Water accumulators of energy for solar power plants

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Abstract

The article discusses a technical solution that transforms any solar panel field into a day-and-night energy source. The system in question combines solar panels, water accumulators of energy and thermal machines - compressors and expanders. This environmentally friendly system includes energy storage devices that are 10-20 times cheaper than electrochemical batteries of equivalent energy capacity and offer twice the service life. The system supplies the consumer with 79 % of the energy that these solar panels would have generated during the day if directly connected via an inverter, achieving efficiency comparable to pumped-storage power plants.

The system is an innovative unique combination of devices and therefore is promising for patenting.

The system does not require the allocation of separate land plots, since the equipment is installed under the solar panels, which saves space and reduces the environmental impact.

The system's capital expenditure (CAPEX) is approximately:

US$ 34/kWh or US$ 500/kWh, and the night energy price is 1¢/kWh.

In 2023, the average capital cost of lithium-ion systems was US$ 304 / kWh.

Research and development of this technology within the framework of R & D will create opportunities for increasing the energy efficiency and environmental friendliness of solar power plants. In 2025, solar power plants with a total capacity of more than 1400 GW are operating in the world, but by 2030 only 345 GW of energy storage capacity is predicted. Therefore, the market for the storage technology under consideration is very relevant and amounts to 1000 GW.

Key words: Solar power plants, solar panels, heat pumps, heat machines, water accumulators, water batteries, energy cost, compressors, expanders, steam piston engines.

1. **Current Situation**

Solar energy is only available during the day. The intermittency of solar and wind energy can only be addressed through the use of energy storage devices. As of May 2024, the average capital costs for thermal energy storage and compressed air storage were US$ 232/kWh and US$ 293/kWh, respectively [1]. By comparison, in 2023 the average capital cost of lithium-ion systems was US$ 304/kWh for systems with a four-hour storage duration, typically for shorter storage periods. It is worth noting that the cost of lithium-ion batteries constitutes 40–60% of the total project cost for Battery Energy Storage Systems (BESS). Moreover, in China, up to 25% of renewable energy is wasted due to insufficient storage capacity.

In 2025, solar power plants with a total capacity of more than 1,400 GW are operating in the world, but by 2030, only 345 GW of energy storage capacity is predicted. Therefore, the global market for the energy storage technology under consideration is very relevant and amounts to 1,000 GW.

Currently, electrochemical batteries, battery inverters and solar charge controllers are primarily used. The most commonly used are lithium-ion (Li-Ion) and lithium iron phosphate (LiFePO4) batteries. Cyclic modes of operation of batteries with periodic or constant deep discharges sharply reduce the service life of batteries. Therefore, the depth of discharge of such batteries should be no more than 80%. The service life of lithium-ion batteries is no more than 5 years. Lithium iron phosphate (LiFePO4) batteries have better characteristics, but are almost twice as expensive.

In the world energy sector, intensive work has begun to use low-energy heat. Geothermal power plants, installations for using waste heat from thermal power plants, expanders with electric generators at gas pumping stations and other heat pumps are being built. These units convert low-energy heat into electrical energy in thermodynamic cycles using expanders operating on various refrigerants.

Refrigeration devices – refrigerators, freezers and air conditioners – have found wide distribution in all countries. For more than a hundred years, these devices have been used in residential apartments, offices, stores, warehouses, ice arenas, in various branches of technology and science. The service life of refrigeration devices exceeds 10 years.

In many industries, pneumatic motors are in great demand due to their undeniable advantages. They guarantee high reliability, have an optimal power-to-weight ratio, do not pollute the environment, and are fairly easy and simple to adjust.

Pneumatic engines operate on compressed air or steam. Industry produces various piston steam engines. But sometimes it is cheaper to convert automobile and tractor gasoline or diesel engines into steam piston engines. Piston steam engines have a specific steam consumption 2-2.5 times less than steam turbines of the same power.

2. **The purpose** of the presented theoretical study**:**

The goal is to confirm the efficiency of using water thermal energy accumulators instead of electrochemical batteries.

Below, a system of equipment for storing energy from solar photovoltaic panels is presented, supplemented by water thermal energy accumulators and thermal machines as an alternative to electrochemical batteries.

3. **Economic sense**

The proposed equipment Complex transforms solar photovoltaic panels into an autonomous, controlled source of round-the-clock generation, both during the day and at night. The consumer receives 79 % of the electrical energy from the panels, offering an energy "return" comparable to that of a pumped storage power plant or electrochemical batteries. The studied system is 10 to 20 times cheaper than electrochemical battery storage systems of the same capacity and also has twice the service life. The capital cost of the system is approximately CAPEX = US$ 34/kWh or US$ 500/kWh and the night energy price is 1 ¢/kWh .

The complex does not require the allocation of separate economic territories, as the equipment is installed beneath solar panels. As an autonomous, controllable source of 24-hour generation in a decentralized energy system, the complex increases the resilience of power supply to consumers in the grid.

