Integration of Solar PV and Battery Energy Storage Systems Towards a Sustainable Street Lighting

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Abstract— **This paper presents and applies a model for optimizing hybrid solar PV and battery energy storage systems (BESS) for street lighting, focusing on the challenges of meeting nighttime electricity demand with a daytime-only renewable energy source. The model determines optimal system sizing for solar PV and BESS by considering various parameters and technical constraints. A case study based on a typical Portuguese municipality is used to evaluate the economic and technical feasibility of this hybrid sourcing. The significant time difference between solar electricity generation and street lighting consumption imposes substantial energy storage capacity to bridge this mismatch. This research provides valuable insights into designing sustainable and cost-effective street lighting systems, enabling municipalities to reduce their reliance on the grid and transition towards greater energy independence. The results offer a framework for evaluating the economic viability under various cost and operational conditions.**

Index Terms-- **Battery Energy Storage Systems, Decarbonization, Energy Efficiency, Hybrid Systems Optimization, Solar PV, Street Lighting.**

I. INTRODUCTION

In typical Portuguese municipalities, public lighting accounts for more than 50% of total electricity consumption, with the remaining 50% attributed to municipal buildings, schools, and other facilities. During last years, the Portuguese electricity consumption for public lighting represented approximately 3% of the total electricity consumed, a highly significant share accounting for 1267 GWh, distributed across 3.32 million lighting points [1]. Globally, street and road lighting, accounts for approximately 1.3% of total electricity consumption in Europe [2] and around 1% of global electricity consumption [3]. The evolution of street lighting toward sustainable, cost-effective, and energy-efficient solutions has driven extensive research into hybrid renewable energy systems integrating solar, wind, and energy storage technologies. The need to transition from grid-dependent street lighting to renewable-powered smart lighting has led to innovations in hybrid PV-wind systems, BESS, and IoT-based management strategies.

Several studies have investigated IoT-enabled smart lighting and real-time monitoring. Authors in [4] examines IoT-based adaptive highway lighting, integrating solar and wind energy to optimize illumination based on real-time traffic density and environmental conditions. In [5] is proposed an IoT-based real-time monitoring system using ESP32 microcontrollers and cloud platforms to detect faults and optimize energy performance in solar-powered streetlights. Similarly, [6] integrates IoT for dynamic energy balancing between solar and wind sources, significantly improving system reliability and reducing maintenance costs.

Hybrid solar-wind systems have been widely studied to enhance power stability and reduce reliance on grid electricity. The study in [7] develops a multi-source hybrid system, integrating solar, wind, and piezoelectric energy from vehicle-induced mechanical stress, ensuring continuous lighting in high-traffic areas. A MATLAB/Simulink-based modeling to optimize hybrid solar-wind street lighting is developed in [8], showing that wind energy reduces energy storage dependency and improves efficiency. Also, in [9] is presented a modular hybrid PV-wind streetlight system with an intelligent energy management controller, demonstrating that wind turbines can significantly reduce energy storage requirements in moderate-wind locations.

To improve energy storage and economic viability, [10] explores an optimized hybrid system with centralized energy storage, showing that annual costs decrease by 47% compared to decentralized systems. Research made by [11] introduces a storage-free hybrid streetlight system, integrating solar PV and thermal energy harvesting, eliminating BESS maintenance costs while ensuring long-term sustainability. In [12], authors investigate a hybrid wind-solar power generation system for highway streetlights, demonstrating that vertical-axis wind turbines (VAWTs) and PV panels ensure autonomous operation and improved energy reliability.

The economic feasibility of hybrid renewable street lighting has been a critical area of research. Study [13] uses PVsyst software to optimize a centralized PV-powered street lighting system, reducing CO_2 emissions by 157.9 tons annually. In the same field [14] evaluates the techno-economic feasibility of using vehicle-induced wind turbulence for energy generation, showing that the system achieves a payback period of 3.2 years with a 221% return on investment over ten years. By integrating plug-in electric vehicle (PEV) charging stations, [15] expands the functionality of solar-powered street lighting, utilizing MATLAB/SIMULINK-based energy optimization to maximize power efficiency and reduce grid dependency. Further studies have examined experimental validation and real-world applications. For instance, [16] develops a hybrid microgeneration streetlight system, integrating a Savonius VAWT within the streetlight post, validated through wind tunnel testing to confirm its feasibility for urban off-grid street lighting. Grid-connected and off-grid PV-wind hybrid systems are evaluated in [17] using MATLAB, Autodesk Inventor, and ANSYS FLUENT, demonstrating that grid-connected solutions achieve the shortest payback period, while off-grid systems enhance energy independence. The economic performance of standalone PV-powered street lighting is assessed in [18] using the annual equivalent cost method, revealing that PV systems reduce costs by 43.65% compared to traditional grid-connected lighting, though BESS lifespan and maintenance remain challenges.

