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COMPARATIVE ANALYSIS OF ENERGY EFFICIENCY AND ECONOMIC SUSTAINABILITY IN PUBLIC BUILDINGS: A CASE STUDY OF A KINDERGARTEN USING HEAT PUMPS AND PHOTOVOLTAIC SYSTEMS

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Abstract

Energy efficiency improvements and renewable energy integration in public buildings represent a significant step toward reducing operational costs and minimizing environmental impact. This study presents a comprehensive analysis of the energy performance of a kindergarten in Macedonia, with a total area of 1 200 m², an annual electricity consumption of 25 000 kWh, and a yearly consumption of 16 700 liters of extra light fuel oil for heating. The objective is to identify the most efficient and cost-effective solution by comparing three scenarios. The first scenario considers the current situation, where electricity is procured from the Universal Supplier, and heating relies on extra light fuel oil. An alternative option is analyzed, considering electricity procurement on the free market. The second scenario involves heating with a 150 kW heat pump powered by electricity procured from the free market and the Universal Supplier. The third scenario includes the installation of a 40 kWp photovoltaic (PV) system on the kindergarten's roof, utilizing the generated electricity for self-consumption, selling the surplus electricity, heating with a 150 kW heat pump, and procuring additional electricity as needed. The findings highlight significant environmental and economic benefits, including reduced CO_2 emissions, lower operational costs, and enhanced energy independence. By showcasing the potential of renewable energy and efficient technologies, this study emphasizes their role in fostering sustainability and aligning public infrastructure with global decarbonization goals.

Keywords: *decarbonization, renewable energy integration, environmental impact, CO_2 emissions, energy independence.*

INTRODUCTION

The continuous rise in energy prices, driven by global market fluctuations and increasing demand, poses significant challenges for public institutions, especially those operating on limited budgets [1]. In Macedonia, many public buildings, such as kindergartens, rely on outdated heating systems and conventional energy sources, leading to high operational costs and elevated CO_2 emissions. The need for energy-efficient solutions has never been more urgent, particularly in the context of the global push toward renewable energy integration and the commitments outlined in the Paris Agreement [2].

This study focuses on a kindergarten with an annual electricity consumption of 25 000 kWh and a heating system consuming 16 700 liters of extra light fuel oil. The analysis aims to identify the most efficient and sustainable solution by comparing three scenarios:

1. Maintaining the current energy system but exploring the potential cost benefits of purchasing electricity on the free market.
2. Replacing the existing heating system with a 150 kW heat pump, coupled with electricity procurement from the free market and the Universal Supplier.

3. Implementing a 40 kWp photovoltaic system on the building's roof, which would supply electricity for self-consumption, with surplus energy sold on the market, and utilizing a 150 kW heat pump for heating.

The techno-economic analysis includes cost assessments for investment and operations, as well as the environmental impact through the reduction of CO_2 emissions. By simulating electricity production from the PV system using the PV*SOL premium software and comparing it with standard load curves, the study aims to provide a practical roadmap for transforming public buildings into energy-efficient and environmentally sustainable facilities.

This paper seeks to highlight the financial and ecological advantages of integrating renewable energy solutions into public infrastructure. By reducing CO_2 emissions, improving local air quality, and decreasing dependence on fossil fuels, the study provides a compelling case for policymakers and local governments to support such initiatives, ensuring long-term sustainability and aligning with global environmental goals.

MATERIAL AND METHODS

The analysis examined electricity consumption on both hourly and monthly levels for a kindergarten in Makedonski Brod, North Macedonia with a surface area of 1 200 m². A 40 kW photovoltaic system was simulated using the PV*SOL premium software to estimate hourly, monthly, and annual electricity generation and avoided CO_2 emissions.

CO_2 emissions were calculated based on the heating energy source. For EL1 oil, emissions were obtained by multiplying the annual consumption by an emission factor of 266.5 g CO_2/kWh [3]. For grid electricity, the emission factor was sourced from the PV*SOL premium, a licensed simulation software that incorporates country-specific data due to the lack of sufficient literature on North Macedonia's energy mix. The avoided CO_2 emissions with the PV system were also estimated using the PV*SOL premium, considering annual electricity production and emission factors. For the PV system with a heat pump, emissions were calculated based on reduced grid electricity consumption, highlighting the environmental benefits of renewable energy integration.