4. Description of the Complex Operation

The system complements the solar power plant and includes water thermal energy accumulators and thermal machines. The layout of the system is shown in Fig. 1.

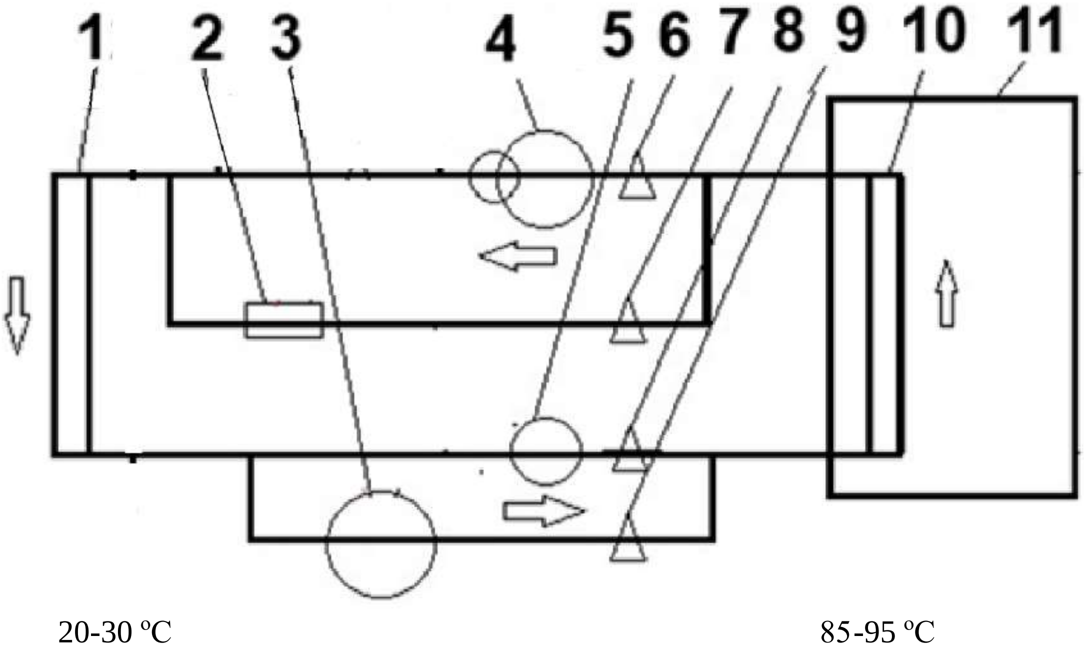

Fig. 1

Designations in Fig. 1:
1 - water-air radiator, 2 - throttle, 3 - piston compressor, 4 - piston expander with electric generator, 5- refrigerant pump, 6, 7, 8, 9 - valve, 10 - heat exchanger, 11 - hot water tank.

Description of the Complex's operation:

4.1. **During Sunny Time**

During the day, the solar photovoltaic panels generate electricity. A portion of this electricity is supplied to the consumer (i.e., the power grid) via the inverter. The solar panels and inverter are not shown in the diagram. The remaining portion of the electrical power is directed to the motor of compressor 3. The refrigeration circuit of compressor 3 consists of throttle 2 and heat exchanger 10. In the radiator 1, the refrigerant takes heat from the surrounding air, i.e. cools it. In the heat exchanger 10, the refrigerant condenses and heats the hot water in the tank 11, i.e. gives off heat to the hot water.

The compressor circuit thus functions as a heat pump: it takes heat from the surrounding air and transfers it to hot water. The air cooled in the radiator can be directed to residential, office or industrial premises.

4.2. **In non-sunny time of day**

During non-sunny periods, the motor of compressor 3 is switched off, valves 7 and 9 are closed, and valves 6 and 8 are opened. Pump 5 and expander 4 are activated. Expander 4 has an electric generator that supplies energy to the consumer, i.e. to the power grid. The expander circuit 4 consists of a pump 5, a radiator 1 and a heat exchanger 10. In the heat exchanger 10 the refrigerant turns into steam and takes heat from the hot water in the tank 11. The thermal energy in the tank 11 was stored during sunny times by the heat pump in the compressor circuit 3. The exhaust steam enters the radiator 1, where the refrigerant condenses and gives off heat to the surrounding air. The air heated in the radiator can be directed for heating to residential, office or industrial premises.

5. **Energy Reference Data**

5.1. The February 2020 report "Estimating the Optimum Tilt Angles for South-Facing Surfaces in Palestine" [2] examined the energy potential of solar panels, particularly in Jerusalem (see Tables 15, 16, 17, and 18 in the Appendix). Let us now consider the analysis

of Tables 15, 16, 17, and 18 from the report:
- Panels with a peak power of 5 kW produce energy per year in a horizontal position (angle 0°) 1523 kWh/kW peak * year (according to 4 dimensions 7664 + 7574 + 7856 + 7371) / 4 = 30465/4 * 5 kW peak).

