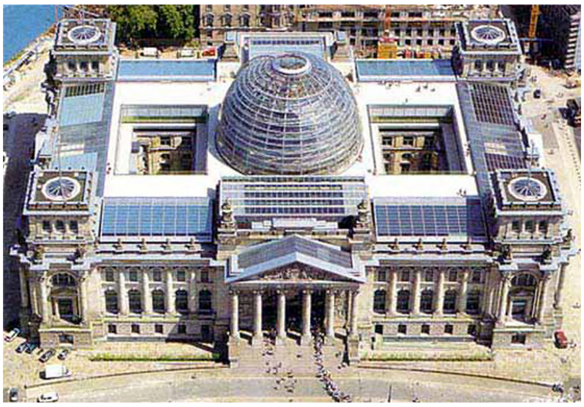
Guided by the concepts of "conservation, restoration, renovation, replacement, adaptation, or reuse," there have been numerous cases in recent years where heritage buildings have been repurposed for new uses. These projects integrate architectural restoration, energy retrofits, and re-functioning. Approaches vary from conservative methods in Mediterranean areas to more radical methods in Northern Europe. Successful retrofits typically involve energy auditing, performance assessment, economic analysis, risk assessment, and measurement of energy savings. The implementation of internal envelope insulation, cool coatings, and window retrofits represents the most effective solutions for improving the energy efficiency of building envelopes [5].

About Renewable Energy Sources (RES) in historic buildings, which contribute significantly to the reduction of energy consumption, their implementation is supported by the European legislative framework, which mandates specific targets to increase RES share, cut CO2 emissions, and enhance building energy performance. RES contributions are crucial for achieving these goals, with legislation requiring 50% of energy for domestic hot water, heating, and cooling to be sourced from RES [4].

Despite previously mentioned aesthetic impact constraints, numerous international and national research projects have demonstrated the technical and economic advantages of integrating RES into heritage buildings. Numerous investigations at the material, system, and building levels have aimed to effectively integrate renewable energy sources into the envelopes of historical buildings. Most efforts have focused on integrating photovoltaic (PV) systems into building roofs, designed to blend with traditional architectural materials, offering a less visually intrusive option for reducing carbon emissions [4].

Building Integrated Photovoltaics (BIPV) and Building Integrated Solar Thermal (BIST) solutions are increasingly suitable for heritage contexts. These technologies replace traditional building elements, combining electricity generation with weather protection, thermal insulation, and noise reduction, ensuring compatibility with heritage aesthetics and functionalities. The use of integrated renewable energy sources is further supported by highly compatible products designed to resemble traditional architectural materials. These advanced customizations include various colors, patterns, special low-reflecting glasses, and innovative, cost-effective coatings. Such technological advances have made these solutions particularly suitable for heritage contexts, ensuring low-rate reflection, compact shapes, and a mimetic appearance [4] [5].

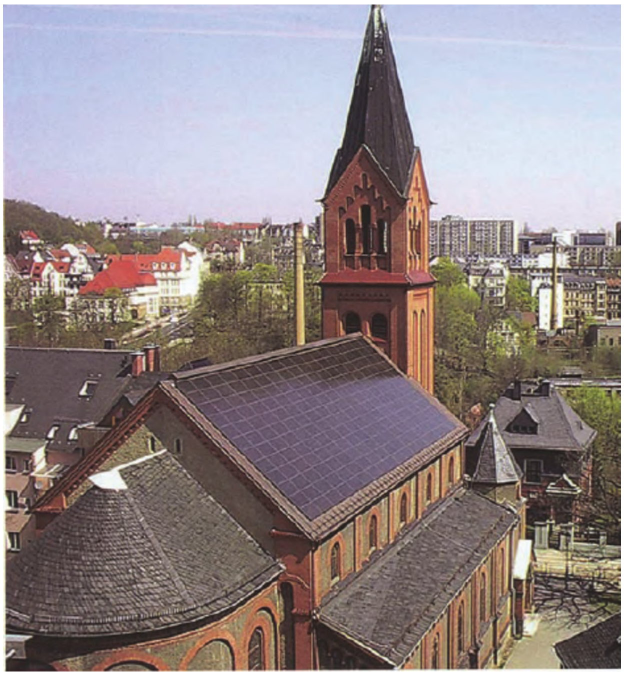
[1] The Venice Charter for the Conservation and Restoration of Monuments and Sites is a set of guidelines, drawn up in 1964 that provides an international framework for the conservation and restoration of historic buildings



(a) Reichstag Building (Berlin,DE)

(b) Nervi Hall (Vatican)

(c) Glaucester Cathedral (UK)



(d) Herz-Jesu Church (Plauen, DE)

Figure 1: Examples of solar panels installation on protected buildings

Successful examples of renewable energy integration include several notable historical buildings. The Reichstag in Berlin, Germany (Fig.1a), and the roof of Nervi Hall in the Vatican (Fig.1b) are prime examples. This integration extends to sacred sites such as Gloucester Cathedral in the UK (Fig.1c) and Herz-Jesu Church in Plauen, Germany (Fig.1d) [6]. Despite these successes, the potential for PV integration in historic buildings remains largely untapped due to economic, knowledge, and aesthetic barriers.

In summary, overcoming the challenges, integrating renewable energies into historical buildings is feasible at material, system, and building levels. This integration contributes to sustainable development and preserves cultural heritage for future generations. With the understanding of the significance of renewable energy systems in households and their feasibility in heritage buildings, we proceed to analyze the data and methodology used to study Amsterdam's energy consumption and uncover the unused power potential of its roofs.

2 Data, Analytics and Results

2.1 Data

Recalling that the main aim of the current project is to analyze Amsterdam's electricity demand together with discovering the untapped potential of the PV panels potentially installable in the city center to prove the advantages of renewable energy both for the climate and residents' finances.The data used for these objectives were collected from various sources.

The data for the analysis of energy consumption were taken from the hourly load curves dataset for all electricity production and consumption downloadable from the Energy Transition Model (ETM) website[2], which is an interactive online simulation tool for energy systems. The acquired time series refers to the year 2019 and reports numerous variables related to various aspects of energy production and consumption across multiple sectors in the city of Amsterdam by hour, measured in megawatts (MW). Each component represents the output or input of energy from different sources, technologies, and sectors.

For the purpose of our study, we cleaned this dataset by eliminating the variables that refer to the production of energy, together with non-informative variables containing only zero values, and grouping them by sector. In the end, we obtained a dataset containing the energy consumption of the city of Amsterdam by hour, measured in megawatt (MW), and divided by the following sectors:

- Agriculture
- Industry
- Energy
- Households
- Buildings
- Transport

To complement the analysis, we incorporated wholesale day-ahead electricity prices data for European countries, obtained from Ember's dataset[3]. This dataset includes average hourly, daily, and monthly wholesale day-ahead electricity prices, reflecting the prices generators receive for selling electricity on the spot market. It is important to note that these prices differ from the prices paid by electricity consumers, which also include taxes, levies, network charges, subsidies, and supplier profits, and do not account for hedging.

The integration of these price data allows us to better understand the financial implications of electricity consumption and the potential economic benefits of increasing the use of renewable energy sources in Amsterdam.

Continuing with our data collection efforts, we secured data on solar panels in Amsterdam — covering both existing installations and potential sites — via MapsData[4], a section of the Municipality of Amsterdam's website dedicated to geographic data on various topics such as sustainability, nature, traffic, and urbanity.

We explored the following datasets:

- **Solar panels**: This dataset provides a mapping of solar panels that have already been installed in Amsterdam, identified through municipal aerial photography. The data includes:
  - Coordinates of the solar panels' locations
  - Function of the building
  - Number of panels installed at each location from 2016 to 2023
  - Estimation rated power of photovoltaic panels for each installation, expressed in Watt peak (Wp)[5] at each location.

[2] https://energytransitionmodel.com/

[3] https://ember-climate.org/data-catalogue/european-wholesale-electricity-price-data/

[4] https://maps.amsterdam.nl/

[5] Watt peak (Wp) is the standard unit of measurement used to describe the maximum output power of photovoltaic (PV) solar cells or panels under standardized test conditions. The peak electrical power output of a solar panel under ideal conditions is defined by:

1. Irradiance (solar radiation): 1000 watts per square meter (W/m^2).
2. Air Mass (AM): 1.5, which corresponds to the path length of sunlight through the Earth's atmosphere when the sun is at an angle of about 48 degrees from the vertical.
3. Cell Temperature: 25 degrees Celsius.