Financial analyses included two scenarios: procurement via the Universal Supplier, based on current prices from the Regulatory Commission of the Republic of North Macedonia's website, and free market procurement, using 2024 monthly average prices from the HUPX electricity exchange. CO_2 emission costs were included based on current European market prices. The price of extra light fuel oil (EL-1) was set at 1.15€ per liter according to the current prices in Macedonia from the website of the Regulatory Commission of the Republic of North Macedonia [4]. Investment costs were calculated using current market prices for a 150 kW heat pump and a 40 kW photovoltaic system, including equipment and installation. All projections were conducted in Excel to generate the financial analysis and supporting charts.

Energy analysis of the current situation of the kindergarten

The energy analysis of the kindergarten's current state focuses on its use of extra light fuel oil (EL-1) for heating and electricity sourced from the universal supplier. The analysis highlights the key parameters that reflect the kindergarten's energy consumption, system efficiency, and associated costs. Key parameters of the current energy system are summarized in Table 1.

Table 7. Energy parameters for the current heating of the kindergarten

EL-1	16 700	liter
	14 028	kg
	1.15 €/l	19 143.90 €
Thermal power	11.61	kg/kWh
Efficiency of the system	0.98	
Energy of heavy oil	162.87	MWh
Energy est. used	159.61	MWh

As shown in Table 1, the kindergarten utilizes 16 700 liters of EL-1 annually, equivalent to 14 028 kilograms based on the fuel's density. At a market price of €1.15 per liter, the annual expenditure for heating amounts to approximately €19 143.90 [4]. This demonstrates the significant cost burden of relying on fossil fuels for heating.

However, the environmental impact of using extra light fuel oil (EL-1) is substantial. Burning fossil fuels like EL-1 releases significant amounts of greenhouse gases, particularly CO_2, contributing to global warming and climate change. In addition to CO_2, the combustion of this oil also produces other harmful pollutants such as particulate matter (PM), nitrogen oxides (NOx), and sulfur dioxide (SO2), all of which degrade air quality and pose health risks to the surrounding community. These emissions contribute to the urban heat island effect, smog, respiratory diseases, and other environmental problems [5].

The thermal power of the fuel is determined to be 11.61 kg/kWh, which translates to a total energy content of 162.87 MWh. However, due to the operational efficiency of the heating system, which is estimated at 98%, the energy effectively utilized for heating purposes is approximately 159.61 MWh. While EL-1 provides a relatively high energy output, the environmental cost is disproportionately high. Transitioning away from this fuel source to cleaner energy solutions, such as heat pumps or photovoltaic systems, would significantly reduce the CO_2 emissions and pollutants associated with the heating process.

The electricity consumption of the kindergarten on a monthly basis is also a consideration, as it leads to additional CO_2 emissions when sourced from conventional grid electricity, often still reliant on fossil fuel-based power plants. According to the current electricity prices from the Universal Supplier, the annual electricity expenses total €6 172.56. Beyond the financial cost, continuing to use non-renewable sources for electricity further exacerbates the environmental footprint of the building, making it clear that integrating renewable energy solutions is crucial for reducing the overall environmental impact of the kindergarten.

Table 8. Tabular presentation of the kindergarten's monthly electricity consumption

Month	Monthly Electricity Consumption of the kindergarten [kWh]
January	2 341.82
February	2 101.86
March	2 171.40
April	2 183.15
May	1 979.43
June	1 806.07
July	1 943.19
August	2 246.82
September	1 810.97
October	2 095.00
November	2 016.65
December	2 303.62
Total	25 000.00

Case 1: Heating with extra light oil and electricity supply from the grid

In this scenario, the financial implications of heating the kindergarten are analyzed using extra light fuel (EL1) as the primary energy source for heating, supplemented by electricity procured from the electric grid. The analysis is conducted for two distinct electricity procurement models: one based on a Universal Supplier with regulated tariffs and the other on the free market, characterized by competitive pricing.

Extra light oil remains a widely used energy source in public buildings due to its established infrastructure and relatively high energy density. However, its rising costs and environmental implications underscore the need to carefully evaluate the feasibility of this energy solution, particularly when paired with electricity sourced from the electric grid. Given the dual reliance on fossil fuels and electricity, this case study provides insight into the economic challenges faced by public institutions operating under traditional heating systems, while laying the foundation for exploring more cost-effective and sustainable alternatives.

The detailed results of the financial analysis are presented in Table 3, summarizing the annual costs for electricity, extra light oil, and the total heating expenses under each procurement model.

Table 9. Financial analysis results for Case 1

	Universal Supplier		Free Market	
Price	246.9€/MWh	Heating with EL1	137.57€/MWh	Heating with EL1
Electricity		6 172.56 €		3 439.30 €
EL1		19 143.90 €		19 143.90 €
TOTAL		25 316.46 €		22 583.20 €

The average price for electricity from the Universal Supplier is taken as 246.9 €/MWh, based on the regulated procurement price published by the Energy and Water Services Regulatory Commission. The Free Market price of 137.57 €/MWh was calculated as the average of hourly electricity prices on the HUPX electricity exchange, with a 20% markup already included, reflecting the contractual conditions usually applied to public institutions.