In recent years, some solar power plants have already installed panels horizontally to increase productivity from the provided territory.

5.2. The peak power of most solar photovoltaic panels is 0.18 kW peak per square meter of panel area. The annual energy obtained per square meter of panel area is 274 kWh/m²·kW peak*year (=1523 * 0.18). On the sunniest days in June and July, based on four measurements over 123 days (see Tables [2] in the Appendix), the electricity generated is 29.6 kWh/5 kW·day (=(908+933+935+867)/123). Per day, we obtain 5.92 kWh/kW*day (= 29.6 / 5), and for one square meter of panel area, the energy produced is 1.066 kWh/m²*day (= 5.92 * 0.18). With an average sunny day length of 8.5 hours, the average panel power is 0.126 kW/m² (= 1.066 / 8.5) during these months. On the hottest days, the maximum panel power will be higher, reaching no less than 0.13 kW/m².

5.3. Conversion of electrical energy from panels into solar time

In this study, based on the above information, we assume that the panels have a maximum power of 0.13 kW/m^2 (per square meter of panel) and produce energy of 1.1 kWh/m^2 during the day in 8.5 hours (=0.13*8.5).

5.4. For example, half of this power 0.065 kW/m2 is received by the inverter, which produces energy of 0.5525 kWh/m2 (=0.065*8.5) in 8.5 hours, and gives the consumer electricity during the day 0.525 kWh/m2 (=0.95*0.5525) with an average power of 0.062 kW/m2 (=0.065*0.95). The inverter has an efficiency of 0.95.

The remaining power of the panels, 0.065 kW/m2 (out of 0.13 kW/m2), is directed to the compressor motor to accumulate energy for non-solar times.

5.5. The power ratio between the inverter and compressor pump may vary depending on the average grid demand. Reducing the share of energy allocated to the compressor decreases the amount of energy generated during non-sunny periods.

6. **Analysis of the efficiency** of the studied complex, including solar panels, water thermal energy accumulators and thermal machines.

6.1. We will study the efficiency assessment of the Complex using the example of a "field" of solar photovoltaic panels with an area of 1000 m2. In this field, in this studied project, 512 solar panels of the most common size of 1 by 2 meters are installed horizontally almost closely. The panels are arranged in 32 rows with 16 panels per row. The total surface area of 512 panels is 1024 m2. In further analysis, for clarity, we assume that the total area of the panels is 1000 m2.

The capacity of the solar photovoltaic panel field is 180 kW peak (=0.18 *1000), the annual productivity is 274 MWh (=1523 kWh/kW peak *180 kW peak).

From solar panels in June-July the consumer receives 525 kWh of electricity per day (=0.525*1000) - see point 5.4.

From the Complex in June-July the consumer receives 300 kWh of electricity (=0.3*1000) during non-sunny times for use for 15.5 hours - see paragraph 6.3.

During the year, during sunny periods, the consumer receives 174,000 kWh of electricity (=274,000*525/825) and during non-sunny periods, 100,000 kWh (=274,000*300/825).

6.2. **Thermodynamic calculations**

- Thermodynamic calculations were performed for the hottest day in June-July.
- In the calculations it was assumed that the ambient air temperature during the day is 30 °C, and the temperature of the refrigerant in the radiator in the compressor circuit due to heat removal is 25 °C.

In non-sunny times, the ambient air temperature is 20 °C. The temperature of the refrigerant in the expander circuit in the radiator is 25 °C due to heat removal from the expander circuit. The temperature of hot water in tank 11 in the morning is 85 °C, by the end of the day it rises to 95 °C in the compressor circuit. In non-sunny times, the temperature of hot water drops from 95 °C to 85 °C by the morning in the expander circuit.

Thermodynamic calculations are given in Appendix 2.

6.3. The following results of thermodynamic calculations were obtained for a panel area of 1000 m2:

- The coefficient of performance in the refrigeration cycle is $\varepsilon\kappa = 4.585$.
- During 8.5 hours of a sunny day, the compressor circuit extracts 6.6 GJ of energy from the surrounding air.
- During these 8.5 hours, hot water 11 accumulates 8.5 GJ of energy.
- In non-solar time, the conversion of heat into work in the expander circuit has a performance factor of $Kp=\tau= 0.179$.
- Expander 4 will produce work and transfer to the consumer energy of 300 kWh in 15.5 hours of non-solar time with an average power of 20 kW.