- **Solar panels 1012**: This dataset identifies suitable solar panel systems within the postcode area 1012, and includes:
  - Geometry of the specific PV system
  - Annual energy output in kWh for each panel in the PV system
  - Visibility of the installations (clearly visible, invisible, reasonably visible, barely visible)
  - Number of panels that make up each PV system
  - Roof slope (flat, oblique, unknown)
  - Building code
  - Output range per solar panel (332/290/254/214/170/125/80 kWh/year per solar panel)
  - Visibility class: 'D' (Duidelijk: Clearly), 'R' (Redelijk: Reasonably), 'N' (Nauwelijks: Barely), 'O' (Onzichtbaar: Invisible)
  - Classification based on visibility, yield, and roof slope
- **Amsterdam Postal Codes**: A mapping of Amsterdam's postal codes, providing:
  - Geometry of each postcode area
  - Postcode
  - Area in square meters

We also gathered additional information on the electrical power output of photovoltaic systems from the PVGIS European website[6], which offers data on solar radiation and the performance of photovoltaic systems globally. Specifically, we retrieved hourly electrical power outputs in watts (W) for Amsterdam. This data extraction targeted four distinct production profiles, each corresponding to the highest output ranges identified in the Solar Panels 1012 database respectively 332, 290, 254, and 214 kWh. This selection strategy was economically motivated by the fact that the lower output ranges are not cost-effective since their installation costs outweigh the potential savings on energy bills due to their lower energy production. To obtain these production profiles, we adjusted the azimuth and panel slope angle parameters of PVGIS, which are critical factors affecting the generation capacity of PV panels. These parameters significantly influence the efficiency and production output of PV panels. The slope of PV modules is the angle of the PV modules from the horizontal plane, for a fixed (non-tracking) mounting, while the azimuth, or orientation, is the angle of the PV modules relative to the due South direction. - 90° corresponds to East, 0° to South, and 90° to West. Other parameters set in PVGIS concern the PV cell technology, assumed to be crystalline silicon, and the nominal power of each individual panel, estimated at 330 Wp, which is an average of the powers of the panels already installed in the city.

For the purpose of our project, we exploited the above mentioned datasets on solar panels in Amsterdam, covering both installed and potential PV systems, along with their production profiles to develop a new dataset for the postcode area 1012. This new dataset encompasses both existing and potential photovoltaic (PV) panel systems, providing detailed insights into:

- The number of PV panels already installed in area 1012
- The number of potential PV panel installations in area 1012
- Hour-by-hour production data throughout the year for the already installed PV panels
- Hour-by-hour production data throughout the year for potential PV panel installations

To create the new dataset, the first issue we faced was that the installed PV systems covered the entire municipality of Amsterdam, indicated only by point coordinates, and did not provide useful data to calculate production profiles. However, the dataset "Solar Panels in 1012" lists all suitable PV systems in the 1012 postcode area, regardless of whether they are already installed or not. Moreover, this dataset provides the yearly production per panel, which is crucial for calculating the hourly energy profile of a year. We leveraged the latter dataset to discern the already installed systems in postcode 1012. To do this, we checked if the coordinates of the installed systems fell within a polygon of the suitable systems; if not, we picked the closest one. In this way, we identified which panels in the group of suitable ones in postcode 1012 were already installed, including their yearly output range from the "Solar Panels in 1012" dataset. Subsequently, once we identified

[6] https://re.jrc.ec.europa.eu/pvg_tools/en/

from the suitable systems of 1012 which systems were already installed, we grouped together panels within the same energy output range, excluding those below 214 kWh. This grouping allowed us to calculate the total number of panels in each range by installed and suitable systems. We then multiplied these totals by the corresponding solar radiation values to estimate the hourly and annual production of solar panels by output range, distinctly for installed and potential systems. By aggregating the data across all output ranges while keeping installed and potential installations separate, we obtained an overview of the current energy production profile from already installed PV panels and the projected potential energy production profile if all suitable areas were exploited.

The last dataset we obtained is the statistical data per square and zip code from the Centraal Bureau voor de Statistiek (CBS), which is the national statistical office of the Netherlands. This dataset includes a variety of indicators encompassing demographic, housing, and socioeconomic aspects. Such a dataset is fundamental for studying any socio-economic correlations with solar panel installations and for rescaling Amsterdam's energy consumption to the 1012 postcode area. This allows us to compare and make assumptions about the potential energy production from renewable resources and the energy consumption of the neighborhood.

2.2 Analytics and Results

2.2.1 Amsterdam Energy Consumption

The comprehensive analysis of Amsterdam's energy consumption, presented through various graphical plots, provides critical insights into temporal energy usage across different sectors, including households and buildings. These data visualizations are pivotal for strategizing the deployment of PV systems within the city, particularly on the rooftops of residential and commercial buildings.

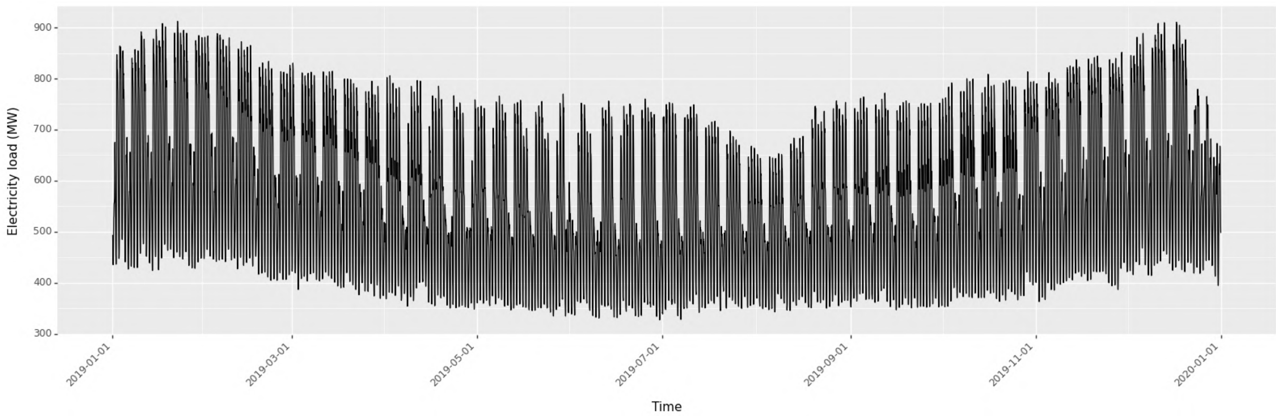
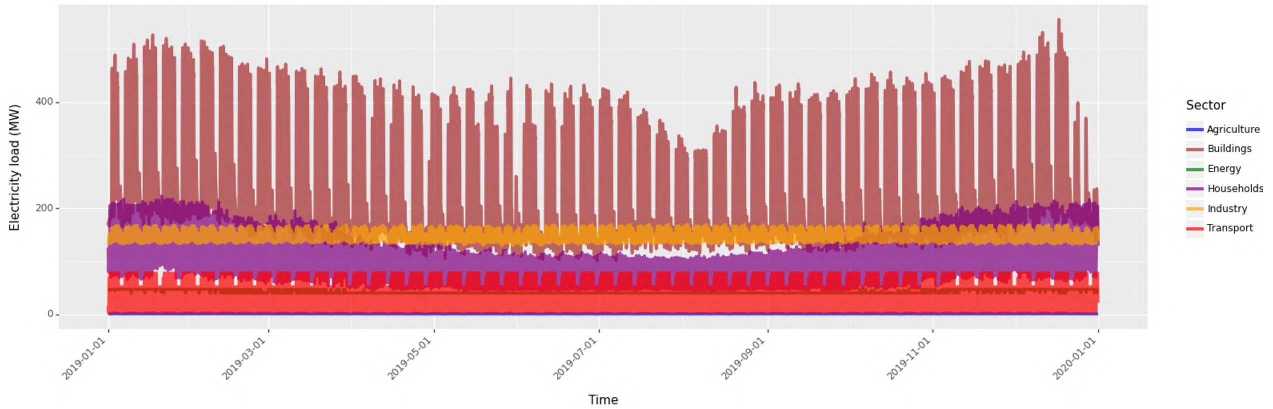
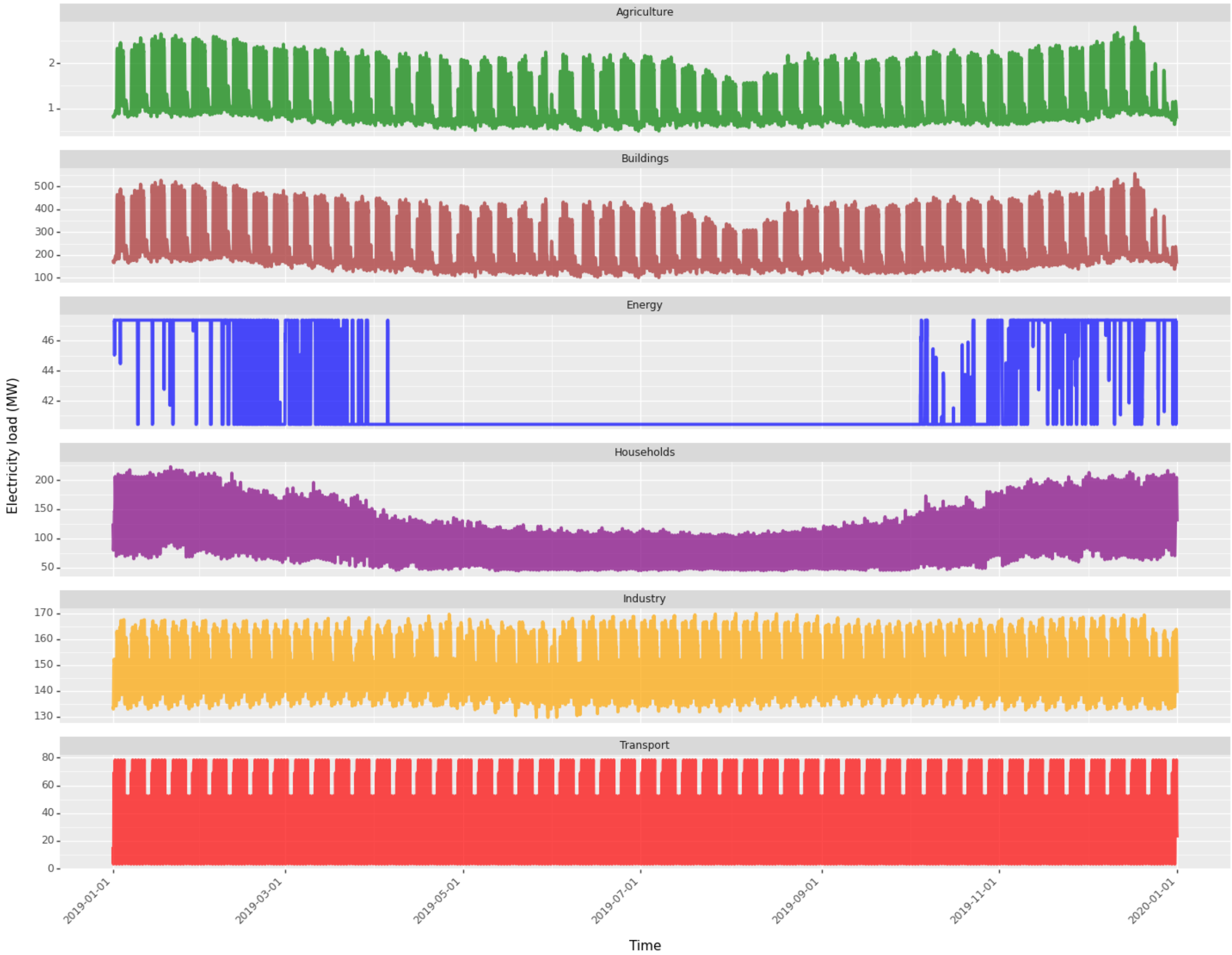