The analysis reveals significant variations in electricity expenses between the two models:

- Under the Universal Supplier model, electricity costs amount to 6 172.56€, reflecting the fixed regulated tariffs applicable to public entities.
- In contrast, procurement through the free market yields lower electricity costs of 3 439.30€, representing a cost reduction of 2 733.26€, or approximately 44%, compared to the Universal Supplier. This reduction highlights the potential economic benefits of leveraging competitive pricing mechanisms on the electricity markets.

The cost of EL1, calculated based on an annual consumption of 16 700 liters at a unit price of 1.15€ per liter, is consistent across both models, amounting to 19 143.90€. This fixed expense constitutes the majority of the total heating costs, underscoring the economic burden of relying on fossil fuels for thermal energy.

The total annual costs for heating the kindergarten are derived as the sum of electricity and fuel expenses:

- For the Universal Supplier model, the total -energy cost is 25 316.46€, making it the more expensive option.
- For the free market model, the total -energy cost is 22 583.20€, reflecting a savings of 2 733.26€, or approximately 11%, compared to the Universal Supplier model.

Case 2: Heating with a thermal pump and electricity supply from the grid

In this case, the financial implications of transitioning to a thermal pump-based heating system, supplemented by electricity from the grid, are analyzed. The proposed system involves the installation of a 150 kW heat pump. This capacity was selected based on the total floor area of the kindergarten (1 200 m²) and considering the local climatic conditions, with design temperatures reaching as low as -15°C. The sizing aligns with standard engineering practices for heating public buildings under such environmental conditions. This analysis evaluates monthly and annual electricity consumption for the thermal pump, as well as the total electricity requirements of the building.

The thermal pump is designed to meet the building's heating needs, replacing the use of extra light oil (EL1). The estimated Coefficient of Performance (COP) for the heat pump is 3, indicating that for every unit of electrical energy consumed, the heat pump delivers three units of thermal energy. This efficiency metric is critical in determining the economic and environmental benefits of the proposed system [6].

The annual energy consumption for heating has been calculated based on the energy equivalent previously supplied by EL1, which totals 159.61 MWh. Using the COP of the heat pump, the required electrical energy for heating is calculated as follows [6]:

$$\mathbf{E_{electricity}} = \frac{\mathbf{E_{thermal}}}{\mathbf{COP}} \tag{1}$$

Where:
$\mathbf{E_{electricity}}$ Is the electricity consumption of the heat pump (kWh);
$\mathbf{E_{thermal}}$ Is the thermal energy demand (kWh);
COP is the coefficient of performance of the heat pump.

$$\mathbf{E_{electricity}} = \frac{\mathbf{159.610\ kWh}}{\mathbf{3}} = \mathbf{53.203\ kWh} \tag{2}$$

This value aligns with the annual electricity consumption for the heat pump presented in Table 4, validating the energy efficiency and sizing assumptions of the proposed system.

Table 4 provides a detailed breakdown of the monthly electricity consumption for the heat pump, alongside the total electricity requirements of the building under this heating configuration. The operation of the heat pump introduces an additional electricity load during the heating months (October–March), as shown in Table 4. The total electricity consumption of the heat pump amounts to 53 202.59 kWh, which, when added to the building's existing consumption, results in a combined annual electricity demand of 78 202.59 kWh.

Table 4. Monthly Electricity Consumption of the kindergarten with and without the Heat Pump, including the Heat Pump Consumption

Month	Monthly Electricity Consumption [kWh]	Electricity Consumption for the Heat Pump [kWh]	Monthly Electricity Consumption with a Heat Pump [kWh]
January	2 341.82	12 236.60	14 578.42
February	2 101.86	10 108.49	12 210.35
March	2 171.40	7 980.39	10 151.79
April	2 183.15	1 596.08	3 779.23
May	1 979.43	-	1 979.43
June	1 806.07	-	1 806.07
July	1 943.19	-	1 943.19
August	2 246.82	-	2 246.82
September	1 810.97	-	1 810.97
October	2 095.00	1 596.08	3 691.08
November	2 016.65	6 384.31	8 400.96
December	2 303.62	13 300.65	15 604.27
Total	25 000.00	53 202.59	78 202.59

The financial evaluation of this case demonstrates the cost implications of operating the heat pump under two electricity supply scenarios. The results are summarized in Table 6.