7. **Main characteristics of the Complex:**

- Solar panels have a total area of 1000 m2,
- Installed capacity: 180 kW peak,
- Annual energy production by panels: 274,000 kWh.
- Annual energy production during daylight hours: 174,000 kWh.
- Annual energy production during non-solar hours: 100,000 kWh.
- Daytime energy: 525 kWh/day in June-July
- Useful returned (night) energy: 300 kWh/day in June-July.
- Capital expenditure (CAPEX) = US $34/kWh or US $500/kW,
- the price of night energy is 1 ¢/kWh – see item 10.5
- Compressor motor capacity is 65 kW.
- Expander generator capacity is 20 kW
- Hot water tank capacity is 200 m3.
- Heat exchanger capacity is 280 kW
- Energy recovery efficiency is 79% - see item 8.
- Radiator capacity is 220 kW.
- Required capacity of the alternative battery: 830 kWh - see item 9.

8**. Energy performance analysis** of a 1000 m2 solar panel field

- The inverter receives an input power of 0.065 kW/m² (out of 0.13 kW/m²) and produces 525 kWh during the day for 8.5 hours, providing an average output power of 62 kW.
- At night, the expander has an average power of 20 kW and produces 300 kWh in 15.5 hours.
- Thus, in total, the consumer receives 825 kWh of energy (=525+300) during the day and at night, with an output power of 62 kW during the day and 20 kW at night.
- If all the energy from the panels were supplied through an inverter, the consumer would receive energy of 1.045 kWh/m2 (=1.1*0.95) but only during sunny periods.

A system with a compressor and an expander-generator gives the consumer 79% of the energy (=0.825/1.045) from the energy from the panels with an inverter.

- This means that the efficiency of energy recovery by the compressor-expander system is 79 %, which is comparable to the efficiency of a pumped-storage power plant.
- It is important that this system also provides the consumer with energy at night, turning the solar panels into a completely autonomous, controllable round-the-clock energy source.

9. Evaluation of the capacity of an alternative battery

We are investigating a system containing solar panels, an inverter, and a battery.
If only part of the energy from the panels on the hottest days is supplied through the inverter, as in the case of water batteries, for example, 0.5525 kWh/m² (= 0.065×8.5), and the remaining energy 0.5525 kWh/m² (= 0.065×8.5) is stored in an electrochemical battery for use in non-sunny periods, then:
The consumer will receive 0.525 kWh/m² during the day (=0.5525×0.95) and
0.42 kWh/m² in non-sunny periods (=0.5525×0.8×0.95).
Here we assume that the inverter operates with 95% efficiency, and the battery (including controller losses) has an energy return efficiency of 80%.
A system containing an inverter and a battery will supply the consumer with a total of 0.945 kWh/m² (=0.525+0.42) during the day and night, which is 90 % (= 0.945/1.045) of the energy produced by a system using only an inverter.
The alternative battery must return this stored energy of 0.5525 kWh/m2 every night, but modern batteries are allowed to discharge only 80 %. Therefore, the battery would have to have a capacity of at least 0.69 kWh/m2 (=0.5525/0.8).
It is known that electrochemical batteries lose 10-20 % of their capacity during operation. To prevent intensive capacity loss of the battery during its nightly discharge, the battery capacity should be increased by at least 20% and be at least 0.83 kWh/m2 (=0.69*1.2).

10. Cost of main equipment and materials for a 180 kW peak solar panel field with a total area of 1000 m²
This section will calculate the cost of the main equipment used in the solar panel system, including compressors, expanders, and their alternatives. Prices are based on available information and assumptions, such as the use of compressors and expanders made from converted car and tractor diesel engines.
10.1. An analysis of heat engine prices is provided in Appendix 3.
The analysis showed that for the 180 kW peak solar panel complex, it is advisable to use converted car and tractor diesels as compressors and expanders. Their average price is US$ 50/kW. The total compressor power is 65 kW and the cost is US$ 3250 (=50*65). The total expander power is 20 kW and the cost is US$ 1000 (=50*20).
10.2. Prices for electric motors for compressors are US$ 1/kW [12]. The cost of
65 kW electric motors is US$ 65.
Prices for electric generators for expanders are US$ 2/kW [13]. The cost of 20 kW electric generators is US$ 40.
10.3. The total power of heat exchangers and the radiator is 0.5 kW/m²**.** Heat exchanger prices, according to information from the internet, range from US$ 1.3/kW [14] to US$ 10/kW [15]. Their average price is US$ 4/kW. The cost of heat exchangers for the 180 kW peak solar panel complex is about US$ 2000 (=4*0.5*1000).
10.4. Cost of insulated tank
The cost of insulated tanks is calculated in Appendix 4.
The cost of materials and concrete work is US$ 3060.
The cost of thermal insulation - foamed polyethylene is US$ 550.
10.5. **The total cost** of main equipment and materials for a 180 kW peak solar panel field with a total area of 1000 m² is approximately:
The total cost is US$ 10,000, including 3,250 (compressor) + 1,000 (expander) + 85 (electric motors) + 40 (generator) + 2000 (heat exchanger) + 3060 (concrete) + 550 (insulation).
The useful stored (night) energy is 300 kWh/day and 100,000 kWh per year.
Capital expenditure (CAPEX) is $34/kWh (=10,000/300) or
$500/kW ($10,000/20 /kW).

