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Sustainable Autonomous Electric Ferry as Part of the Energy Ecosystem

Abstract

This paper presents a conceptual design for an autonomous electric ferry connecting the mainland and a nearby island. The ferry will be powered by batteries charged from solar panels on its roof and from a solar power plant on the hotel roof on the island. The goal is to create an integrated energy system linking the ferry, hotel, and solar sources, minimizing the need to purchase electricity from the grid. The ferry will operate frequently during the tourist season and serve other purposes, including supporting the local energy supply, in the off-season. The analysis will explore the optimal balance between ferry power, battery capacity, and solar generation, considering both economic and environmental objectives. This paper demonstrates sustainable integration of maritime transport and local renewable energy sources.

Keywords: autonomous electric ferry, renewable sources, sustainable transport, local energy

1. Introduction

In contemporary energy and transport planning, justifying the adoption of any new technology is essential to support sustainable decision-making. This paper critically assesses the feasibility of deploying an autonomous electric ferry on a short island route and evaluates its potential contribution to the local energy community. In this study, the term "autonomous" primarily relates to the energy concept of the system, indicating a high level of independence from the external power grid achieved through the integration of local renewable generation and onboard energy storage [1]. As such, it does not refer to autonomous navigation capabilities, which are beyond the scope of this analysis. The analysis begins with the concept that the ferry, together with a hotel and solar power plants, forms an integrated functional system capable of reducing the need for electricity purchased from the grid. To identify the optimal propulsion and energy storage configuration, key parameters such as vessel power demand, battery capacity, and solar generation must be measured. The resulting data enable comparison of different energy-use scenarios, assessment of the ferry's dual role as both a mobile consumer and a potential virtual power plant, and confirmation of the sustainability of the proposed solution.

Special attention is given to selecting a configuration that accommodates seasonal navigation patterns while also exploring broader opportunities for the ferry's operation outside the main season. In this way, both the technical and economic aspects of the project are evaluated, providing a well-founded argument for how an electric ferry can contribute to a sustainable energy transition at the local level [2].

2. Material and methods: Optimization of electric power management

The optimization of electric power management in an autonomous electric ferry system plays a crucial role in improving efficiency and reducing operational costs. The self-sufficient electric ferry is designed as a sustainable solution for connecting the mainland and nearby islands along short routes. Solar panels integrated on the ferry's roof enable additional electricity generation during operation, reducing the need for recharging from the grid or external sources. This increases the vessel's energy independence and supports the goals of the green transition. The distance between the mainland and the island on the observed route is approximately 600 meters, representing the minimum segment that the autonomous electric ferry must cover. The planned cruising speed is set between 5 and 7 knots. Taking into account the maneuvers during departure and docking, the total travel time is expected to be under six minutes per direction.

This dynamic allows for a high frequency of daily trips, which is particularly important during the tourist season when passenger and hotel guest traffic intensifies. Given the short travel time and relatively low speed, energy consumption is optimized while maintaining a high level of maneuvering safety near the shore and docking areas. The short duration of each trip also provides flexibility for integrating battery charging cycles between crossings, as part of the required energy can be replenished during brief stopovers in the port. Based on the conducted calculations and assumed operating conditions, the energy consumption per trip of the electric ferry over a 600-meter distance is estimated at approximately 1.10 kWh. This value includes the energy required to power the propulsion system at speeds between 5 and 7 knots, as well as the basic auxiliary systems operating during navigation. The daily energy consumption was obtained using a deterministic calculation based on a resistance and power model of the vessel, which includes hydrodynamic resistance, inertial effects, wind force, frontal area, and propulsion efficiency. Therefore, the reported value represents a baseline operating scenario under fixed, representative conditions. However, real operating conditions in the Adriatic are subject to variability due to wind, waves, and sea currents which are not explicitly modeled in a time-varying manner. For this reason, a simple sensitivity analysis was introduced to assess the impact of adverse environmental conditions on energy demand [3].