Figure 2: Time series of total electricity load profile (MW) for Amsterdam from January 2019 to December 2019

From the total and sector-specific energy consumption time series plots in Fig.2 and Fig.3, distinct patterns of energy demand emerge throughout the year. These fluctuations reflect varying energy needs driven by seasonal changes, economic activities, and other socio-economic factors. For instance, the building and household sectors are notably influenced by yearly seasonality, as seen in Fig. 3b, whereas transport and industry maintain a more constant behavior throughout the year.



(a) Time series of electricity load profile (MW) for various sectors in Amsterdam from January 2019 to December 2019



(b) Electricity load profile (MW) by sector over time in Amsterdam from January 2019 to December 2019

Figure 3: Time Series of energy consumption in Amsterdam by sector

Specifically, the household sector shows a significant drop in energy consumption during the summer months. In the building sector, there is a slight increase in early summer, likely due to the use of air conditioning, although it is not heavily needed in the Netherlands. This is followed by an evident decrease in energy consumption in August, coinciding with the holiday season when many businesses temporarily close. Additionally, a similar trend is observed in the building sector at the end of the year during the Christmas holidays. In contrast, the household sector experiences an increase in energy demand during this time of year.

Notably, all sectors, except for energy, are influenced by daily and weekly seasonality. Moreover, from the time series in Fig. 3a, it is evident that buildings have the highest energy demands.

In view of the main purpose of the present project, daily, weekly, and annual seasonality of the building and household sectors are analyzed more in depth.

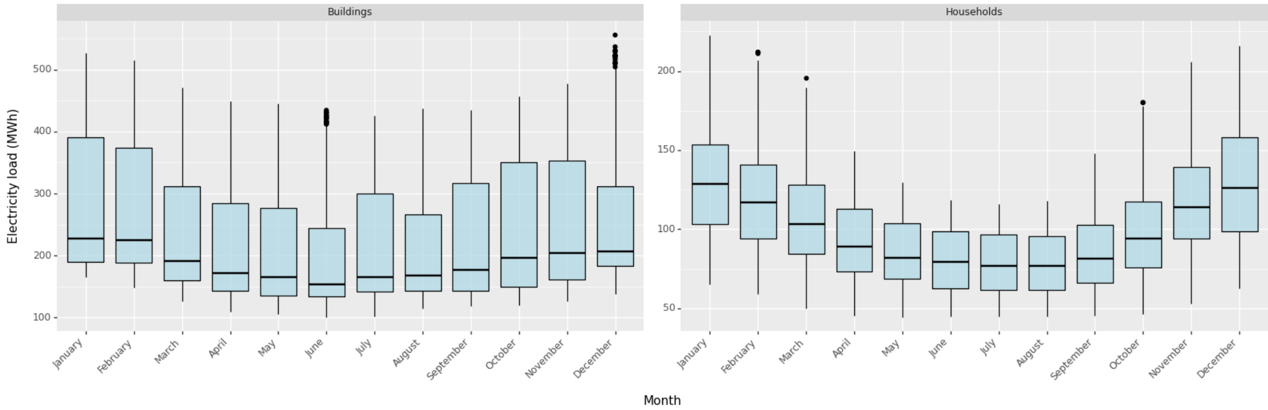


Figure 4: Box plots of the energy consumption (MWh) of the household and building sectors by month

The box plots in Fig. 4 further emphasize the previously noted yearly seasonality, showing a decrease in energy consumption in the household sector during the warmer months compared to the winter months. This pattern is also observed in the buildings sector, with an exception in July, where there is an increase in consumption likely due to heavier usage of air conditioning, especially in commercial activities.

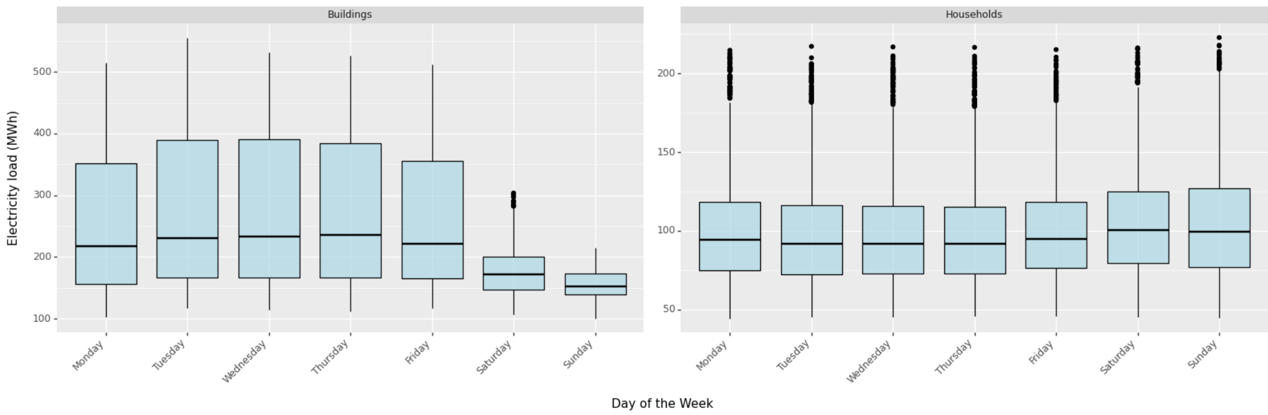


Figure 5: Box plots of the energy consumption (MWh) of the household and building sectors by day of the week

From the time series in Fig. 3, we can observe a weekly seasonality, which is examined in detail in the box plots of Fig. 5. The energy load distribution varies across the days of the week for the two sectors. In the building sector, energy consumption is higher on weekdays, likely when most businesses are open, with an increase from Tuesday to Thursday and a significant drop during the weekends. Conversely, the household sector maintains a more consistent energy load, with a slight increase during the weekend when most people are at home.