The equipment cost's share of the annual nighttime energy price
is 1¢/kWh (=$10,000/100,000*10). Here:
equipment cost is $10,000,
annual nighttime energy production is 100,000 kWh,
the refrigeration equipment has a service life of 10 years.
The cost of equipment for experimental and pilot kits will naturally be 2-3 (or more) times higher than the cost of kits for sufficiently large-scale serial production.
In Israel, the selling price of solar energy is 0.02 $/kWh = 2 ¢/kWh [23]
10.6. The average capital costs for May 2024 [1] for thermal energy and compressed air storage were US$ 232/kWh and US$ 293/kWh, respectively. In 2023, the average capital costs of lithium-ion systems were US$ 304/kWh for systems with a four-hour storage duration, that is, as a rule, for shorter storage periods.
10.7. An alternative electrochemical battery for the investigated 180 kW peak solar panel complex with a total area of 1000 m² would have to have a capacity of at least 830 kWh - see clause 9.
The price of LiFePO4 batteries is US$ 290/kWh [19], [20], [21].
The price of lithium-ion batteries (Li-Ion) is US$ 151/kWh November 2024 [22]
The cost of lithium-ion batteries instead of the investigated complex would have to be at least US$ 126,000 (=151*830), and the price of LiFePO4 batteries would be at least US$ 241,000 (=290*830).

11. Results

11.1. Comparison of the cost of the complex
- The cost of the equipment complex for solar panels (including compressors, expanders, heat exchangers, concrete work and thermal insulation) is US$ 10,000.
- This cost is 10-20 times less than the cost of alternative batteries (US$ 126,000 or US$ 241,000) required to store the same amount of electricity.

The capital cost (CAPEX) is US$ 34/kWh or $500/kW and the night energy price is 1¢/kWh.
11.2. Environmental Considerations
- The solar panel system in question uses water and refrigerants circulating in closed circuits that are not exposed to the atmosphere, making it environmentally friendly.
- The refrigeration units and refrigerants used in the system have not created environmental problems for over a hundred years of operation.
- However, electrochemical batteries create environmental problems during production, operation and disposal, which must be taken into account.

12. Conclusion

12.1. Advantages of the complex
- The complex of equipment for solar panels, consisting of refrigeration compressors, expanders and water thermal energy accumulators, offers a highly profitable and environmentally friendly alternative to electrochemical batteries.
- The overall capital cost of the system is significantly lower than storing equivalent electricity using lithium-ion or LiFePO4 batteries.
- The long-term operational sustainability of the system, combined with a lower environmental impact, makes it an attractive alternative to electrochemical batteries.

12.2. Research Submission
This research should be forwarded to technical experts and potential sponsors who may consider this approach a viable and more sustainable option for energy storage and solar energy management.

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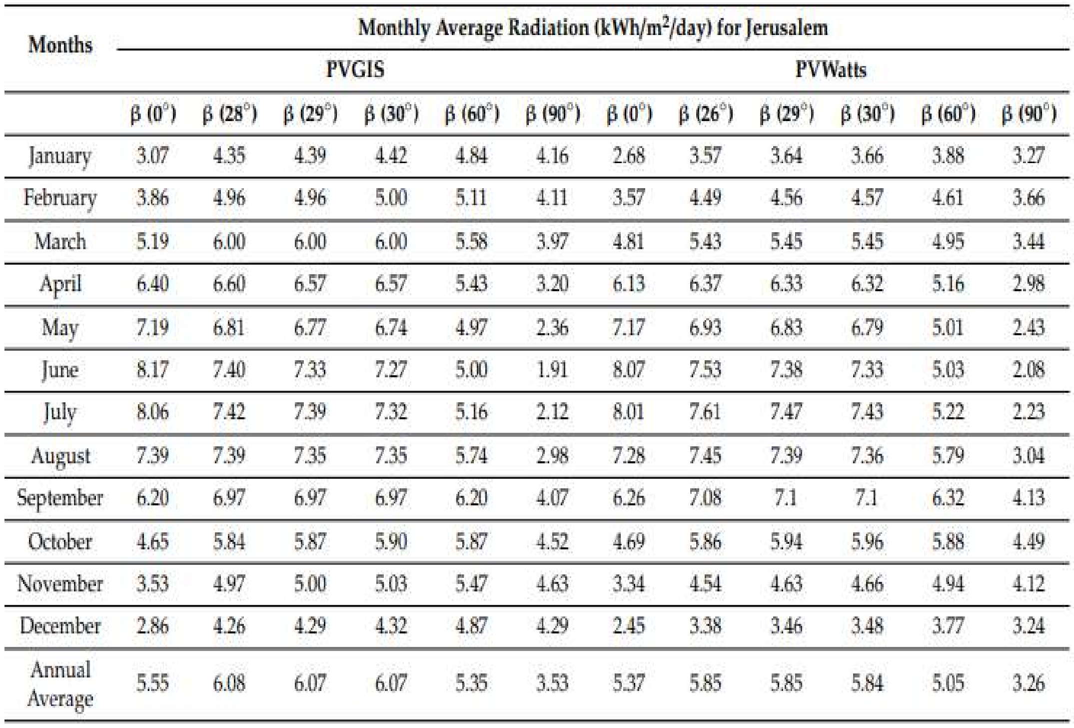
Application 1

Tables 15, 16, 17, 18 from the report Estimating the Optimum Tilt Angles for South-Facing Surfaces in Palestine dated February 2020 [2]

Table 15. The monthly average global radiation in Jerusalem for different tilt angles (β).