While previous studies have examined hybrid solar-wind street lighting, IoT-based smart control mechanisms, and economic feasibility assessments, our research addresses a critical gap by proposing an optimized investment model for integrating solar PV and BESS for public street lighting. Unlike standalone solar-wind solutions, this study explores how grid-connected BESS can store surplus solar energy generated during the day for use at night, effectively bridging the mismatch between solar production and streetlight demand. By introducing a model for sizing hybrid PV+BESS for street lighting systems, this study advances prior research by demonstrating the economic and technical feasibility of fully renewable public street lighting. Through investment analysis and energy optimization, it provides valuable insights for transitioning toward 100% renewable infrastructure.

II. METHODOLOGY

The present study develops and implements a Renewable Energy Community (REC) model that evolves from a previous modelling presented in [19]. This new setting simulates the realization of a solar photovoltaic plus storage project to supply Lighting systems under the REC framework. It also contemplates a post-processing module that computes the monetization of the surplus energy, not consumed and not stored, at market marginal prices and explores typical financial indicators. The post-processing module does not influence the optimal solution identified without the revenue from sales. The model determines the optimal investment decision in PV and storage for one REC member to serve the demand of another REC member, by minimizing the annualized costs of the electricity supply, as presented in the constrained optimization problem (1) to (13). The mathematical model is designed to incorporate multiple production facilities and multiple consumers.

The objective function C represents the total cost of sourcing the lighting system. This function, that we aim to minimize, includes: (i) the annualized investment costs; (ii) the cost of the electricity sourcing form the grid; (iii) the variable costs of sharing electricity from generation to demand; and (iv) the revenues coming from the surplus of electricity generation that is sold to the grid. Being a revenue, this last term is included in the objective function as a negative cost.

$$\begin{aligned} C = \sum_{i}\sum_{r} CRF_{i,r} \cdot CAPEX_{i,r} \\ + \sum_{t}\sum_{i} T_{i,t} \cdot buyGrid_{i,t} + SCME^{V} \cdot buyREC_{i,t} \\ - S_{t}^{DAM} \cdot sellGrid_{i,t} \end{aligned} \tag{1}$$

The capital recovery factor of each renewable technology r (CRF_r) is given the following formula.

$$CRF_r = \frac{\alpha\,(1+\alpha)^{\tau_r}}{(1+\alpha)^{\tau_r} - 1} \tag{2}$$

where α is the discount rate, τ_r is the lifetime of technology r, $CAPEX_r$ is the capital expenditure of technology r, $T_{i,t}$ is the electricity tariff of REC member i in period t, $buyGrid_{i,t}$ is the electricity supplied from the grid to REC member i in period t, $SCME^V$ is the variable cost of the Self-Consumption Managing Entity ($SCME$), $buyREC_{i,t}$ is the electricity shared from other REC members to member i in period t, S_t^{DAM} is the day-ahead market (DAM) price for selling electricity surplus to the grid in period t and $sellGrid_{i,t}$ is the electricity sold to the grid by REC member i in period t.

$$\begin{aligned} D_{i,t} = \sum_{r} R_{r,t} P_{i,r} + buyGrid_{i,t} + buyREC_{i,t} \\ + BESSout_{i,t} - BESSin_{i,t} - sellREC_{i,t} - sellGrid \end{aligned} \tag{3}$$

The optimization model is implemented as a mixed integer linear programming problem using the General Algebraic Modeling System (GAMS) [20] using constraints (3) to (13).

