Roadside Solar Power Plants with Water-Based Thermal Energy Storage and Heat Pumps

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Abstract

This paper presents an energy storage system for roadside solar power plants (SPPs) based on the use of a water-based thermal energy storage and a heat pump. The main goal of the complex is to accumulate that portion of solar energy that the power grid does not receive during the sunny day, and then transfer this energy to the grid at night.

Unlike the conventional approach, in which storage efficiency is evaluated exclusively by round-trip efficiency, this work proposes to assess the effectiveness of the Complex by the total electrical energy actually absorbed by the grid over a 24-hour period. It is shown that, due to the use of a heat pump and the operation of all thermal machines strictly in optimal regimes, a high energy and economic effect of up to **75% of previously curtailed solar energy** can be achieved, even with moderate conversion efficiencies.

The paper describes the composition of the Complex, its operating modes during daytime and nighttime, the results of thermodynamic analysis, an evaluation of electrical energy efficiency, approximate capital expenditures, and environmental advantages compared to electrochemical batteries. The specific cost of energy storage is estimated to be 5–10 times lower than that of electrochemical batteries: **CAPEX ≈ 34 USD/kWh or 500 USD/kW**, while the cost of nighttime electricity is approximately **1 cent/kWh**, assuming a storage lifetime of **30–50 years**.

1. Introduction

The large-scale deployment of solar power generation leads to a well-known problem: during daytime hours, the electric grid is not always capable of accepting all the generated energy. As a result, a portion of solar electricity is forcibly curtailed and effectively lost.

This problem is particularly acute for extended roadside solar power plants installed within highway right-of-way zones. Such SPPs possess significant generation potential, while the grid often lacks sufficient capacity to absorb all the produced energy.

In the author's previous works [1, 2], a concept of solar energy accumulation using water as a durable and low-cost energy carrier was proposed. The present paper develops this concept specifically for roadside SPPs and focuses on the **energy and economic effect**, rather than on formal efficiency metrics alone. Thus, curtailment represents not only an energy issue but also a direct economic loss for solar power plant owners.

To reduce the volume of the paper, detailed derivations and calculation dependencies are provided through references to the author's previously published works [1, 2].

2. Current State of the Art

At present, electrochemical batteries represent the dominant solution for energy storage in solar power plants. Despite their advantages, they exhibit several fundamental limitations:

- high energy storage cost (USD 200–300/kWh);
- limited service life (8–12 years);
- fire and explosion hazards;
- reliance on scarce materials (Li, Co, Ni);

- difficulties associated with end-of-life recycling.

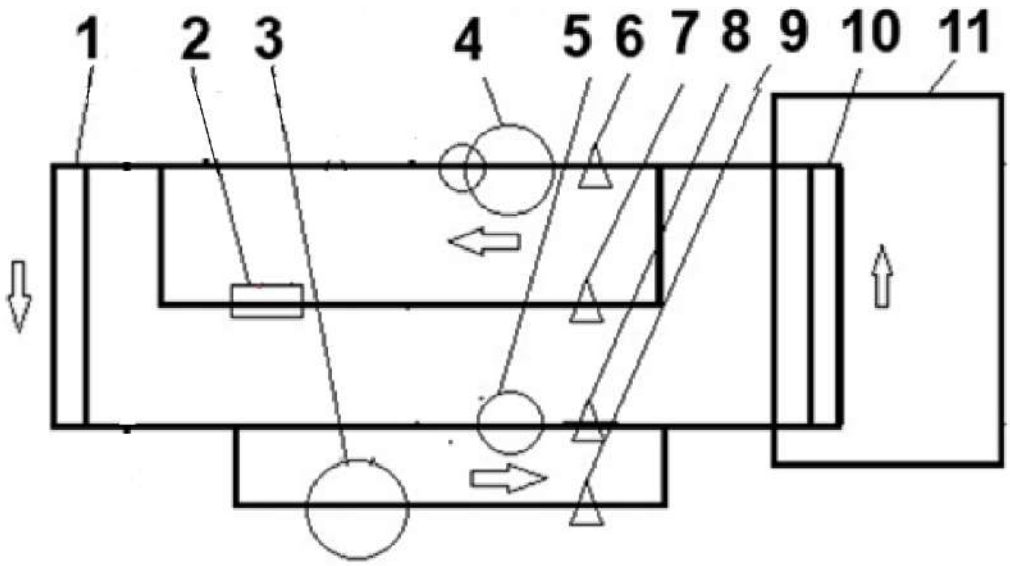
These factors complicate the application of electrochemical batteries for extended energy facilities designed for service lifetimes of 30–50 years.