To evaluate the efficiency and energy production of the photovoltaic (PV) system installed on the ferry's roof, three main parameter groups must be defined: (1) surface coverage, (2) module characteristics and system losses, and (3) solar irradiance at the location and in the actual orientation of the modules. For the studied area in the Istria region, hourly solar irradiation data on a horizontal plane during a typical summer day were used. The table presents the values of solar irradiance expressed in W/m², along with the estimated energy output of the PV system (in kWh) for each hourly interval. It can be observed that solar irradiation begins around 4:45 a.m., reaches its maximum at noon with values exceeding 780 W/m², and gradually decreases towards the evening. The peak energy production occurs between 11:45 a.m. and 12:45 p.m., amounting to approximately 7.38 kWh, while total daily generation is achieved over the entire period from sunrise to sunset.

Table 1. Irradiance of the observed area during the day

Time [h]	Irradiance [W/m2]	Energy [kWh]
0.45	0	0
1.45	0	0
2.45	0	0
3.45	0	0
4.45	47	0.43428
5.45	170	1.5708
6.45	323	2.98452
7.45	473	4.37052
8.45	616	5.69184
9.45	716	6.61584
10.45	784	7.24416
11.45	799	7.38276
12.45	764	7.05936
13.45	705	6.5142
14.45	593	5.47932
15.45	468	4.32432

16.45	314	2.90136
17.45	166	1.53384
18.45	41	0.37884
19.45	0	0
20.45	0	0
21.45	0	0
22.45	0	0
23.45	0	0
24	0	0

To more precisely determine the amount of solar energy available during the ferry's voyage, we must account for the fact that each crossing lasts roughly 6 minutes or less, corresponding to a time interval of about 0.1 h. Since the irradiance data in the available database are given as hourly values, linear interpolation between the two nearest known points is used to estimate irradiance at the moments of departure and arrival. The general form of linear interpolation is

$$G(t) = G_i + \left((G_{i+1} - G_i) / (t_{i+1} - t_i) \right) \cdot (t - t_i) \tag{1}$$

where is:
t – the desired time (e.g., the ferry's arrival time)
t_i, t_{i+1} – adjacent known time stamps from the table
G_i, G_{i+1} – the corresponding irradiance values [W/m^2]

Once the solar irradiance at specific moments of the voyage has been obtained by interpolation, the next step is to estimate the electrical energy that can be captured and produced by the photovoltaic panels installed on the ferry's roof. For this calculation, the general power equation for a PV system is used:

$$P\_PV = (G / G\_st) \cdot P\_nom \cdot \eta \tag{2}$$

where is:
G – instantaneous solar irradiance [W/m^2], derived from measurements and interpolation
G_st = 1000 W/m^2 – the reference irradiance under Standard Test Conditions (STC)
P_nom – the rated installed power of the PV array, computed as the product of the total effective panel area [m^2] and the panels' peak power per unit area
η – the overall system efficiency, encompassing the efficiency of the solar modules

Based on the solar irradiance data for the observed area, the amount of energy that the photovoltaic panels on the ferry's roof can generate during the day has been calculated [4]. The estimation is derived from the known panel surface area, their efficiency, and standard operating conditions, while irradiance values were interpolated for individual time steps. The results are shown in the figure 1., illustrating that the energy production follows a typical daily solar irradiance curve gradually increasing in the morning hours, reaching its peak around noon, and then declining in the afternoon, as previously presented in Table 1.

In the example shown for the month of April, the maximum power output of the panels reaches nearly 6 kWh around midday, while generation in the early morning and late evening hours is significantly lower.