Electricity Balance constraint (3) means that each REC member's electricity demand in period t equals their self-generated renewable power, plus electricity purchased from the grid and received from other members, minus any electricity shared with other members or sold to the grid, minus the electricity used to charge their BESS, plus electricity discharged from their BESS. where $R_{r,t}$ is the normalized generation profile of renewable technology r in period t, $P_{i,r}$ is the installed capacity of REC member i in renewable technology r, $buyREC_{i,t}$ is the electricity shared from other REC members to member i in period t, $sellREC_{i,t}$ is the electricity shared by REC member i with other REC members in period t and $BESSin_{i,t}$ is the electricity used for charging the BESS of REC member i in period t, $BESSout_{i,t}$ is the electricity used from discharging the BESS of REC member i in period t.

$$SoC_{i,t} = SoC_{i,t-1} + BESSin_{i,t} \cdot \sqrt{EFF_{BESS}} - \frac{BESSout_{i,t}}{\sqrt{EFF_{BESS}}} \tag{4}$$

BESS State of Charge Constraint (4): The BESS state of charge in period t depends on its state in period $t-1$, plus the electricity charged, minus the electricity discharged. In this constraint, $SoC_{i,t}$ is the state of charge of REC member i BESS in period t, $SoC_{i,t-1}$ is the state of charge of REC member i BESS in period that precedes t and EFF_{BESS} is the round-trip efficiency of the $BESS$.

$$\sum_i buyREC_{i,t} = \sum_i sellREC_{i,t} \tag{5}$$

REC Energy Exchanges Constraint (5): Internal electricity exchanges among members must net to zero; the total electricity sent by some members equals the total electricity received by others in each period t.

$$P_{i,r_{min}} \leq P_{i,r} \leq P_{i,r_{max}} \tag{6}$$

$$P_{i,BESS_{min}} \leq P_{i,BESS} \leq P_{i,BESS_{max}} \tag{7}$$

$$E_{i,BESS_{min}} \leq E_{i,BESS} \leq E_{i,BESS_{max}} \tag{8}$$

Capacity Limits Constraints (6) – (8): Each REC member's renewable and BESS peak power capacities, as well as the BESS energy storage capacity, must lie between specified minimum and maximum bounds. In this constraint $P_{i,r_{min}}$ and $P_{i,r_{max}}$ are, respectively, the minimum and maximum installed capacity of REC member i in renewable technology r, $P_{i,BESS_{min}}$ and $P_{i,BESS_{max}}$ are, respectively, the minimum and maximum installed capacity of REC member i in $BESS$ and $E_{i,BESS_{min}}$ and $E_{i,BESS_{max}}$ are, respectively, the minimum and maximum energy storage capacity of REC member i in $BESS$.

$$SoC_{i,t} \leq E_{i,BESS} \tag{9}$$

$$\begin{gathered} buyGrid_{i,t}\ , buyREC_{i,t}\ , sellREC_{i,t}, \\ sellGrid_{i,t}, BESSin_{i,t}, BESSout_{i,t}, SoC_{i,t} \geq 0 \end{gathered} \tag{10}$$

SoC constraint (9) imposes BESS state of charge cannot exceed its installed energy storage capacity. Here the $E_{i,BESS}$ is the energy storage capacity of REC member i in $BESS$.Non-Negative Flows Constraints (10): All flow variables, such as electricity purchased, sold, or shared, must be non-negative.

$$BESSin_{i,t} \ \leq BESSch_{i,t} \cdot P_{i,r} \tag{11}$$

$$BESSout_{i,t} \leq BESSds_{i,t} \cdot P_{i,r} \tag{12}$$

$$BESSch_{i,t} + BESSds_{i,t} \leq 1 \tag{13}$$

Charge/Discharge Constraints (11) – (13) sates that BESS cannot charge and discharge during the same period. In this constraint, $BESSch_{i,t}$ and $BESSds_{i,t}$ are binary variables for the charging and discharging status of $BESS$ from REC member i in period t.

III. CASE STUDY

As presented in Figure 1, a REC concept with two members (REC1, REC2) is used as a case study in which we apply the model described in the previous section. Thus, REC2 is a Lighting electricity consumer and REC1 is an electricity producer holing a PV plant equipped with an energy storage system. REC1 can invest in PV and in BESS to reduce electricity sourcing costs paid by REC2.