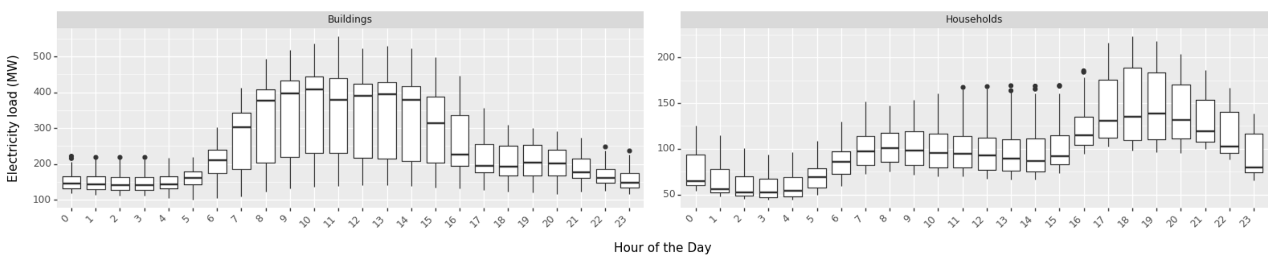


Figure 6: Box plots of the energy consumption (MW) of the household and building sectors by hour of the day

We further analyze seasonality by examining how energy consumption is distributed throughout the day in Fig. 6. In the buildings sector, the main demand is centered around working hours, with a rapid increase between 6 AM and 7 AM, and a sharp decrease between 4 PM and 5 PM. In contrast, the household sector experiences its peak energy demand during the early evening hours, from 5 PM to 11 PM.

We now explore the interactions between these seasonal patterns. Specifically, we are interested in determining whether the hourly energy load remains constant throughout the year and across different days of the week, or if the demand throughout the day varies with seasons, weekdays, and weekends.

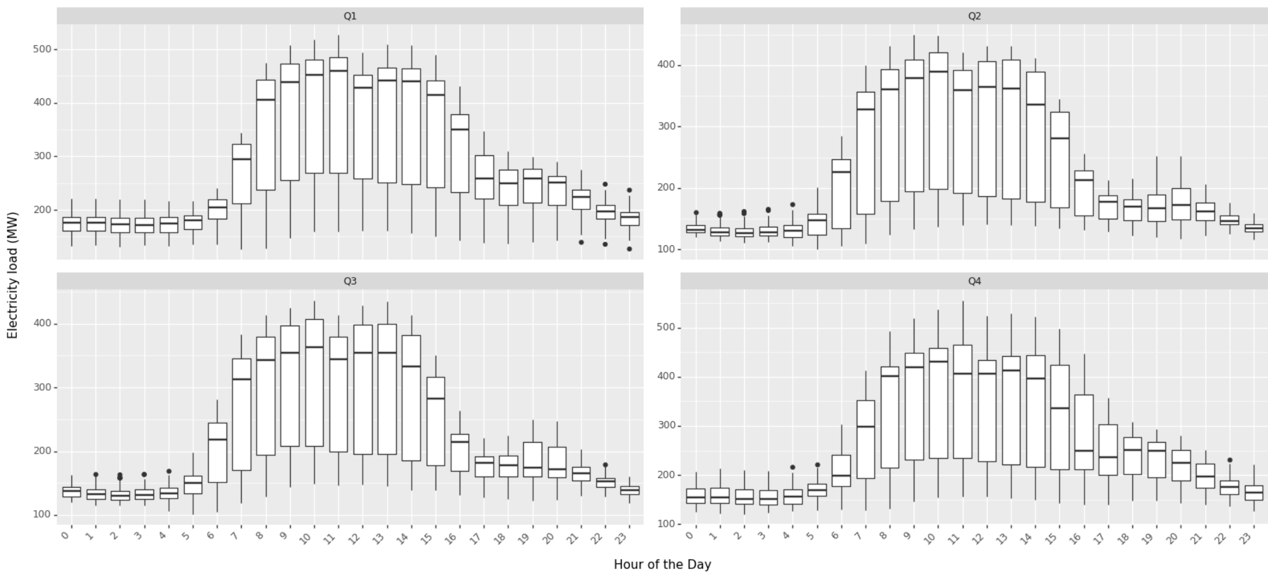


Figure 7: Box plots of the energy consumption of the building sector by hour of the day and quarter of the year

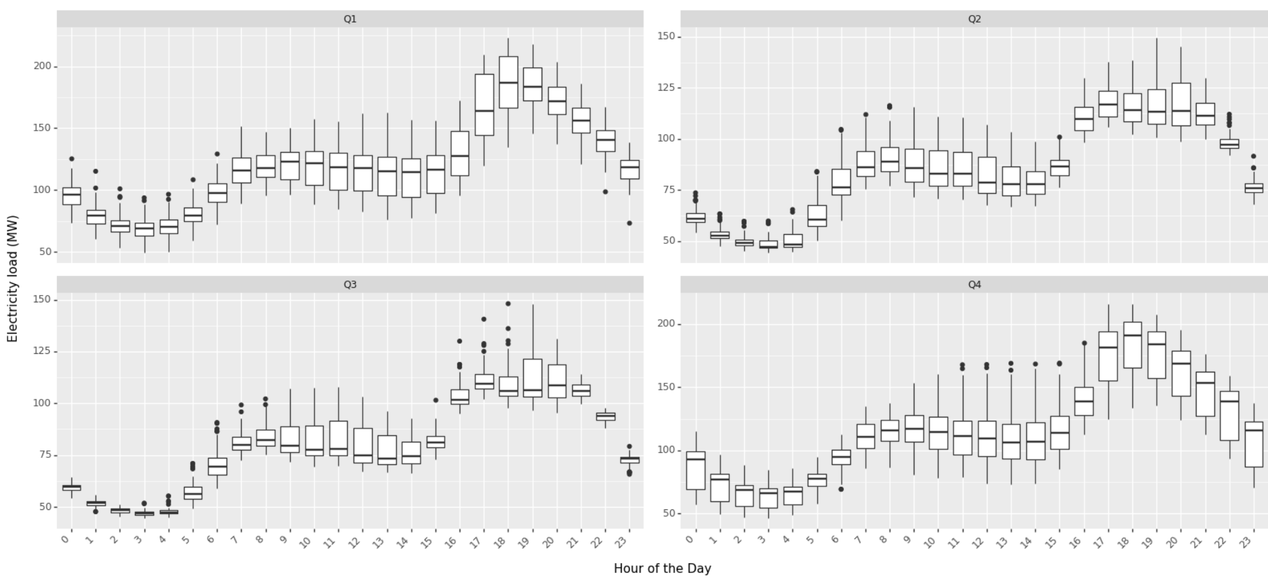


Figure 8: Box plots of the energy consumption of the household sector by hour of the day and quarter of the year

Indeed, from the box plots in Fig. 7 and Fig. 8, we can see that the behavior in energy demand for both sectors is analogous across the four quarters of the year, apart from the overall quantity of energy demand, which is lower during warmer months. Interestingly, during the winter months (the first and last quarters), the transition from off-load hours to peak hours is smoother. In contrast, during the warmer months, the change in demand from hour to hour is sharper, and the hourly energy demand is less variable.

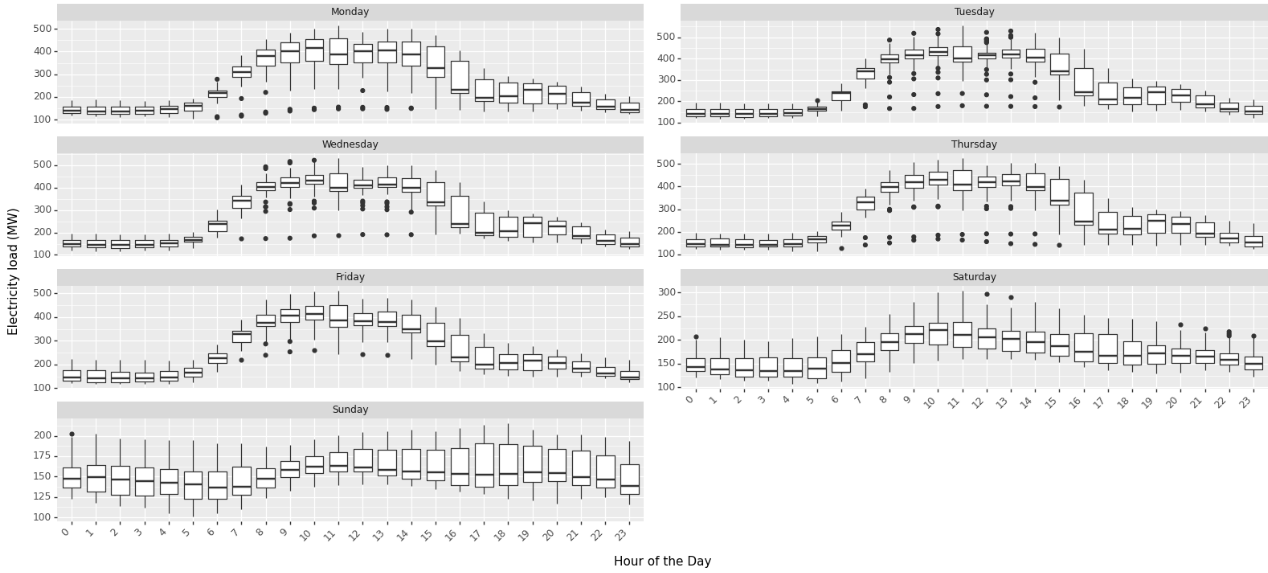


Figure 9: Box plots of the energy consumption of the building sector by hour of the day and day of the week