Months	Monthly Average Radiation (kWh/m²/day) for Jerusalem											
	PVGIS						PVWatts					
	β (0°)	β (28°)	β (29°)	β (30°)	β (60°)	β (90°)	β (0°)	β (26°)	β (29°)	β (30°)	β (60°)	β (90°)
January	3.07	4.35	4.39	4.42	4.84	4.16	2.68	3.57	3.64	3.66	3.88	3.27
February	3.86	4.96	4.96	5.00	5.11	4.11	3.57	4.49	4.56	4.57	4.61	3.66
March	5.19	6.00	6.00	6.00	5.58	3.97	4.81	5.43	5.45	5.45	4.95	3.44
April	6.40	6.60	6.57	6.57	5.43	3.20	6.13	6.37	6.33	6.32	5.16	2.98
May	7.19	6.81	6.77	6.74	4.97	2.36	7.17	6.93	6.83	6.79	5.01	2.43
June	8.17	7.40	7.33	7.27	5.00	1.91	8.07	7.53	7.38	7.33	5.03	2.08
July	8.06	7.42	7.39	7.32	5.16	2.12	8.01	7.61	7.47	7.43	5.22	2.23
August	7.39	7.39	7.35	7.35	5.74	2.98	7.28	7.45	7.39	7.36	5.79	3.04
September	6.20	6.97	6.97	6.97	6.20	4.07	6.26	7.08	7.1	7.1	6.32	4.13
October	4.65	5.84	5.87	5.90	5.87	4.52	4.69	5.86	5.94	5.96	5.88	4.49
November	3.53	4.97	5.00	5.03	5.47	4.63	3.34	4.54	4.63	4.66	4.94	4.12
December	2.86	4.26	4.29	4.32	4.87	4.29	2.45	3.38	3.46	3.48	3.77	3.24
Annual Average	5.55	6.08	6.07	6.07	5.35	3.53	5.37	5.85	5.85	5.84	5.05	3.26

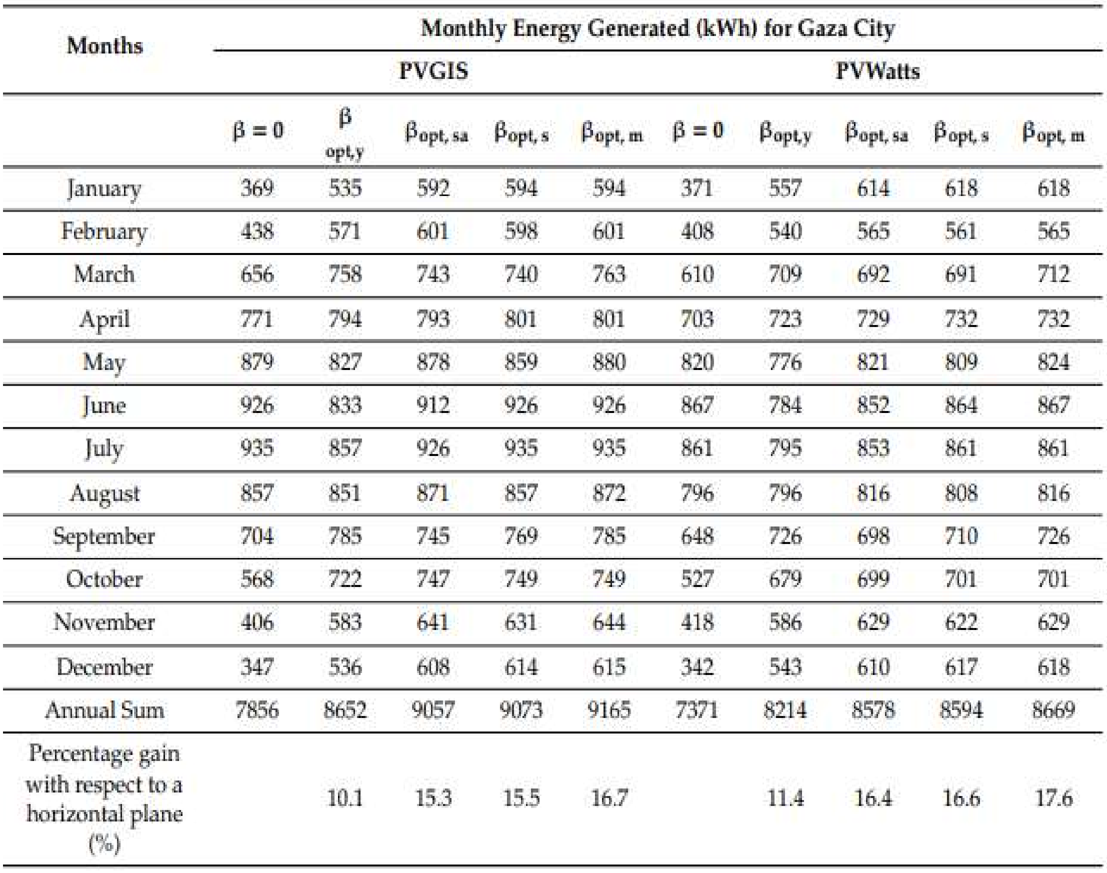
Table 16. The monthly average global radiation in Gaza city for different tilt angles (β).