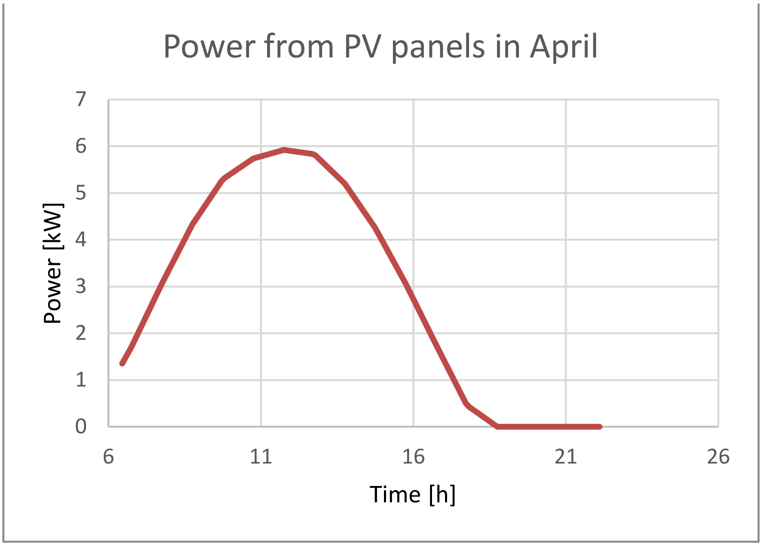

Figure 1. PV panel production during April

Since a single 600-meter trip requires approximately 1.10 kWh of electricity, daily energy consumption quickly reaches several dozen kilowatt-hours. This is considerably higher than the current output of the photovoltaic panels on the ferry's roof, which can cover only a portion of the energy demand during sunny hours [5].

To describe real-time navigation more accurately, it must be linked to acceleration. The graph in Figure 2 clearly shows three distinct phases of the route: initial acceleration (positive, increasing acceleration), steady cruising (acceleration around zero), and regenerative braking (negative acceleration). During acceleration, the required propulsion power is higher because, in addition to overcoming hydrodynamic resistance, the propulsion system must also accelerate the vessel's mass, including the added-mass effect. During cruising, the propulsion system maintains speed and compensates for resistance as a function of velocity, while during deceleration, the power demand decreases. Depending on the propulsion setup, part of the energy can be recovered; however, in practice, this is limited by the propeller and control electronics.

By combining the resistance function with the acceleration profile, a time-dependent power profile can be obtained. Integrating this over the entire trip provides a realistic estimate of the total energy required. This approach allows for more reliable sizing of the propulsion system and batteries, as well as for comparing different operational scenarios without relying on rough assumptions.

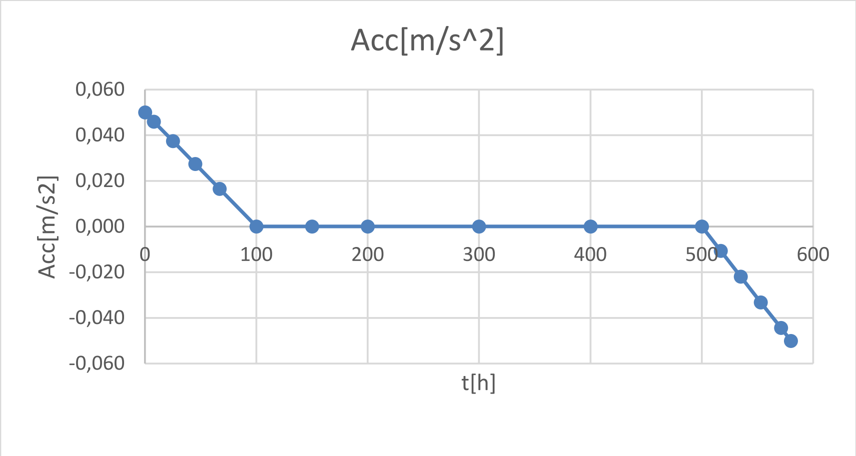

Figure 2. Acceleration achieved by the electric ferry during cruising

To achieve full energy autonomy, the ferry must be equipped with an energy storage system of sufficient capacity. Such a battery system enables the storage of surplus energy generated by solar power plants during the day both from the panels installed on the ferry's roof and from the hotel's solar installation. The stored energy can then be used to power the ferry when solar production is insufficient, for example, in the evening or during cloudy and rainy weather. In this way, a closed loop energy system is established, integrating local renewable energy generation and storage, thereby reducing dependence on grid electricity and enhancing the sustainability of maritime transport.