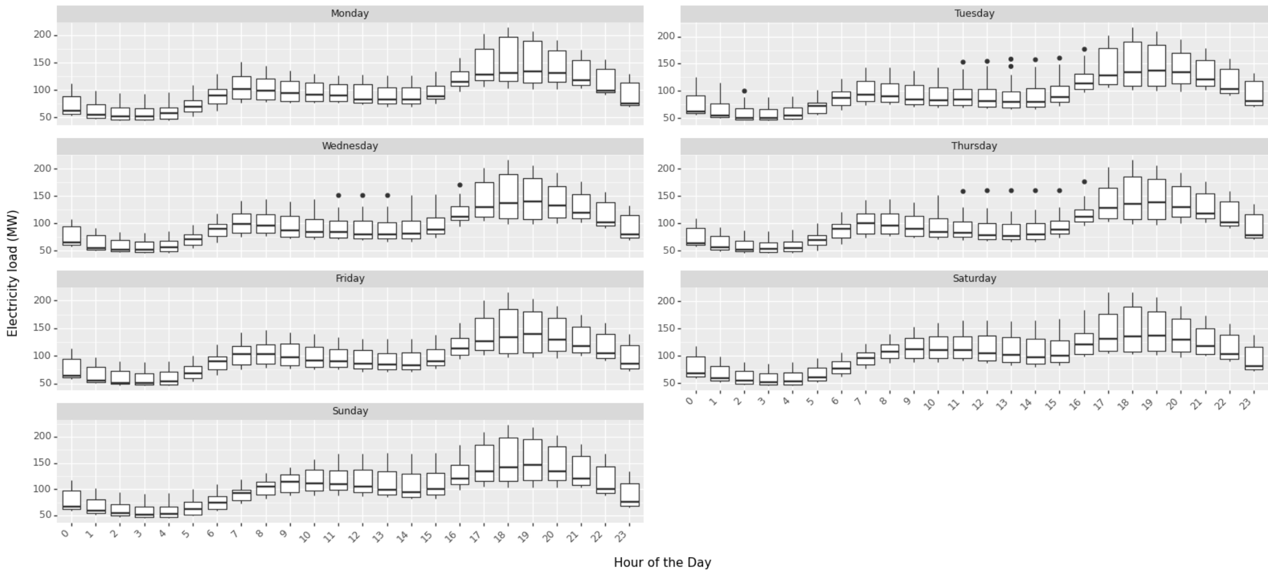


Figure 10: Box plots of the energy consumption of the household sector by hour of the day and day of the week

Regarding the hourly energy demands across different days of the week, the box plots for the household sector in Fig. 10 indicate no significant differences in load between weekdays and weekends. In contrast, for the building sector, the energy demand throughout the day during weekends is more consistent, particularly on Sundays, with a less pronounced peak during the central hours of the day.

In conclusion, our detailed analysis underscores the significant role of Amsterdam's household and building sectors in the city's overall energy demand, collectively accounting for nearly 60% of the total and requiring almost 3 terawatt-hours (TWh) annually. Marked daily, weekly, and yearly seasonal patterns in energy usage are evident, with the building sector's pronounced daytime energy consumption highlighting its potential for integrating photovoltaic (PV) systems. Such alignment between peak energy demand and daylight hours maximizes the utility of solar energy, presenting a compelling option to reduce reliance on conventional power sources and enhance sustainability.

In contrast, the household sector exhibits higher energy demand at night, which may necessitate the installation of batteries for storing daytime-produced energy for evening use. Although this would entail additional investment, it could lead to greater independence and self-sustainability for families.

Implementing PV technology in these sectors could play a pivotal role in Amsterdam's transition towards a more sustainable and resilient energy framework. By capitalizing on the distinct temporal patterns of energy consumption, the city can more effectively manage its energy resources and move towards a greener future.

In the next section, we will analyze the current deployment of PV panels in the city and assess the potential for energy production from renewable sources.

2.2.2 Financial implications of electricity consumption

To understand the financial implications of energy consumption and the potential economic benefits of increasing the use of renewable energy sources, we incorporated wholesale day-ahead electricity prices data for European countries. This dataset, obtained from Ember, includes average hourly, daily, and monthly wholesale day-ahead electricity prices. These prices reflect the rates generators receive for selling electricity on the spot market, which differ from the prices paid by electricity consumers.

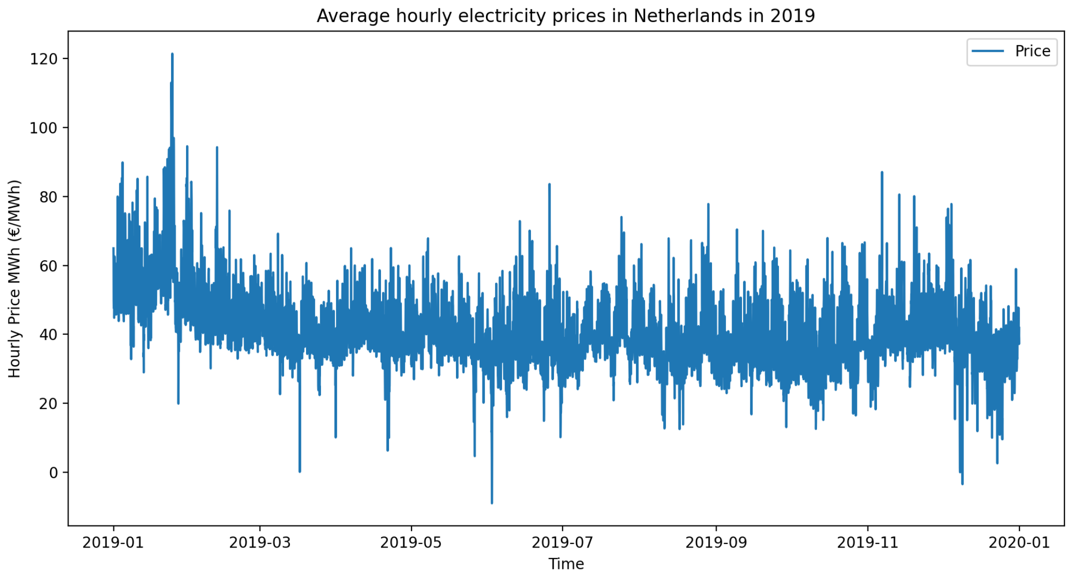


Figure 11: Hourly electricity prices in the Netherlands for the year 2019

The graph in Figure 11 illustrates the average hourly electricity prices in the Netherlands throughout 2019. Key observations from the graph include:

The data spans from January 2019 to December 2019, providing a full year of hourly price information. The electricity prices exhibit significant fluctuations, with notable peaks exceeding €120/MWh in early 2019. As the year progresses, prices stabilize within a range of approximately €40-60/MWh. The graph reveals seasonal variations in electricity prices, likely driven by changes in demand and supply conditions across different times of the year.

The variability and peaks in electricity prices underscore the potential economic advantages of installing PV systems. By generating electricity during high-price periods, PV systems can significantly reduce costs and enhance the sustainability of the energy supply. The strategic deployment of PV infrastructure can leverage these temporal price patterns to maximize financial returns and environmental benefits.