Months	Monthly Average Radiation (kWh/m^2/day) for Gaza city										
	PVGIS						PVWatts				
	β (0°)	β (28°)	β (29°)	β (30°)	β (60°)	β (90°)	β (0°)	β (29°)	β (30°)	β (60°)	β (90°)
January	3.02	4.29	4.32	4.35	4.77	4.10	3.05	4.53	4.57	5.04	4.34
February	3.96	5.11	5.14	5.18	5.29	4.25	3.72	4.93	4.96	5.07	4.04
March	5.32	6.19	6.19	6.19	5.77	4.06	4.97	5.8	5.81	5.37	3.76
April	6.53	6.77	6.73	6.73	5.53	3.22	6.19	6.4	6.39	5.21	3.01
May	7.29	6.90	6.87	6.84	5.03	2.33	7.08	6.74	6.7	4.93	2.39
June	8.07	7.30	7.23	7.20	4.90	1.86	7.84	7.11	7.06	4.85	2.04
July	7.94	7.32	7.26	7.23	5.06	2.07	7.55	7.00	6.95	4.93	2.2
August	7.32	7.32	7.29	7.26	5.68	2.92	7.03	7.06	7.03	5.51	2.92
September	6.17	6.90	6.93	6.93	6.17	4.03	5.84	6.58	6.58	5.84	3.82
October	4.81	6.10	6.13	6.13	6.13	4.71	4.56	5.89	5.91	5.91	4.54
November	3.50	4.97	5.00	5.03	5.47	4.63	3.63	5.08	5.11	5.44	4.54
December	2.89	4.32	4.39	4.42	4.97	4.35	2.84	4.43	4.47	5.05	4.44
Annual Average	5.57	6.12	6.12	6.12	5.40	3.55	5.36	5.96	5.96	5.26	3.50

Table 17. Monthly energy generated by a 5 kWh system in Jerusalem.

Months	Monthly Energy Generated (kWh) For Jerusalem									
	PVGIS					PVWatts				
	$\beta = 0$	$\beta_{opt,y}$	$\beta_{opt,\,sa}$	$\beta_{opt,\,s}$	$\beta_{opt,\,m}$	$\beta = 0$	$\beta_{opt,y}$	$\beta_{opt,\,sa}$	$\beta_{opt,\,s}$	$\beta_{opt,\,m}$
January	382	553	612	614	617	339	457	496	498	498
February	431	556	584	580	584	410	517	540	539	540
March	632	726	708	712	730	602	676	663	663	679
April	732	751	752	758	758	721	746	746	751	751
May	832	782	830	810	833	844	813	847	838	848
June	896	804	881	893	896	918	853	909	915	918
July	908	832	899	907	908	933	883	931	935	935
August	841	837	856	848	857	845	861	869	864	872
September	697	776	738	761	776	706	793	759	784	795
October	548	689	709	713	713	557	692	718	718	718
November	413	592	651	640	653	393	534	580	573	582
December	352	539	611	616	617	306	426	469	473	474
Annual Sum	7664	8437	8831	8852	8942	7574	8251	8527	8551	8610
Percentage gain with respect to a horizontal plane (%)		10.1	15.2	15.5	16.7		8.9	12.6	12.9	13.7

Table 18. Monthly energy generated by a 5 kWh system in Gaza City.