The relationship between the ferry's energy consumption, solar power generation, and battery system sizing was analyzed using monthly data from April to October. The total daily energy consumption of the electric ferry amounts to approximately 95.28 kWh, which remains relatively stable under the assumption of an equal number of trips per day. In contrast, the average daily energy generation from solar panels varies significantly throughout the year: in June, it reaches up to 47.2 kWh, while in October it drops to just 17.49 kWh. This seasonal variation clearly demonstrates that solar panels alone cannot meet all of the ferry's energy needs, leading to daily and monthly energy deficits that must be compensated by the battery storage system.

In this study, a lithium iron phosphate ($LiFePO_4$) battery was selected. This battery technology has proven to be among the most reliable for maritime applications, offering excellent performance even under demanding conditions such as high charge and discharge currents, exposure to humid environments, and mechanical shocks or vibrations [6]. The total nominal capacity of the installed battery modules is approximately 160 kWh, providing the ferry with a high degree of operational autonomy and safety. In contrast to most existing electric ferry projects like the Norwegian ferry MF Ampere, which operate on routes of several kilometers and require battery capacities in the range of 1–4 MWh, the case analyzed in this paper considers a very short connection of only 600 m. Due to the low energy demand per trip and a total daily consumption below 100 kWh, the system can be dimensioned with a significantly smaller battery. Accordingly, the selected capacity of approximately 160 kWh reflects the specific short-route, high-frequency operational profile of the ferry.

Table 2. shows that the energy deficit that is the amount of energy the solar panels fail to produce which ranges from 48.1 kWh per day in June to as much as 77.8 kWh per day in October. When these values are converted into ampere-hours, the monthly energy shortfall exceeds 21,000 Ah in September. Therefore, to ensure a reliable and autonomous energy supply for the ferry, the battery system must be sized to bridge these deficits. For this purpose, a nominal battery capacity of 1,740 Ah was defined, while the maximum usable capacity amounts to 1,566 Ah, respecting the safe depth-of-charge and depth-of-discharge (DoD) limits of 90% during charging and 30% during discharging. An analysis of the state of charge (SoC) indicates that the battery must maintain sufficient reserve capacity to guarantee uninterrupted ferry operation throughout the entire day. It should be noted that the resulting 60% value does not represent the electrochemical efficiency of the battery system but rather the usable capacity window defined by these operational constraints. Limiting the state of charge within this range is a standard practice in lithium-based battery systems, as it significantly improves battery lifetime, safety, and overall system reliability.

Equally important is the analysis of charging current and the time required for recharging the battery. When using the fastest charging mode with a 220 A charger, the charging time ranges from 2.28 hours in June to 3.68 hours in October. Alternatively, if the battery is charged over a six-hour period, the required charging currents vary between 83.5 A and 135.1 A, depending on the month. These results enable detailed operational and maintenance planning, as well as proper sizing of the charging infrastructure.

Table 2: Monthly energy balance and charging requirements

Parameter	Apr	May	Jun	Jul	Aug	Sep	Oct
Total energy consumption per day [kWh]	95.28	95.28	95.28	95.28	95.28	95.28	95.28
Average Sun Generated Energy per day [kWh]	33.97	42.56	47.2	45.92	39.82	27.39	17.49
Missed energy per day [kWh]	61.3	52.7	48.1	49.4	55.5	67.9	77.8
Missed energy per day [Ah]	638.6	549.2	500.8	514.2	577.7	707.2	810.3
Monthly missed energy [Ah]	19159.4	17024.2	15025.0	15939.2	17909.0	21215.6	25119.7
Nominal battery capacity [Ah]	1740	1740	1740	1740	1740	1740	1740
Maximum available battery capacity [Ah]	1566	1566	1566	1566	1566	1566	1566
Minimal capacity of battery for charging [Ah]	522	522	522	522	522	522	522
Charging DoD [%]	90%	90%	90%	90%	90%	90%	90%
Discharging DoD [%]	30%	30%	30%	30%	30%	30%	30%
State of Charge [Ah]	927.4	1016.8	1065.2	1051.8	988.3	858.8	755.7
Charging current (Fastest way) [A]	220	220	220	220	220	220	220
Time of charging [h] (I=220A)	2.90	2.50	2.28	2.34	2.63	3.21	3.68
Charging current (6 hour window) [A]	106.4	91.5	83.5	85.7	96.3	117.9	135.1