3. Composition and Operating Principle of the Complex

The proposed Complex includes the following main components:
- solar panels installed along roadways;
- a heat pump;
- a hot zone (hot water tank) and a cold zone (radiator);
- piston machines: a compressor and an expander;
- an electric generator.

Energy is stored in the form of **thermal energy of water at elevated temperature**.

A structural diagram of the Complex is shown in Fig. 1.



20-30 oC 85-95 oC

Fig. 1

Figure notation:
1 – air radiator; 2 – throttle valve; 3 – piston compressor;
4 – piston expander with electric generator; 5 – refrigerant pump;
6, 7, 8, 9 – valves; 10 – heat exchanger; 11 – hot water tank.
The compressor and expander operate on refrigerants in closed circuits. Solar panels and the inverter are not shown in the diagram.

4. Operating Modes of the Complex

4.1. Daytime Mode

During daytime hours, solar energy is partially supplied directly to the grid, while surplus energy is used to drive the heat pump. The heat pump transfers thermal energy and stores it in water, creating a temperature difference between the hot and cold zones of the storage system.
A key point is that each **1 kWh of electrical energy not accepted by the grid** is converted by the heat pump into **4–5 kWh of stored thermal energy** (COP = 4–5). Subsequent conversion

of thermal energy back into electricity is inevitably associated with losses, which are considered in Section 5.
4.2. Nighttime Mode
During nighttime hours, the thermal energy stored in water is used to drive a piston expander. The expander rotates an electric generator, and the generated electricity is supplied to the grid. In this way, the Complex provides power output during periods when solar generation is absent.

5. Selection of Efficiencies and Thermodynamic Analysis

All thermal machines in the Complex operate exclusively in optimal regimes: either at nominal load or completely switched off. Partial-load operation is excluded. For example, based on network needs, automation or operators turn on only some Complexes, while the rest are turned off.
Therefore, the calculations employ efficiency values achieved in serial or pilot-industrial installations under nominal operating conditions:
- heat pump: COP = 4.0–5.0 (small temperature lift);
- piston compressor: $\eta \approx 0.65–0.70$;
- piston expander with generator: $\eta \approx 0.60–0.65$.
A detailed thermodynamic analysis of the cycles is presented in [1, Appendix 2].

6. Electrical Energy Efficiency

Crucially, the effectiveness of the Complex is determined not only by nighttime energy recovery but by the **total electrical energy actually absorbed by the grid**: E{ day,total } = E{ day } + E{night}.
The use of a heat pump significantly increases (E{ night }), since thermal rather than electrical energy is stored, with a magnitude equal to the electrical input multiplied by the COP.
As a result, the total energy delivered to the grid over a 24-hour period is substantially higher than in the absence of storage or under simple curtailment. Without storage, surplus daytime generation is entirely lost, whereas in the proposed Complex a significant portion of this energy is returned to the grid during nighttime hours.

7. Main Characteristics of the Complex (Estimated)

- service life: 30–50 years;
- number of cycles: practically unlimited;
- energy storage medium: water;
- specific energy storage cost 5–10 times lower than that of electrochemical batteries of comparable capacity [1]: CAPEX ≈ 34 USD/kWh or
- 500 USD/kW; nighttime electricity cost ≈ 1 cent/kWh [1, Section 10.5];
- scalability: linear along roadways.
- Cost estimates and calculations are provided in [1, Appendix 3, Section 10].

8. Environmental Aspects

The Complex offers the following environmental advantages:more than 100 years of successful operation of refrigeration cycles;
- absence of fire-hazardous components;
- absence of toxic electrolytes;
- no use of scarce materials;

- simple end-of-life disposal.

These features are particularly important for installations along highways and near populated areas.

9. Conclusions

Roadside solar power plants equipped with water-based thermal energy storage and heat pumps enable effective accumulation of surplus daytime solar generation that would otherwise be lost. The proposed Complex represents a realistic alternative to electrochemical batteries for large-scale roadside SPPs.

In Israel, solar power plants with a total area of **50–100 km²** could potentially be deployed along several thousand kilometers of highways. All components of the Complex are based on serial or well-established technical solutions and on more than 100 years of successful refrigeration-cycle operation.

The Complex can also be applied to convert existing solar fields into round-the-clock energy sources**.** As of 2025, global installed solar capacity exceeds 1400 GW, while energy storage capacity is projected to reach only 345 GW by 2030, which indicates a potential market for the energy storage technology under consideration of approximately 1000 GW.

References

[1] Rosenberg S. *Water Accumulation of Energy for Roadside Solar Power Plants*, 2025. https://netanyascientific.com/English/Stati/Stati-7/data/Wae7.pdf

[2]. Rosenberg S. *Water Accumulation of Energy Using Heat Pumps and Piston Machines*, 2025. https://netanyascientific.com/English/Stati/Stati-7/data/Waehphb.pdf