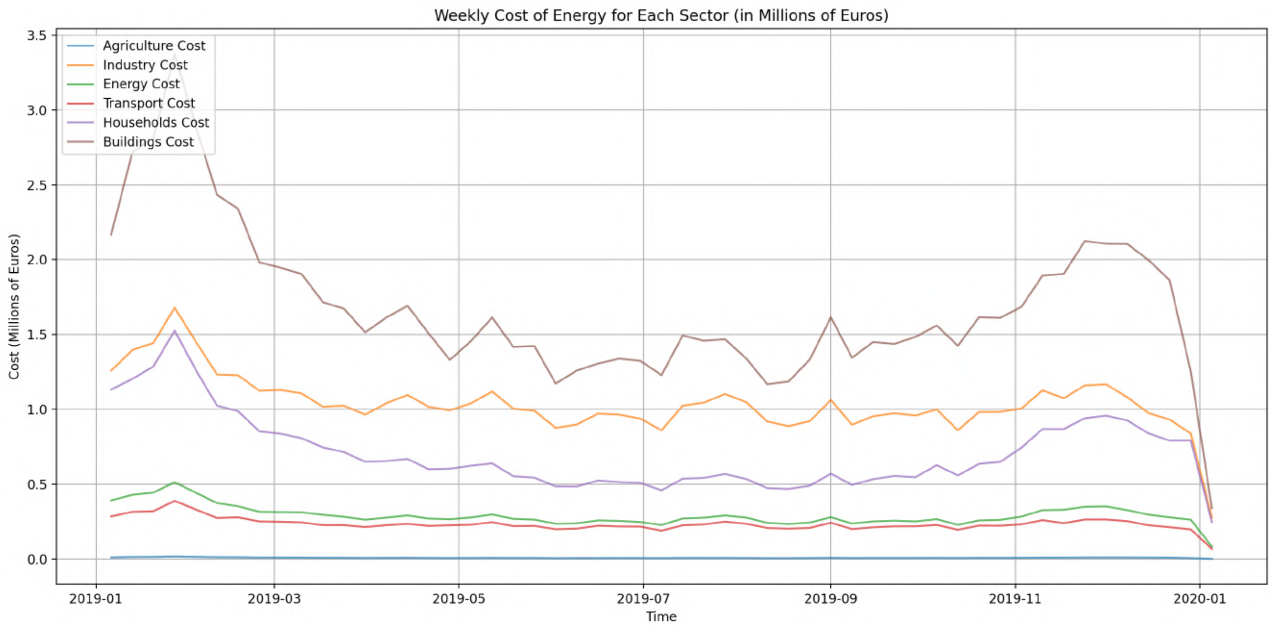


Figure 12: Weekly energy costs for each sector throughout 2019

Figure 12 illustrates the weekly energy costs for each sector throughout 2019. The energy costs exhibit variability across different sectors and over time, reflecting changes in energy consumption and price fluctuations. The household sector consistently incurs the highest energy costs, peaking above €3 million per week at the beginning of the year and gradually decreasing to around €2 million by the year's end. The industry sector follows a similar trend, with costs starting above €1.5 million per week and declining steadily over the year. Both sectors show relatively stable costs, with minor fluctuations around €0.5 million per week. The agriculture sector maintains the lowest energy costs, remaining nearly constant and negligible throughout the year.

Again, the significant energy costs in the household and industry sectors present substantial opportunities for deploying PV systems. By offsetting electricity consumption during high-cost periods with solar energy, these sectors can achieve considerable financial savings. The stable cost patterns in the transport and energy sectors also suggest potential benefits from PV installations, albeit on a smaller scale.

2.2.3 Photovoltaic Panels in Amsterdam - an overview

Amsterdam has been proactive in integrating photovoltaic systems as part of its strategy to enhance renewable energy usage within the city. To date, the city boasts 23,348 PV installations, encompassing 816,775 panels across various districts, with an average output of 11 kW-peak (kW_p) per installation. Notably, 33% of these panels are mounted on residential buildings, with the proportion increasing to nearly 50% when including buildings with mixed-use functions that have residential components.

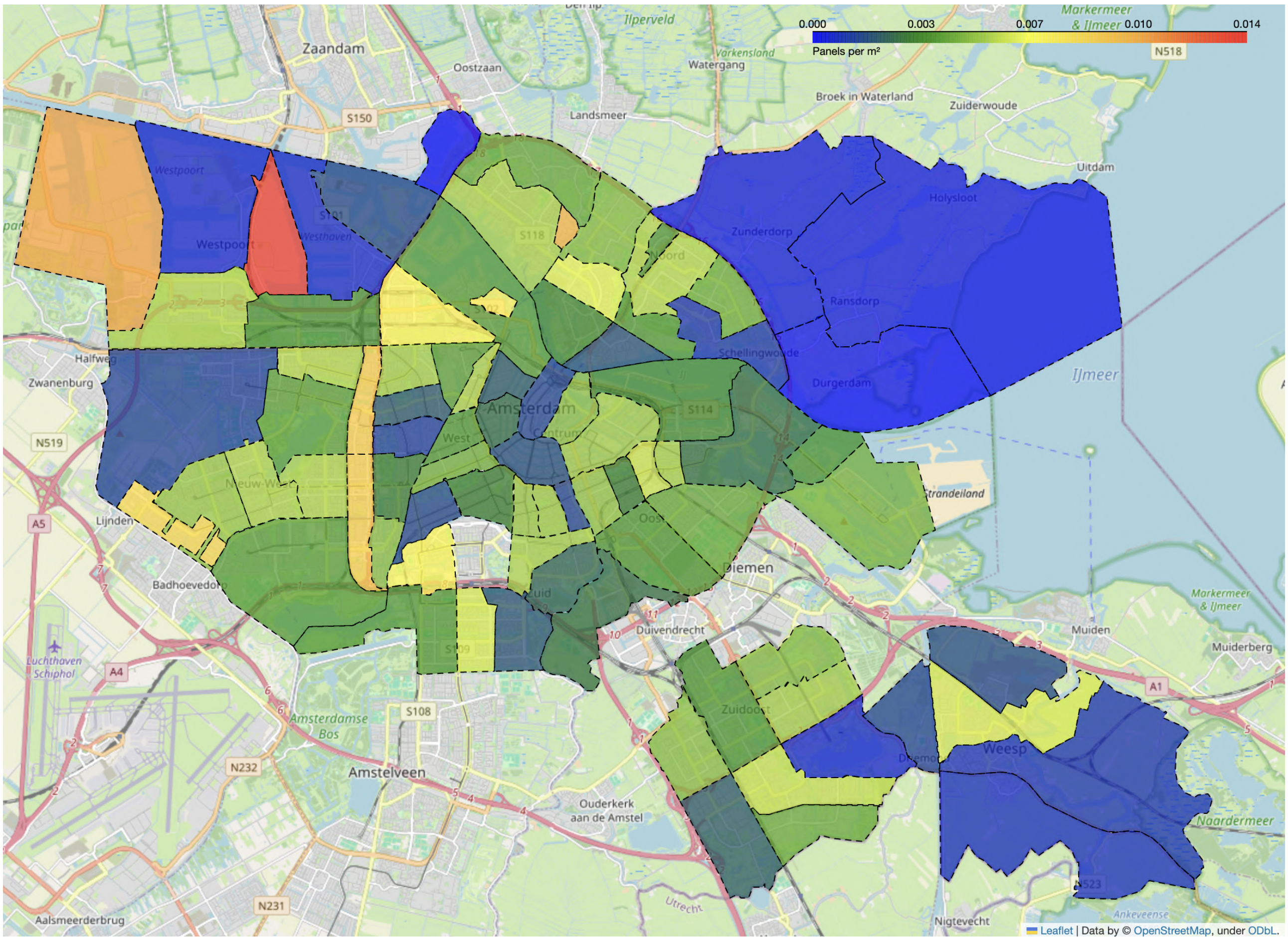


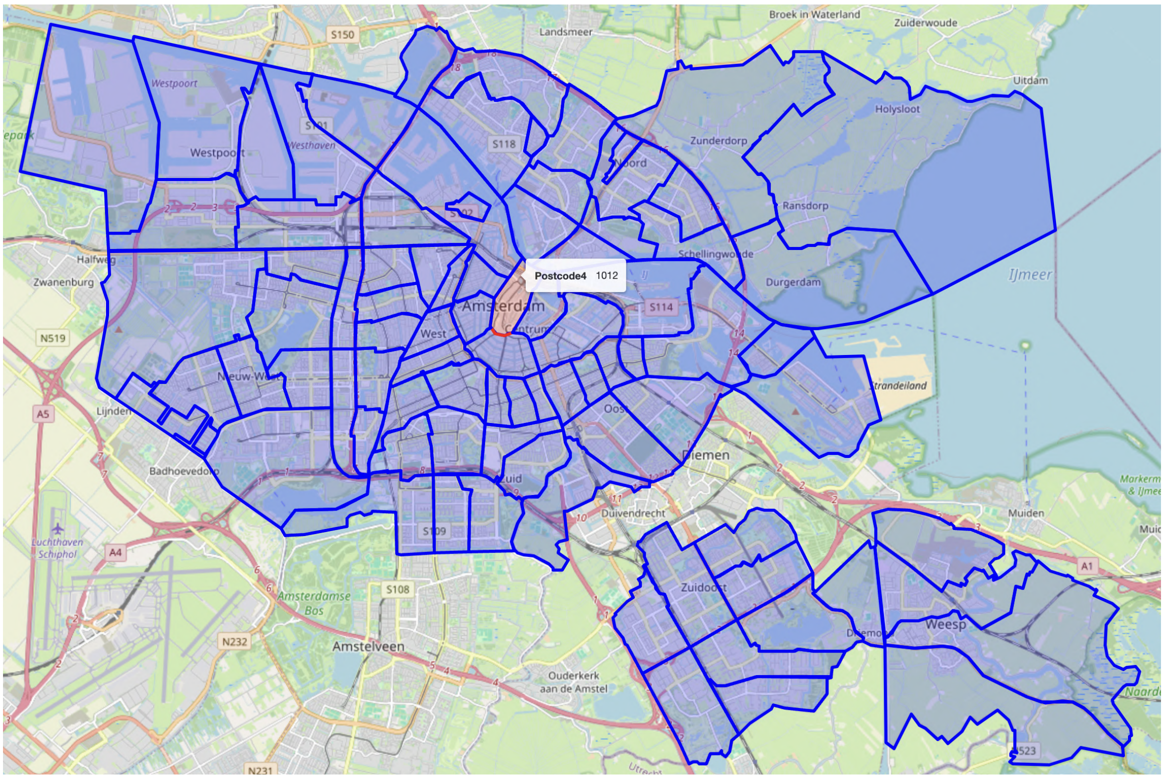
Figure 13: Heatmap of density of Solar Panels per Square Meter across Amsterdam's postcodes