This approach to battery system sizing proves essential for ensuring the energy independence and reliability of the electric ferry. By integrating local solar generation with an efficient energy storage system, a sustainable and self-sufficient energy network is established by reducing dependence on the power grid and ensuring stable vessel operation under all conditions. Each battery module has a capacity of 580 Ah at a nominal voltage of 2 V, corresponding to an energy value of approximately 1.16 kWh. The mass of a single module is 50 kg, making the total system mass considerable. To achieve the required capacity for ferry propulsion, the installation of 144 battery modules is planned. This configuration provides a total usable energy of 167.04 kWh, taking into account a system efficiency of 60%. The total mass of the complete battery assembly is around 7,200 kg, which represents a significant technical factor in the ferry's design due to its impact on displacement and stability [7].

At each step of the analysis, several parameters are monitored: the remaining energy in the battery, the level of solar irradiance, the instantaneous power output of the photovoltaic panels, and the total generated energy. This allows for a detailed overview of changes in the battery's state of charge (SoC) throughout the day. The initial available battery energy is determined by the nominal capacity of the storage system, and with each subsequent ferry trip, the stored energy decreases according to the energy consumed per route. Simultaneously, the energy produced by the solar panels is added to the current battery state, simulating real operating conditions in which the battery is discharged during ferry operation while being partially recharged by the photovoltaic system [7].

The table for the month of June clearly illustrates several important phenomena. Without photovoltaic panels, the battery discharges much more rapidly, leading to a significant drop in available energy over the course of the day. When PV generation is taken into account, the discharge rate decreases, and around midday when solar irradiance is at its highestthe battery's state of charge stabilizes or even slightly increases, as the energy produced by the solar panels is nearly sufficient to cover the ferry's entire energy demand. On cloudy or rainy days, the situation is less favorable, since the photovoltaic system generates less power, causing the battery to discharge more quickly, although still at a slower rate than in scenarios without PV support.

Table 3: Full-day PV and battery profile for all trips under different weather conditions

Time[h]	**Avail. Batt. Energy [kWh]**	**Sun irr [W/m2]**	**PV Power [kW]**	**Sun Gen. Energy [kWh]**	**Avail. Batt. Energy w PV [kWh]**	**CLOUDY DAY-15% Sun Gen. [kWh]**	**CLOUDY DAY-15% Avail. Batt. w PV [kWh]**	**RAINY DAY-10% Sun Gen. [kWh]**	**RAINY DAY-10% Avail. Batt. w PV [kWh]**
6.75	130	0.0	0.0	0.00	130	0.00	130	0.00	130
6.84	128	336.0	3.1	0.27	130	0.04	130	0.03	130
6.94	128	351.0	3.2	0.32	129	0.05	129	0.03	129
7.02	127	363.9	3.4	0.29	129	0.04	129	0.03	129
7.12	127	378.9	3.5	0.35	129	0.05	128	0.04	127
...	...	...	...	...	...	...	...	...	...
	35			61	97	9	45	6	42

This method of monitoring and modeling energy consumption and generation is extremely important, as it provides a realistic representation of the ferry's overall energy system operation. It not only reflects total daily values but also illustrates how energy is consumed and replenished minute by minute. This level of detail is essential for selecting an appropriate battery storage system, ensuring that the battery capacity is sufficient to prevent the state of charge from dropping below a safe threshold. Moreover, this approach enables accurate estimation of the required charging times and power levels during the night or between trips, while clearly showing the contribution of solar panels to the overall energy balance. The results demonstrate that photovoltaic panels can significantly extend the ferry's autonomy and reduce the daily decline in battery energy. However, to achieve fully independent operation under conditions of low solar irradiance, a battery storage system of adequate capacity must be provided, ensuring safe, reliable, and sustainable ferry operation throughout the entire day and under all weather conditions [8].