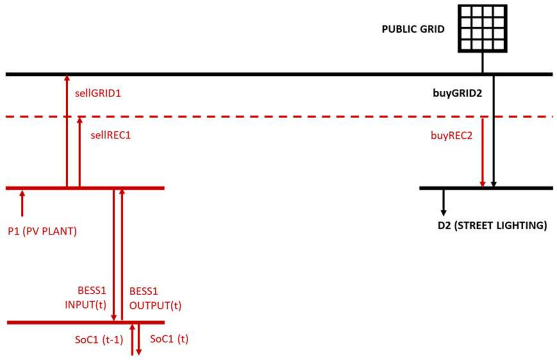

Figure 1. Electricity flows of the lighting system supplied by the hybrid system PV and BESS

A. Input Data

A normalized profile for the PV generation (in Portugal) is used for a full year which is scaled-up according to the installed capacity suggested by the model. The main features of the PV and BESS technologies are presented in Table I.

TABLE I. DATA USED FOR PV AND BESS TECHNOLOGIES.

Technology	CAPEX Scenarios	Lifetime	a	EFF
PV	1200, 1000, 800, 600, 400 EUR/kW	20 years	5%	-
BESS	500, 400, 350, 300, 200, 100 EUR/kWh	20 years	5%	90%

where α is the discount rate and EFF the roundtrip efficiency of the BESS. Multiple scenarios for the capital expenditure (CAPEX) of PV and BESS are considered from the highest to the lowest value, representing the potential technological development of these technologies. For the Base Case scenario, we take the CAPEX of PV at 1000 EUR/kW and the CAPEX of BESS at 200 EUR/kWh, that corresponds to the current standard CAPEX values. The peak demand of the street lighting under consideration is 3174 kW with a yearly consumption of 13 GWh. For the grid sourcing, an electricity price of 140 EUR/MWh is used as a typical value. Revenue from surplus electricity sold to the grid is not included in the objective function to prevent any impact on the optimal investment decisions for PV and BESS. Instead, this contribution is incorporated into the post-optimization process as an additional revenue stream, based on the average monthly prices from the day-ahead Iberian market, as presented in Table II.

TABLE II. AVERAGE ELECTRICITY PRICES TO VALUE THE SURPLUS SOLD TO THE GRID (S_t^{DAM}), IN EUR/MWH

Month	Price	Month	Price
January	62.42	July	84.42
February	120.81	August	88.07
March	80.96	September	93.74
April	69.26	October	80.87
May	68.48	November	56.93
June	86.03	December	64.98

IV. RESULTS

Results were obtained by simulating an entire year of operation with an hourly resolution using the model detailed in Section II. The optimal investment decisions for solar PV and BESS are presented in Table III and Table IV , respectively, for all scenarios. The Base Case results are highlighted with a black border. Blank cells in the tables indicate scenarios where sourcing for street lighting with Solar PV and BESS is not economically viable.

TABLE III. OPTIMAL CAPACITY OF SOLAR PV IN THE DIFFERENT SCENARIOS, IN MW

	PV 1200	PV 1000	PV 800	PV 600	PV 400
BESS 500					
BESS 400				5.9	7.4
BESS 350			5.3	6.3	7.9
BESS 300	4.0	4.7	5.6	6.8	8.3
BESS 200	4.9	**5.4**	6.2	7.6	9.2
BESS 100	5.4	6.1	7.0	8.6	10.4

TABLE IV. OPTIMAL CAPACITY OF BESS IN THE DIFFERENT SCENARIOS, IN MWH

	PV 1200	PV 1000	PV 800	PV 600	PV 400
BESS 500					
BESS 400				24.8	26.8
BESS 350			25.5	26.7	28.4
BESS 300	23.0	25.2	26.8	28.5	30.0
BESS 200	28.5	**29.2**	30.2	32.3	33.7
BESS 100	31.9	33.2	34.6	36.8	38.6

It can be observed that the hybrid system (PV+BESS)is not viable for a BESS CAPEX of 500 EUR/kWh, regardless of the PV CAPEX. For scenarios where the hybrid system is viable, the investment decisions range from 4.0 to 10.4 MW in solar PV, with BESS energy capacity ranging from 23.0 to 38.6 MWh. In the Base Case Scenario, with a PV CAPEX of 1000 EUR/kW and a BESS CAPEX of 200 EUR/kWh, hybrid sourcing proves to be clearly viable, requiring an investment of 5.4 MW in PV and 29.2 MWh in BESS.