As depicted in the heatmap of Fig. 13, the highest concentration of PV panels, indicated by the red area, is found in postcode 1044, an industrial zone located in the Westpoort district. This area, less constrained by visibility and heritage restrictions, allows for extensive and straightforward deployment of solar technologies. All installations in this postcode are on non-residential buildings, enhancing the district's capacity for substantial energy production without the complexities associated with residential areas.

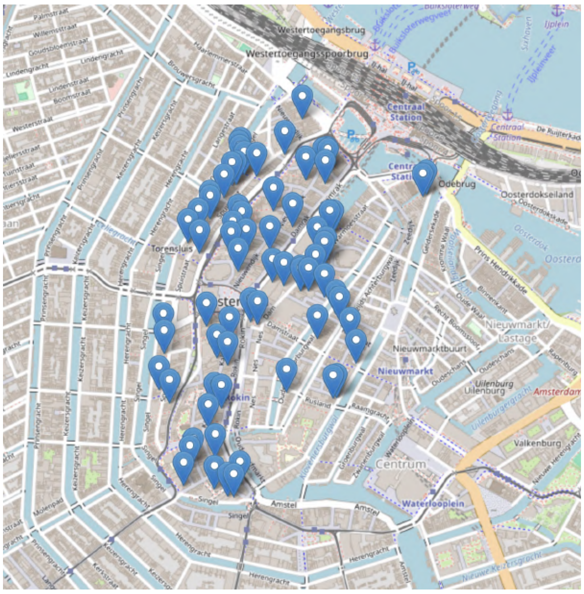
In contrast, postcode 1012, located in Amsterdam's historic city center (Fig. 14a), has one of the lowest concentrations of PV installations in the city, accounting for only 0.4% of Amsterdam's total PV coverage, normalized by area, with a total of 1,822 panels (Fig, 14b. The panels in this postcode predominantly fall into the higher output ranges, with a combined annual production of 484,586 kWh.

2.2.4 Potential solar energy

As noted in the previous section, the installation of PV panels in historical centers is limited by policies aimed at conserving cultural heritage, but not impossible. Indeed, the number of identified feasible installations for central postcode 1012 is around 22,749 with a total of 62,219 panels 14c which would be able to produce 14.5 GWh/year. If we exclude the panels with the lowest output ranges and keep only those with a production above 214 kWh/year, we could still reach a production of over 11 GWh/year.



(a) Position of postcode 1012 in Amsterdam municipality

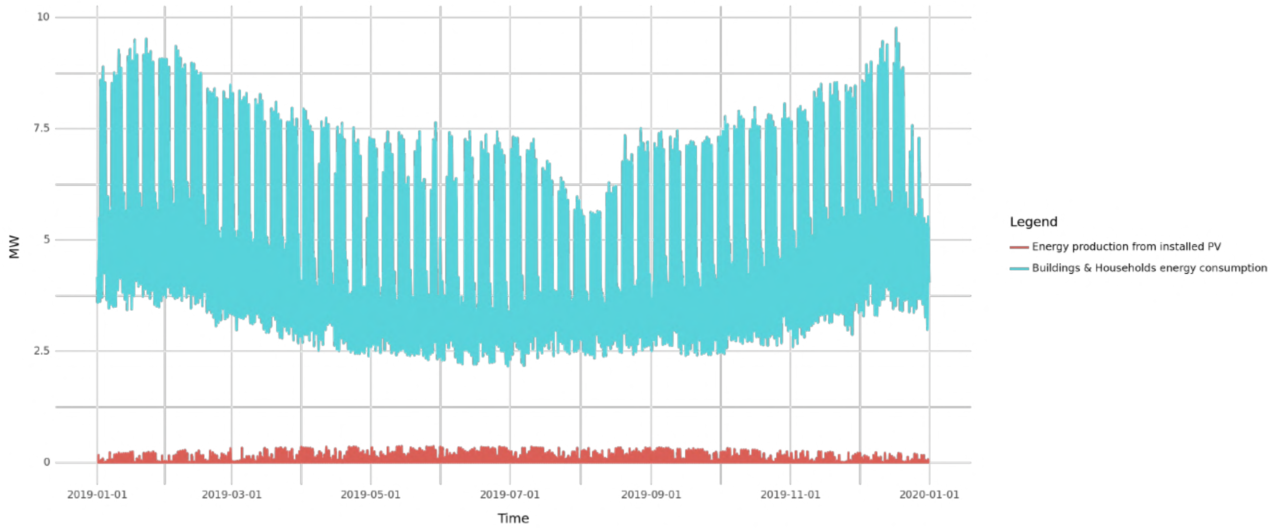


(b) Coordinates of already installed PV systems in postcode 1012

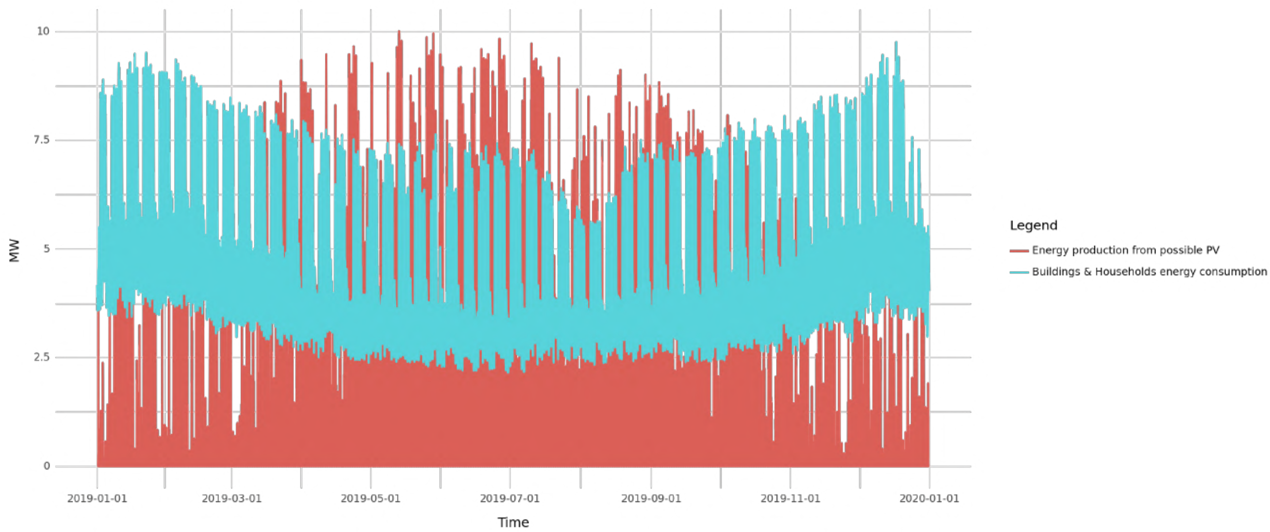
(c) Maps of the feasible PV installations in postcode 1012 in red and the already exploited one in green

We now proceed by analyzing the hourly production of PV panels and compare them with the consumption in the postcode 1012.

To further analyze the feasibility of self-sufficiency in postcode 1012, we adjusted the city-level consumption data to this specific postcode using demographic information, such as population, and the number of households and buildings. Postcode 1012 represents 1.27% of Amsterdam's total households and 1.50% of its total buildings. These figures allowed us to scale down the energy consumption data for both the building and household sectors, providing a basis to compare current and possible PV energy production with actual consumption at the postcode level.



(a) Energy production by nowadays installed PV panels compared to energy consumption in the postcode 1012



(b) Energy production by feasible PV panels compared to energy consumption in the postcode 1012

Our findings indicate that the combined energy consumption from buildings and households in postcode 1012 totals over 42 GWh per year. Currently, the energy produced by the PV panels installed in this area, which we recall being 484 MWh, covers just slightly more than 1% of this consumption. Fig. 15a visually represents this comparison over a year. However, as shown in Fig. 15b, if all eligible surfaces were fully exploited and only the most efficient panels (yielding more than 214 kWh/year) were installed, the potential annual production could be 26 times higher than the current output, reaching a production of 11 GWh per year.