The analysis of battery charging and discharging cycles is a key component in designing the energy system of an autonomous electric ferry. Since the ferry operates with relatively short and frequent energy consumption cycles, while photovoltaic generation follows the diurnal pattern of solar radiation, it is essential to synchronize these two processes to ensure a stable power supply. Battery charging occurs during the day when the available PV power exceeds the ferry's instantaneous consumption. In those periods, surplus energy should not go unused but rather be stored in the batteries. Conversely, during the evening and nighttime hours when solar generation ceases the battery provides the energy required to power the ferry.

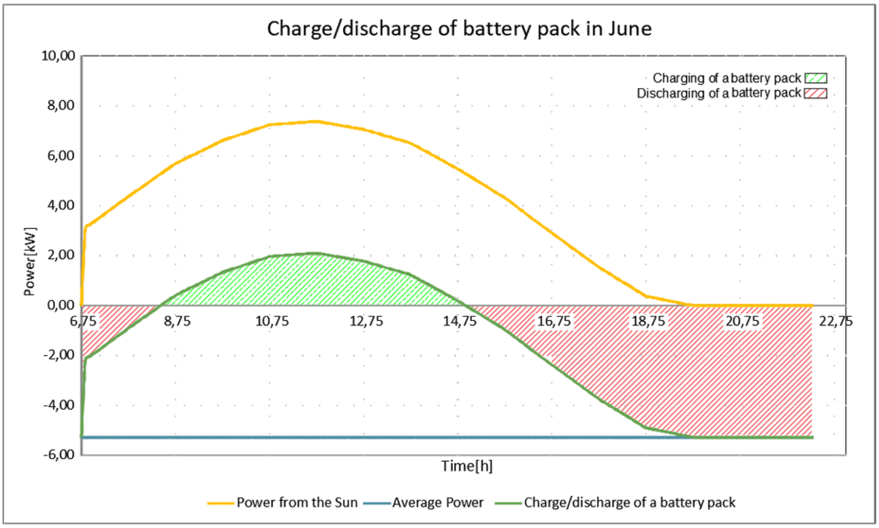

Figure 3. Daily battery charging and discharging cycle

This approach enables the assessment of the required battery pack capacity. If the battery capacity is too small, the ferry will be unable to complete all scheduled trips during periods of reduced solar irradiance. Conversely, an oversized battery system would increase both the mass and cost of the vessel, thereby reducing its economic and operational efficiency. Therefore, analyzing the charging and discharging cycles is essential for determining the optimal battery capacity and developing an effective energy management strategy [9].

3. Electric ferry as a flexible Virtual Power Plant capacity

The ferry's energy requirements are not constant but depend on the timetable, cruising speed, weather conditions, and seasonal variations in traffic. At the same time, energy production from photovoltaic sources fluctuates throughout the day and across different seasons. For this reason, it is essential to develop optimized energy management strategies that ensure intelligent distribution between immediate consumption, battery charging, and potential energy export to the grid.

Challenges such as system intermittency can be mitigated by enabling bidirectional energy flows between the ferry, shore infrastructure, and the electrical grid, while also integrating prosumers located in the port and advanced storage systems both onboard and onshore. By aggregating multiple sources and storage systems such as ferry fleets, shore-based batteries, rooftop photovoltaic installations, and port consumers, a more stable and predictable power portfolio can be achieved.

A new market actor, the aggregator, manages this ensemble within a clearly defined grid area, actively coordinating energy demand and supply, including flexible loads such as cranes, cooling systems, and charging stations. The architecture of a Virtual Power Plant (VPP) is designed to integrate various Distributed Energy Resources (DERs) into a unified system that can be operated either centrally or in a decentralized manner. Operators of virtual power plants aggregate distributed generation and storage assets so that they function as a single, flexible power unit with defined minimum and maximum capacity and standardized ramp rates. Such a system can then participate in electricity and ancillary service markets [10].