Table 5. Financial analysis results for Case 2

	Universal Supplier	Free Market
	Heating with electricity from the grid	
Electricity	19 308.41 €	10 758.48 €

When electricity is purchased from the Universal Supplier, the annual cost is 19 308.41 € [12]. When electricity is purchased from the free market, the cost is significantly reduced to 10 758.48 €, representing savings of 44.3% compared to the Universal Supplier.

When compared to the costs of heating with EL1 fuel and electricity supply in Case 1, the annual cost of 19 308.41 € under the Universal Supplier is 23.7% lower than the 25 316.46 € cost of heating with EL1 fuel. The Free Market option, with a cost of 10 758.48 €, achieves a 52.4% reduction in heating costs compared to Case 1.

As of December 2024, North Macedonia has not implemented a carbon tax. However, discussions and plans are underway to introduce such measures to align with global environmental standards. A carbon tax would impose a fee on CO_2 emissions, incentivizing reductions in greenhouse gas outputs.

In this analysis, a carbon tax rate of 65€ per metric ton of CO_2 is assumed, reflecting the average rates in European countries. For instance, as of April 2024, several European nations have implemented carbon taxes with varying rates, with some exceeding €60 per metric ton.

Incorporating a carbon tax influences the payback period by effectively increasing the cost of conventional energy sources that emit CO_2. By investing in a 40 kW photovoltaic system and a heat pump, the kindergarten reduces its carbon footprint, thereby avoiding potential carbon taxes. This avoidance translates into additional financial savings, shortening the payback period.

The total investment for the heat pump system amounts to €50 000, which is taken into account in the payback period calculation. Furthermore, the implementation of the heat pump results in an estimated annual CO_2 emission reduction of approximately 28.356 tons (Table 8). This figure was also included in the financial evaluation, using a reference CO_2 price of €65/ton, in line with EU ETS benchmarks.

So, the payback period for the investment is:

- 8.32 years for the Universal Supplier scenario, reduced to 6.37 years when accounting for CO_2 reduction.
- 4.23 years for the free market scenario, reduced to 3.66 years when accounting for CO_2 reduction.

The integration of a heat pump system proves to be a highly efficient and cost-effective heating solution for the building. The calculated energy savings and cost reductions emphasize the financial and environmental benefits of this transition. The significant difference in costs between the Universal Supplier and free market options highlights the importance of selecting competitive electricity pricing to maximize the system's economic advantages.

Case 3: Using the electricity produced from the 40 kW PV System, heating with a heat pump and additional electricity supply from the electric grid

According to the new amendments in the Regulation of Renewable Energy Sources in Macedonia from June 2021, the maximum installed capacity of a photovoltaic system on a roof for a legal entity that wants to acquire prosumers status is 40 kW. Therefore, this case analyzes the installation of a 40 kW photovoltaic (PV) system alongside a 150 kW heat pump to meet the heating demands of the kindergarten in Makedonski Brod. The PV system is designed to primarily supply electricity for the heat pump and the building's other energy needs, with any surplus electricity sold either through the Universal Supplier or on the free market [7]. The goal of this case is to evaluate the financial and energy efficiency benefits achieved by combining on-site renewable energy production with efficient heating technology.

In addition to financial and energy efficiency benefits, this solution significantly contributes to environmental protection by reducing CO_2 emissions [8]. The transition from conventional fossil fuel-based heating to renewable energy sources decreases the carbon footprint of the kindergarten. By harnessing solar energy and utilizing an energy-efficient heat pump, the kindergarten avoids the combustion of non-renewable energy resources, promoting cleaner air and aligning with global efforts to mitigate climate change.

The total investment for the proposed system amounts to €75 000, comprising €50 000 for the heat pump system and €25 000 for the photovoltaic system. These figures represent turnkey prices, covering all costs related to equipment procurement, installation, commissioning, integration with the building's existing infrastructure (including plumbing and heating distribution), and all auxiliary works required to bring the systems into full operation. Figure 1 shows the designed PV system on the kindergarten in the PV*SOL premium.