For illustrative purposes, the hourly results of the Base Case Scenario for a 4-day winter period and a 4-day summer period are presented in Figure 2 and Figure 3 , respectively.

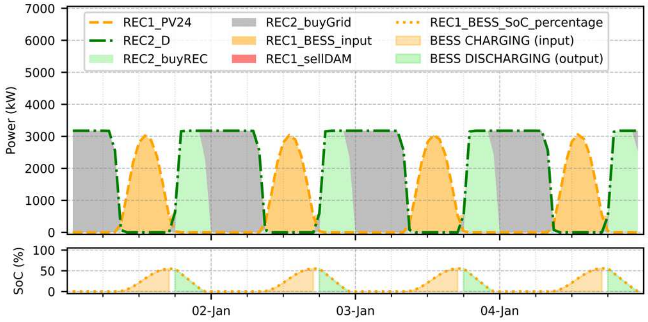

Figure 2. Hourly results of a 4-day winter period. The upper chart shows the hourly power flows of solar PV generation and the Lighting demand sourcing. The lower chart shows the hourly BESS State of Charge dynamics.

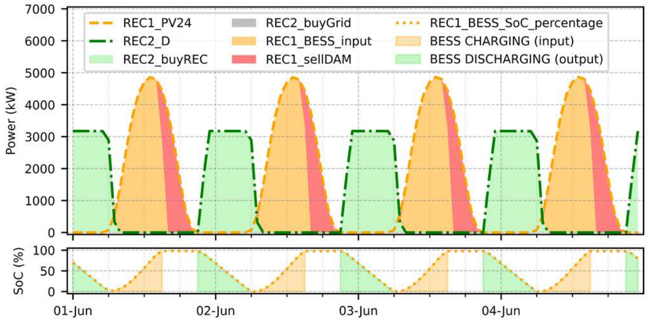

Figure 3. Hourly results of a 4-day Summer period. The upper chart shows the hourly power flows of solar PV generation and the Lighting demand sourcing. The lower chart shows the hourly BESS State of Charge dynamics.

From these figures, one can argue that the hybrid system is undersized for the Winter (Figure 2) conditions, with supply partially coming from the grid, and oversized for the Summer (Figure 3) conditions, with the hybrid system exceeding the street lighting consumption and generation a surplus that can be sold as an extra revenue. It is also useful to compute the self-sufficiency of the system that represents the share of the street lighting consumptions that is supplied by renewable energy from the hybrid system. This is shown in Table V. The self-sufficiency in the Base Case Scenario is 68% which means that only 32% needs to be bought from the grid.

TABLE V. SELF-SUFFICIENCY INDEX IN THE DIFFERENT SCENARIOS

	PV 1200	PV 1000	PV 800	PV 600	PV 400
BESS 500					
BESS 400				63%	70%
BESS 350			62%	67%	74%
BESS 300	53%	59%	65%	71%	77%
BESS 200	65%	**68%**	72%	78%	83%
BESS 100	70%	74%	78%	84%	89%

The results show that the hybrid system can be economically feasible under certain market circumstances. Its merit can be quantified in several metrics, being the main criteria the ability to save costs compared to the full grid supply costs (1.82 MEUR/year). The overall economic savings considering the revenues from the self-sufficiency, the surplus sold to the grid and the cost of the investment in solar PV and BESS, is presented as annual cost savings in Table VI.

TABLE VI. ANNUAL COST SAVINGS ACHIEVED BY THE SOURCING FROM THE HYBRID SYSTEM (PV+BESS) IN THE DIFFERENT SCENARIOS, IN KEUR

	PV 1200	PV 1000	PV 800	PV 600	PV 400
BESS 500					
BESS 400				72	181
BESS 350			85	177	296
BESS 300	33	103	190	294	416
BESS 200	253	333	430	546	685
BESS 100	497	591	699	829	984

The financial indexes Net Present Value (NPV) for 20-year analysis and Internal Rate of Return (IRR) are computed for the same set of scenarios, including the Base Case Scenario. These values are presented in Table VII and Table VIII.