In the winter months, solar irradiation is low, resulting in limited solar panel production that cannot entirely meet the electricity demand. Conversely, during the summer months, there is a significant increase in solar irradiation, leading to solar production that often exceeds consumption. This phenomenon, known as overgeneration, occurs when the energy produced surpasses the demand. This excess energy presents new challenges, such as deciding whether to sell it to neighboring areas that can absorb the surplus, or store it in batteries to use during periods of low production.

Although reliance on the electricity grid is inevitable during the winter, an increase in installed solar panels could allow households and buildings in Amsterdam to be energy self-sufficient during the summer months. Under optimal conditions, this could even result in energy overproduction.

2.2.5 Financial implications of PV panel installation

In the previous section, we explored the potential of PV panels to reduce reliance on conventional energy sources, particularly during the summer months in the central postcode of Amsterdam. Extending this analysis, we now consider the financial implications of such PV installations. By considering the price of energy, the consumption of the neighborhood, and the net consumption after accounting for energy produced by the scenario previously depicted—which considers all possible PV panels installable in postcode 1012 with a yearly energy production above 214 kWh—we are able to assess whether such interventions could benefit the finances of residents and building owners. We also have to consider that the economic viability of shared PV systems strongly depends on the absolute value of the variable component of the retail electricity price. [7]

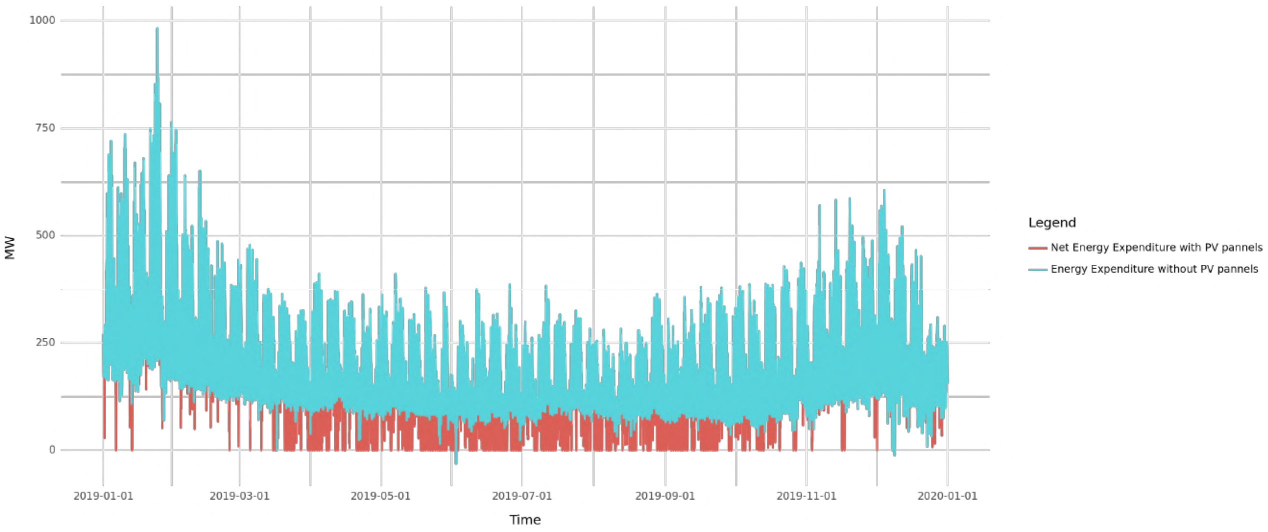


Figure 16: Expenditure for electricity without PV pannels vs with PV pannels

We find that the sectors of households and buildings in postcode 1012 have an annual energy expenditure exceeding €1.8 million. With the potential installation of PV panels capable of generating over 11.8 GWh/year, the financial expenditure for energy could drop by 23%, since the reliance on the energy grid would then be slightly less than 31.8 GWh/year, which in monetary terms translates to a cost of €1.4 million. As we can see from the plot of Fig. 16, the most significant savings occur during the summer months, aligning with expectations due to peak production from PV panels. On several days throughout the summer, it is possible to achieve complete independence from the power grid. Additionally, the data reveals reduced energy expenditures on certain days during the winter months as well.

However, it is important to acknowledge that the 23% savings do not include the initial costs associated with installing the PV panels and managing the overgenerated energy. While the reduction in energy costs is notable, the upfront investment for panel installation, necessary infrastructure for energy storage, and potential revenue from selling excess energy must be comprehensively evaluated. These factors are crucial for a thorough financial analysis to accurately determine the overall return on investment of this sustainable initiative. Additionally, potential long-term benefits such as increased property values, reduced carbon emissions, and energy price stability should be incorporated into the economic assessments. Policymakers are encouraged to implement supportive measures, including tax incentives, subsidies, or feed-in tariffs, to enhance the economic viability and attractiveness of renewable energy projects.

3 Conclusion and Policy Suggestion

This comprehensive study underscores the significant opportunity and imperative for Amsterdam to expand its integration of photovoltaic (PV) systems, particularly in historically significant areas like postcode 1012. Despite the aesthetic and heritage constraints that often hinder modern interventions in these zones, the potential for PV installations to contribute to substantial economic savings and environmental benefits remains largely untapped. By increasing the proportion of energy derived from renewable sources, Amsterdam can reduce its dependency on fossil fuels, decrease greenhouse gas emissions, and make strides toward its ambitious sustainability goals.

Moreover, integrating PV systems in heritage buildings not only aligns with global climate objectives but also promotes a resilient energy infrastructure capable of adapting to future demands and technological advancements. This approach does not merely preserve the past; it actively incorporates these structures into the city's future, enhancing their utility and ensuring their continued relevance in a modern urban landscape.

However, the path to achieving these objectives is complex and requires a multi-faceted strategy. Economic challenges, such as the initial high costs of PV installations and the retrofitting of heritage buildings, must be balanced against long-term gains in energy savings and environmental impact. Additionally, there is a crucial need for updated policies and regulatory frameworks that facilitate the adoption of renewable technologies while respecting architectural heritage.

To address these challenges, the following policy recommendations are proposed:

1. **Enhanced Incentives for Renewable Energy Integration:** Develop and implement policies that provide financial incentives for the installation of PV systems in order to increase the penetration of such renewable energy sources into the energy mix. The incentives could include tax reductions, grants, and subsidies that help offset the initial costs of installation and incentivize property owners to invest in renewable technologies.

2. **Streamlined Regulations and Guidelines:** Establish clear, streamlined guidelines and regulations that facilitate the integration of PV systems in heritage buildings. This includes simplifying the approval process for retrofitting historic structures with modern energy solutions, while ensuring that these interventions preserve the cultural and architectural integrity of the buildings.

3. **Education and Awareness Programs:** Increase awareness and knowledge among stakeholders, including property owners, architects, and urban planners, about the benefits and possibilities of integrating PV systems in heritage buildings. Educational programs and workshops can help overcome reluctance to adopt new technologies and demonstrate successful examples of integration that respect architectural heritage.

4. **Innovative Design Solutions:** Encourage and support the development of Building Integrated Photovoltaics (BIPV) and Building Integrated Solar Thermal (BIST) solutions that are aesthetically pleasing and compatible with historical architecture. Investment in research and development can lead to innovations that minimize the visual impact of solar installations and enhance their acceptance among conservationists and the public.

5. **Collaborative Planning and Management:** Foster a collaborative approach to urban planning and management that includes stakeholders from the conservation, energy, and urban development sectors. This collaborative framework should aim to balance conservation needs with modern energy requirements, ensuring that heritage conservation becomes an integral part of sustainable urban development.

6. **Localized Renewable Energy Solutions:** Explore alternative options for localizing renewables in areas adjacent to heritage sites that are less visible and intrusive. Utilizing nearby non-heritage buildings or infrastructures for large-scale PV installations can reduce the aesthetic impact on protected areas while still contributing to the energy needs of the historic center.

7. **Targeted Energy Efficiency Programs:** Implement targeted energy efficiency policies that aim to reduce final energy consumption by promoting energy-saving measures and technologies in both residential and commercial sectors. This can involve enhanced building codes and standards, energy efficiency grants and rebates, smart metering and energy management systems, public-private partnerships, awareness campaigns, and benchmarking and performance standards to encourage property owners to invest in energy-efficient upgrades.

By adopting these policy recommendations, Amsterdam can lead by example in merging heritage conservation with sustainable development. The city's efforts to expand the use of renewable energy in sensitive areas not only enhance its sustainability profile but also set a precedent for other cities worldwide, demonstrating that historical preservation and modern energy needs are not mutually exclusive but can be synergistically aligned for a sustainable future.

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