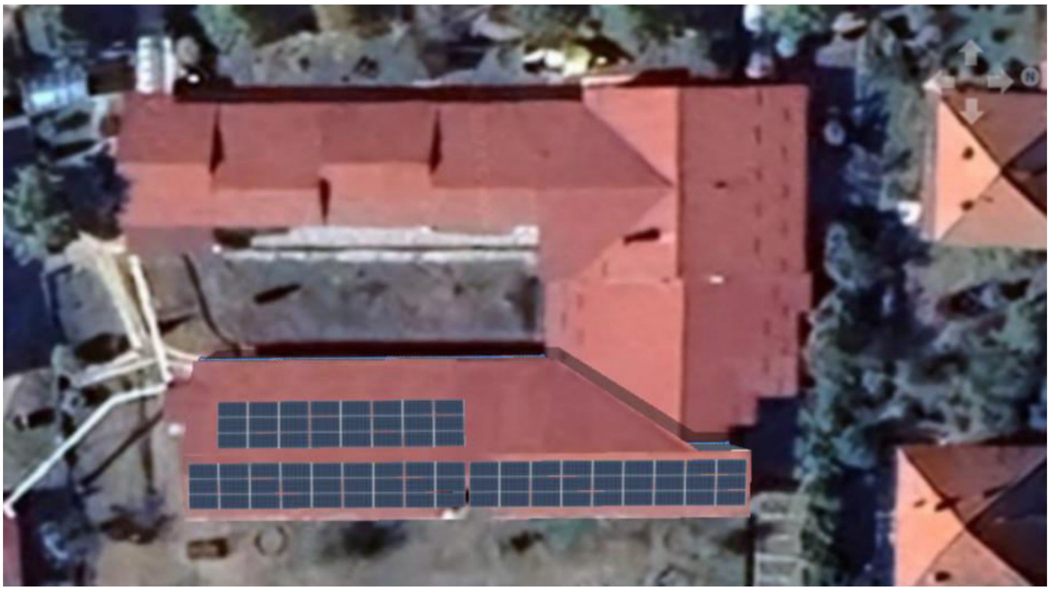

Figure 4. Visual presentation of the designed photovoltaic system

According to the PV*SOL premium simulation results, the PV system is projected to generate 53 764 kWh of electricity annually. The calculations are performed on an hourly basis and, based on the hourly production of electricity from the PV system and the hourly electricity consumption of the kindergarten, the total electricity consumption of the kindergarten, including the consumption of the heat pump, will decrease from 78 202.59 kWh to 54 519.69 kWh annually [9,10]. This indicates that 23 682.9 kWh, or approximately 30.28% of the annual electricity needs, are met by the PV system, with the remaining electricity supplied by the electric grid. Additionally, the PV system generates 30 081.1 kWh of surplus electricity on an annual basis. The monthly energy performance of the system is summarized in Table 7.

Table 6. Monthly electricity consumption and production balance with a 40 kW PV system and a heat pump

Month	Monthly Electricity Consumption [kWh]	Monthly Electricity Consumption with a Heat Pump [kWh]	Monthly Electricity Production from 40 kW PV System [kWh]	Monthly Electricity Consumption with 40kW PV System [kWh]	Surplus Electricity from the PV System [kWh]
January	2 341.82	14 578.42	1 914.45	12 675.23	8.45
February	2 101.86	12 210.35	2 819.28	9 334.17	83.56
March	2 171.40	10 151.79	4 327.35	6 258.75	486.17
April	2 183.15	3 779.23	5 235.03	1 355.69	2 635.76
May	1 979.43	1 979.43	6 618.50	558.87	5 404.03
June	1 806.07	1 806.07	7 154.04	467.83	5 673.95
July	1 943.19	1 943.19	7 082.95	539.19	5 792.83
August	2 246.82	2 246.82	6 544.22	669.67	4 930.25
September	1 810.97	1 810.97	4 798.05	656.64	3 530.96
October	2 095.00	3 691.08	3 556.07	1 555.22	1 416.03
November	2 016.65	8 400.96	2 104.84	6 432.16	112.68
December	2 303.62	15 604.27	1 609.22	14 016.26	6.43
Total	25 000.00	78 202.59	53 764.00	54 519.69	30 081.09

Table 7 highlights the monthly electricity consumption under three scenarios: the baseline electricity consumption, consumption with the heat pump, and consumption with the integrated PV system. Additionally, it outlines the surplus electricity produced by the PV system, which can either be sold to the Universal Supplier or on the free market. Figure 2 shows the current monthly electricity consumption of the kindergarten, the electricity consumption with a heat pump and the electricity consumption with a heat pump and a PV system with the installed capacity of 40 kW. As can be seen, the new electricity consumption in the winter months is noticeably increased, due to the heat pump electricity consumption which is presented in Table 4.