TABLE VII. NET PRESENT VALUE AT 5% DISCOUNT RATE, IN MEUR

	PV 1200	PV 1000	PV 800	PV 600	PV 400
BESS 500					
BESS 400				3.59	6.01
BESS 350			2.40	3.77	6.36
BESS 300	0.88	1.49	2.54	4.25	6.78
BESS 200	1.21	**1.86**	2.98	5.02	7.88
BESS 100	1.54	2.47	3.77	6.37	9.48

TABLE VIII. INTERNAL RATE OF RETURN

	PV 1200	PV 1000	PV 800	PV 600	PV 400
BESS 500					
BESS 400				8.0%	9.8%
BESS 350			7.1%	8.2%	10.2%
BESS 300	5.9%	6.4%	7.3%	8.7%	10.9%
BESS 200	6.2%	**6.9%**	8.0%	9.9%	12.8%
BESS 100	6.8%	7.9%	9.5%	12.5%	16.7%

The hybrid system (PV+BESS) demonstrates a NPV ranging from 0.88 to 9.48 million euros and an IRR between 5.9% and 16.7%. In the Base Case Scenario, hybrid sourcing is evidently viable, with an NPV of 1.86 million euros and an IRR of 6.9%.

The isocontour plots for NPV and IRR are presented in Figure 4 and Figure 5, respectively.

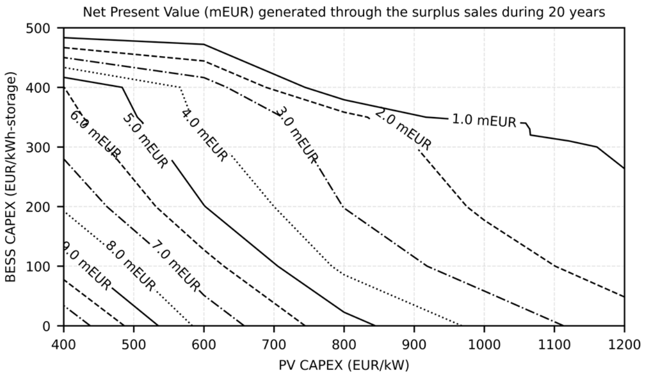

Figure 4. Isocontour of the NPV of the combined revenue streams (Lighting savings and surplus sold to the grid)

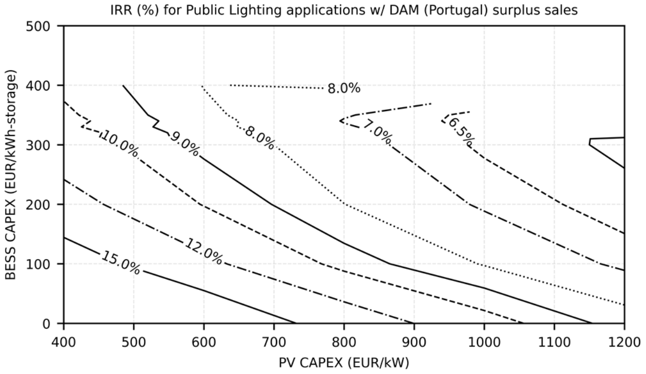

Figure 5. Isocontour of the IRR of the combined revenue streams (Lighting savings and surplus sold to the grid)

The isocontour plots are useful to analyze the combination of CAPEX PV and CAPEX BESS that jointly achieve a certain value showing that technological improvements can come either from the solar PV or BESS and obtain the same result.

V. CONCLUSIONS

This study optimized hybrid solar PV and BESS for sustainable street lighting, addressing the challenges of integrating renewable energy sources into a system with predominant nighttime demand. The model, applied to a typical municipal scenario, determined optimal investment strategies for a hybrid systems of solar PV and BESS across varying investment unit cost parameters. Results confirmed the economic and technical viability of these hybrid systems under specific conditions, showcasing substantial cost savings compared to grid-only solutions. The analysis highlighted the critical dependence of the hybrid systems viability on BESS storage capital expenditure, with higher CAPEX rendered hybrid systems uneconomical.

However, within economically viable scenarios, the model provided optimal PV and BESS sizing, demonstrating considerable potential for grid reduction and CO_2 emission reduction. The Base Case scenario proved particularly promising, achieving a NPV of 1.86 million euros and an IRR of 6.9% over 20 years.

Hourly simulations demonstrated the system's effectiveness in meeting street lighting demand, storing surplus daytime solar energy for nighttime use, and generating surplus in Summer for sale to the grid. Future research could explore the impact of other renewable energy sources, such as wind.

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