In this context, the electric ferry is no longer just a consumer. Electric ferry can act as a flexible energy storage unit when docked. Based on the installed battery capacity of approximately 160 kWh and the defined operational limits (30–90% SoC), around 90–100 kWh of energy can be considered available for flexible use without compromising daily operation. During periods of low transport demand or when the vessel is idle, a portion of this energy can be used for peak shaving at the port or, where applicable, injected back into the local grid. Assuming that 20–30% of the available battery capacity can be allocated for such services on a daily basis, this corresponds to approximately 20–30 kWh of flexible energy per day. If this energy is traded on the electricity market under typical price differences of 50–100 €/MWh, the expected daily revenue remains relatively modest, on the order of 1–3 € per day. However, the primary value of the system lies not in direct energy arbitrage, but in improving local grid stability, enabling peak load reduction, and supporting the integration of renewable energy sources within the port energy system. It should be noted that the regulatory framework for integrating mobile energy storage units, such as electric ferries, into Virtual Power Plant operation is still not fully defined in Croatia. However, existing mechanisms related to balancing services, managed by the Croatian Transmission System Operator, provide a partial foundation for such applications. In particular, participation in ancillary services and balancing markets is already regulated at the system level, although currently limited to conventional and stationary assets. The inclusion of distributed and mobile energy resources, such as electric ferries, is therefore expected to follow broader European Union trends related to aggregators and decentralized flexibility, but remains a developing area within the national regulatory framework.

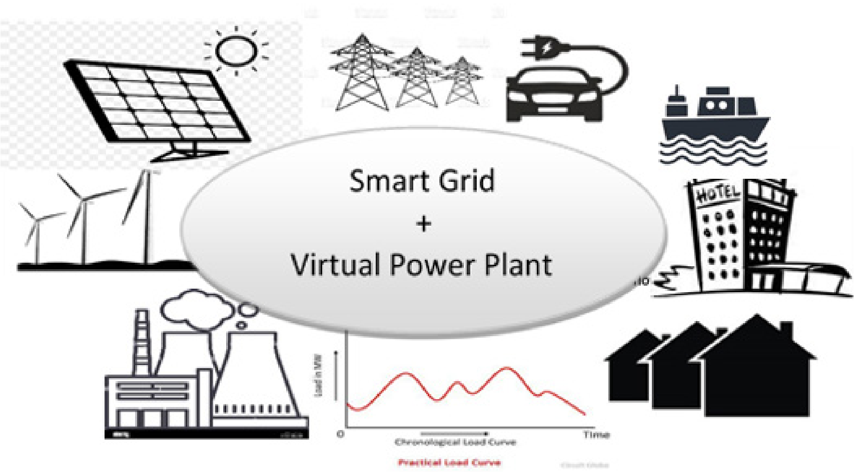

Figure 4. Virtual Power Plant concept

Monitoring and optimization are carried out by the central information system of the virtual power plant, which integrates weather forecasts, photovoltaic generation estimates, expected port demand, wholesale market prices, and the current grid status. Based on these inputs, the decentralized energy management system (DEMS) performs power and energy scheduling, deciding when the ferry should charge, when it should feed energy back to the shore grid, and how to align the sailing schedule with market and grid signals [11] [12].

It is important to note that the DEMS does not replace the local operational automation. Both the ferry and the port must have local control systems, including battery management, power converters, protective equipment, and islanding capabilities, to ensure basic functionality and safety even in the absence of the central system. The central coordination point of the port–ferry energy park is the energy management system that integrates shipborne and onshore resources.

A key component of the DEMS is its connection to the advanced distribution management system (ADMS), and, when necessary, to the corresponding transmission system operator. This link enables real-time data exchange on voltage levels, power flows, operational constraints, and service availability, ensuring safe and optimal use of the ferry as a resource within the virtual power plant. In this way, the ferry becomes a controllable, mobile flexibility unit that meets its own energy needs while sailing and provides measurable, market-valued services to the power system when docked, all while maintaining vessel safety and grid integrity.

By applying optimization algorithms, it is possible to reduce the depth of battery discharge, thereby extending battery life, minimizing energy conversion losses, and ensuring that available solar energy is utilized to its fullest extent. For example, scheduling charging during peak solar irradiance periods and operating trips under energy-optimal conditions creates a balanced relationship between energy consumption and generation.