Table 7. Monthly electricity distribution for the heat pump and kindergarten loads from PV and the grid

Month	Electricity Consumption for the Heat Pump [kWh]	Electricity from the PV System for the Heat Pump [kWh]	Grid Electricity for the Heat Pump [kWh]	Electricity from the PV System for kindergarten electricity needs [kWh]
January	12 236.60	1 890.33	10 346.27	12.85
February	10 108.49	2 824.63	7 283.86	51.55
March	7 980.39	3 669.86	4 310.53	223.18
April	1 596.08	1 095.55	500.53	1 327.99
May	0	0	0	1 420.56
June	0	0	0	1 338.24
July	0	0	0	1 404.00
August	0	0	0	1 577.15
September	0	0	0	1 154.33
October	1 596.08	1 001.14	594.94	1 134.73
November	6 384.31	1 883.25	4 501.07	85.56
December	13 300.65	1 574.53	11 726.12	13.48
Total	53 202.59	13 939.28	39 263.31	9 743.63

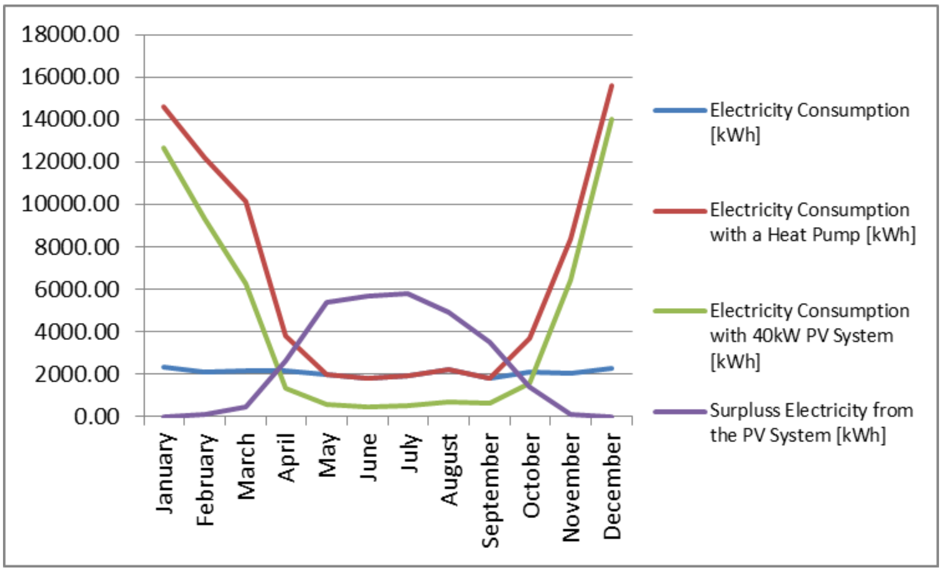

Figure 5. Graphical presentation of the current electricity consumption of the kindergarten, electricity consumption with heat pump, electricity consumption with 40 kW PV System and heat pump and surplus electricity from the PV System.

Figure 3 illustrates the electricity consumption of the kindergarten with a heat pump and the predicted electricity production from the proposed PV system. As can be seen, in the heating season, additional electricity will have to be procured to meet the energy needs of the heat pump with low electricity surpluses from the PV system, and in the summer months there are large surpluses of electricity that will be sold and generate additional income for the kindergarten.

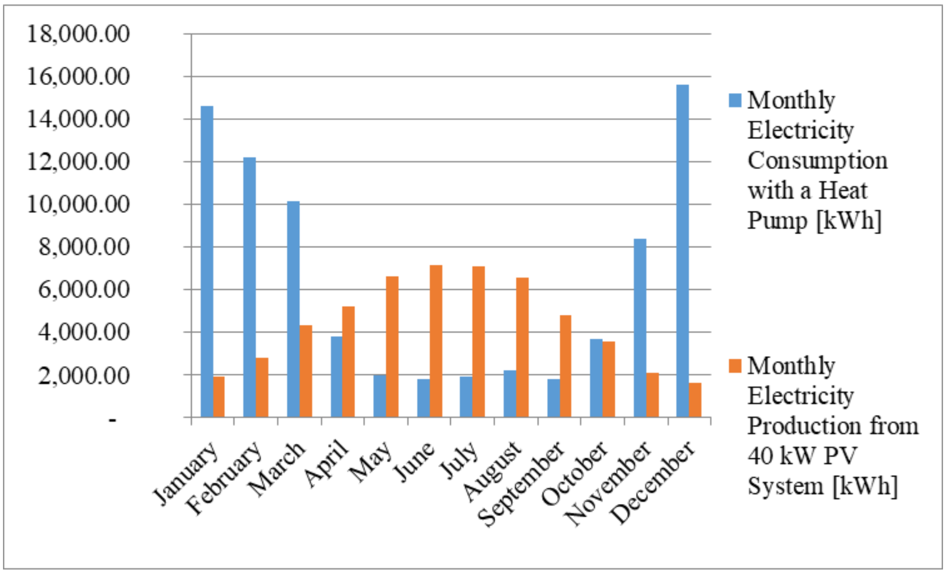

Figure 6. Graphical presentation of the kindergarten's electricity consumption with a heat pump and the predicted electricity production from the PV System

The financial evaluation considers both scenarios for selling surplus electricity, as shown in Table 8.

Table 10. Financial analysis results for Case 2

	Universal Supplier	Free Market
	Heating with electricity + PV System 40kW	
Electricity	11 807.81 €	4 718.74 €

In the Universal Supplier scenario, the total annual cost for electricity consumption with the integration of the 40 kW PV system is 11 807.81 € [11]. This cost reflects the reduced dependency on grid electricity due to the energy generated by the PV system, which offsets a significant portion of the heat pump's electricity requirements. The remaining electricity demand is supplied by the Universal Supplier at a standard tariff rate.

In the free market scenario, the annual cost for electricity with the 40 kW PV system is significantly lower, amounting to 4 718.74 € [12]. This lower cost is due to the free market electricity prices being more competitive than those of the Universal Supplier. Additionally, the surplus electricity generated by the PV system can be sold back to the market at favorable rates, further reducing the overall costs.

The total annual cost savings and revenue from selling surplus electricity directly impact the investment's financial viability.

The payback period for the investment is:

- 5.55 years for the Universal Supplier scenario, reduced to 4.66 years when accounting for CO_2 reduction.
- 4.20 years for the free market scenario, reduced to 3.67 years when accounting for CO_2 reduction.

RESULTS AND DISCUSSION

The three cases analyzed in this study, Case 1 (Heating with EL1), Case 2 (Heating with electricity from the grid using a heat pump), and Case 3 (Heating with electricity using a heat pump and produced electricity from 40 kW PV system) demonstrate significant differences in terms of cost efficiency and payback periods.

Heating with EL1 incurs the highest annual cost due to the high price of extra light oil, amounting to 24 650 €, combined with the inefficiency of the heating system. Switching to electricity from the grid for the energy requirements of the heat pump significantly reduces energy costs. Under the universal supplier scenario, the annual energy costs are reduced to 19 308.41 €, while opting for the free market scenario further lowers costs to 10 758.48 €. Incorporating a heat pump alongside a 40 kW PV system results in the lowest annual energy costs. In this case, the universal supplier scenario brings the costs down to 11 807.81 €, and the free market scenario reduces them further to 4 718.74 €, making it the most economically favorable option.

Regarding the payback period, no payback analysis is applicable for heating with EL1 as it serves as the baseline scenario. For the grid electricity option, the payback periods are 5.55 years under the universal supplier scenario and 4.20 years under the free market scenario. These periods are further reduced to 4.66 years and 3.67 years, respectively, when potential CO_2 taxation is factored in. The integration of the PV system improves the payback periods due to the significant cost savings it offers. In this case, the universal supplier scenario achieves payback in 5.55 years, while the free market scenario offers the fastest payback at 4.20 years. These periods are further reduced when accounting for CO_2 taxation, to 4.66 years and 3.67 years, respectively.

The environmental impact of transitioning from extra light oil (EL1) to electricity and renewable energy integration has been analyzed through annual CO_2 emission calculations. The results are presented in Table 9 and discussed in detail to highlight the implications of each heating scenario.

Table 11. Annual CO_2 emissions (kg) for Different Heating Scenarios

<table>
<tr><th colspan="6">CO_2 emissions [kg]</th></tr>
<tr><th></th><th>Heating with EL1</th><th>Heating with electricity</th><th>Heating with electricity +PV 40kW</th><th>DIFFERENCE 2 & 3</th><th>DIFFERENCE 2 & 4</th></tr>
<tr><td>Electricity</td><td>24 650.00</td><td>24 650.00</td><td rowspan="3">27 585.86</td><td rowspan="3">28 356.98</td><td rowspan="3">39 599.61</td></tr>
<tr><td>EL1</td><td>42 535.47</td><td>14 178.49</td></tr>
<tr><td>TOTAL</td><td>67 185.47</td><td>38 828.49</td></tr>
</table>

Case 1: This scenario represents the highest environmental burden due to the exclusive reliance on EL1 oil as the primary energy source. The combustion of EL1 oil generates 67 185.47 kg of CO_2 emissions annually, contributing significantly to air pollution and the greenhouse effect. EL1 oil is known to release harmful pollutants, including sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM), further degrading air quality and posing risks to human health and the environment.