This approach provides multiple benefits:

- ◊ Economic advantage – reduced energy costs and the potential for additional revenue from feeding electricity into the grid.
- ◊ Technical flexibility – improved balancing of generation and consumption within the local system.
- ◊ Sustainability – reduced CO_2 emissions and enhanced integration of renewable energy into the maritime and local energy sectors.

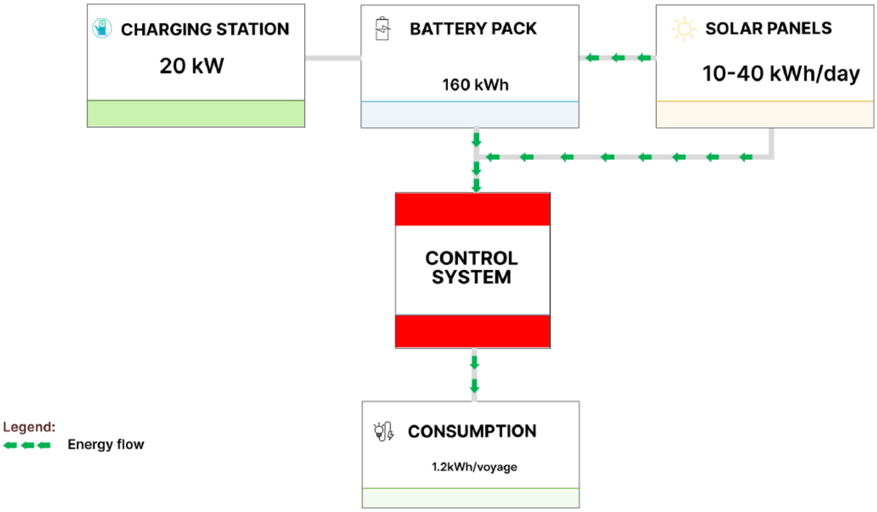

Figure 5. Virtual Power Plant management system on the electric ferry

Ultimately, the optimization of electric power management and the integration of the virtual power plant concept form the foundation for the long-term sustainability and autonomy of electric ferries. This model can serve as an example of how the maritime sector can actively contribute to the development of smart energy grids. The systems on board and on shore operate as a unified whole. When the ferry approaches the charging station, the shore unit receives data on energy consumption recorded during the voyage. At the same time, the condition of the grid is verified and, if necessary, adjusted to prevent voltage disturbances. The charging system itself is designed to minimize voltage fluctuations by returning reactive power to the grid during charging, which helps maintain voltage stability. As a result, the local grid can deliver more energy while the vessel is charging [6].

Through active management, monitoring, and grid support using onshore battery systems, the overall setup provides the high peak power required for fast charging without the need to expand existing infrastructure. Instead of additional investment, the concept of peak shaving is applied. Peak shaving balances the flow of energy between the grid and the local onshore storage system to cover short-term power surges without overloading the electrical network. Excess energy is stored during periods of low demand and lower electricity prices, ensuring both technical efficiency and economic viability [13] [14].

4. Conclusion

This analysis shows us that integrating an autonomous electric ferry into a locally managed energy system based on solar generation and battery storage can significantly improve energy efficiency and sustainability in maritime transport. By optimizing power management and incorporating the virtual power plant concept, the ferry becomes an active element of the local energy network rather than a passive consumer. The results confirm that solar panels can cover a substantial portion of the ferry's energy needs, while the battery system ensures operational reliability even under reduced solar irradiance. The application of advanced energy management systems, such as DEMS, enables intelligent coordination between energy production, storage, and consumption. This integration supports flexible operation, reduces dependence on the grid, and lowers operational costs. Through active participation in energy markets, the ferry can also contribute to peak load management and grid stability. The proposed model illustrates how the maritime sector can support the broader energy transition by adopting renewable sources and smart control technologies. Furthermore, combining onboard and onshore storage enhances system resilience and makes better use of existing infrastructure. Overall, the project confirms that autonomous electric ferries, when properly integrated into local energy communities, represent a viable path toward a cleaner, more efficient, and interconnected energy future.

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