Case 2: Transitioning to grid electricity considerably lowers the carbon footprint, reducing annual CO_2 emissions to 38 828.49 kg, due to the lower emissions intensity of grid electricity compared to EL1 oil. However, reliance on grid electricity still depends partially on non-renewable energy sources, leaving room for improvement in achieving sustainability goals.

Case 3: The implementation of a photovoltaic (PV) system and a heat pump marks the most environmentally friendly scenario. By significantly reducing grid dependency and replacing fossil fuel-based heating, this combination cuts CO_2 emissions to their lowest level. The system not only meets energy demands efficiently but also offsets emissions by generating renewable energy. This approach aligns with global decarbonization goals and supports efforts to combat climate change.

Case 3 clearly outperforms Cases 1 and 2 in terms of operational cost savings, environmental impact, and payback period. The combination of renewable energy from the PV system and the efficiency of a heat pump presents a future-proof solution for reducing costs and emissions in public buildings. Case 3 demonstrates that investing in renewable energy and energy-efficient systems is not only environmentally responsible but also economically advantageous.

Switching to grid electricity for the heat pump presents a viable transition option, reducing annual CO_2 emissions by 28 356.98 kg, which equates to a decrease of over 42%. This substantial reduction highlights the immediate environmental benefits of electrification, even in scenarios where the electricity grid is not fully decarbonized. By replacing EL1 with grid electricity, substantial progress can be made toward reducing the carbon footprint of heating systems.

The integration of a 40 kW photovoltaic system further amplifies the environmental benefits, achieving an additional reduction of 11 242.63 kg CO_2 emissions annually. Compared to the baseline emissions of the EL1 system, the combined impact of grid electricity and the PV system results in a total reduction of 39 599.61 kg CO_2 per year. This outcome underscores the critical role of on-site renewable energy generation in minimizing environmental impact and supports the adoption of photovoltaic systems as an integral part of sustainable energy solutions.

CONCLUSION

The analysis conducted provides a comprehensive evaluation of the environmental, financial, and operational implications of transitioning to more sustainable heating systems for a public building. By comparing three distinct scenarios: heating with extra light oil (EL1), grid electricity, and a combination of grid electricity with a 40 kW photovoltaic (PV) system, the study offers valuable insights into the feasibility and impact of energy-efficient transformations [13].

The third scenario, which integrates a 40 kW PV system with the heating system, presents the most sustainable and cost-effective solution. By leveraging on-site renewable energy, this approach achieves a remarkable reduction of 39 599.61 kg of CO_2 annually compared to the baseline scenario. This significant decrease demonstrates the potential of photovoltaic systems to address both local and global environmental challenges. The PV system not only offsets CO_2 emissions but also reduces dependency on grid electricity, leading to a lower carbon footprint for the building. Financially, this scenario offers substantial cost savings, particularly when surplus electricity is sold on the free market. The payback periods for this investment, ranging from 4.20 to 5.55 years depending on market conditions and potential CO_2 taxation, further solidify its viability.

The transition from EL1 oil to renewable and efficient energy systems achieves remarkable reductions in CO_2 emissions. Compared to Case 1, Case 3 avoids approximately 28 356.98 kg of CO_2 emissions annually, demonstrating the potential of renewable energy systems to drastically mitigate environmental impacts. The avoided emissions are equivalent to the annual carbon sequestration of approximately 1 500 mature trees or the emissions from burning over 11 300 liters of diesel fuel.

From an environmental perspective, the integration of a PV system and efficient heating technologies aligns with global decarbonization goals and the European Green Deal. By adopting such solutions, public buildings can play a pivotal role in reducing CO_2 emissions, promoting energy independence, and fostering a sustainable future [13]. This scenario exemplifies the dual benefits of reducing operational costs while significantly mitigating environmental impacts, making it a model for future energy transitions in public infrastructure.

In conclusion, this research provides a robust framework for evaluating the transition to sustainable heating systems in public buildings. The findings not only highlight the environmental and economic benefits of replacing EL1 with electrified systems but also underscore the strategic importance of integrating renewable energy sources like photovoltaics. The results demonstrate that adopting renewable energy technologies leads to significant reductions in CO_2 emissions, enhances air quality, and contributes to global climate targets. As Macedonia progresses toward aligning its energy and environmental policies with European standards, the adoption of such solutions will be instrumental in achieving national and regional sustainability goals. This study serves as a compelling call to action for policymakers, energy planners, and building managers to prioritize investments in clean, efficient, and environmentally friendly energy systems for a sustainable future.

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