Months	Monthly Energy Generated (kWh) for Gaza City									
	PVGIS					PVWatts				
	$\beta = 0$	$\beta_{opt,y}$	$\beta_{opt,sa}$	$\beta_{opt,s}$	$\beta_{opt,m}$	$\beta = 0$	$\beta_{opt,y}$	$\beta_{opt,sa}$	$\beta_{opt,s}$	$\beta_{opt,m}$
January	369	535	592	594	594	371	557	614	618	618
February	438	571	601	598	601	408	540	565	561	565
March	656	758	743	740	763	610	709	692	691	712
April	771	794	793	801	801	703	723	729	732	732
May	879	827	878	859	880	820	776	821	809	824
June	926	833	912	926	926	867	784	852	864	867
July	935	857	926	935	935	861	795	853	861	861
August	857	851	871	857	872	796	796	816	808	816
September	704	785	745	769	785	648	726	698	710	726
October	568	722	747	749	749	527	679	699	701	701
November	406	583	641	631	644	418	586	629	622	629
December	347	536	608	614	615	342	543	610	617	618
Annual Sum	7856	8652	9057	9073	9165	7371	8214	8578	8594	8669
Percentage gain with respect to a horizontal plane (%)		10.1	15.3	15.5	16.7		11.4	16.4	16.6	17.6

Application 2

Thermodynamic calculations

1. The calculations were carried out using the methodology and data from the works:
- “Determination of the energy efficiency of devices, installations and systems”
by PhD A.V. Martynov. [3]
- “Accumulation of cold in air conditioning systems of buildings and structures”
by A.E. Semenov, A.I. Andreev. [4 pp.300-303.]

In the work [4] the authors performed calculations using the CoolPack program. Also, based on the information available to the authors, the indicator coefficient $\eta i = 0.8$, the effective coefficient - $\eta eff = 0.95$, the electric efficiency - $\eta el = 0.95$ were adopted in the calculations. The same efficacy values were adopted in this study.

2. **Electricity from the panels during sunny periods** is accumulated in water tanks for subsequent conversion into work - into electricity for the consumer.
- In this study, based on the above information, we assume that the panels have a maximum power of 0.13 kW/m^2 (per square meter of panel) and produce energy of 1.1 kWh/m^2 during the day in 8.5 hours (=0.13*8.5).
- For example, half of this power 0.065 kW/m2 is received by the inverter, which produces energy of 0.5525 kWh/m2 (=0.065*8.5) in 8.5 hours, and gives the consumer electricity during the day 0.525 kWh/m2 (=0.95*0.5525) with an average power of 0.062 kW/m2 (=0.065*0.95). The inverter has an efficiency of 0.95.

The remaining power of the panels, 0.065 kW/m2 (out of 0.13 kW/m2), is directed to the compressor motor to accumulate energy for the non-sunny period.

- The power ratio for the inverter and compressor pump may be different depending on the average grid demand. Reducing the share of energy for the compressor reduces the amount of energy generated in non-solar times.

The processes occur as follows.

- Half of the electricity from the solar panels goes to the compressor, for example, 0.065 kW h/m2 h out of 0.13 kW h/m2 h. Here and further in Appendix 2, all calculations are performed for 1 square meter of solar panel.

-The total real power supplied to the compressor is

Nk=N/ ηi *ηeff*ηel = 0.065 kW/m^2. See [4]

- The efficiency coefficients are specified in paragraph 1 and their product is equal to 0.722 (=ηi *ηeff*ηel =0.8*0.95*0.95).

-The theoretical power of the compressor in the thermodynamic cycle is therefore

N =Qo/ εк= Nk * ηi *ηeff*ηel=0.065 *0.722=0.047 kW/m^2.

- In the hot tank 11, the temperature in the middle of the cycle is Th = 90 oC = 363 K.

-The temperature of the refrigerant in the radiator during the day in the middle of the cycle Tx=25 oC=298 K (cooling from 30oC outside to 25oC refrigerant).

- The refrigeration coefficient is εk = Tc / (Th - Tc), where Tc and Th are the absolute temperatures of the cold refrigerant in the radiator and the hot water:

εk = 298/(363-298)=4.585.

-The cooling energy (cooling capacity) per hour is calculated as:

Eo=Qo= N*εк =0.047 ***4.585=**0.2155 kWh/h*m^2=0.776 MJ/h*m^2.

During 8.5 hours of average solar time, the compressor circuit extracts energy from the air through the radiator of 6.6 MJ/m2 (=0.776 *8.5)

This energy Eo cools the air through radiator 1, i.e. the cold refrigerant takes away 6.6 MJ/m2 of energy from the surrounding air.

The hot water 11 in the compressor circuit received during a sunny day the energy of the thermodynamic cycle Eo = Qo plus the energy Ep used by the pump:

Eh = Eo + Ep = 0.2155 + 0.065 = 0.2805 kWh/ h*m^2= 1.0 MJ/h*m^2.

Eo=Qo= N*εк =0.047 ***4.585=**0.2155 kWh/h*m^2=0.776 MJ/h*m^2.

The energy consumed by the pump in one hour is Ep=0.065 kWh/ h*m^2.

Over 8.5 hours, hot water 11 accumulates a total energy of Eh=8.5 MJ/m^2 (=1.0*8.5).

3. Conversion of electrical energy of panels in non-solar time

In the studied system, both the compressor and expander are identical thermal piston machines, differing only in their valve drive mechanisms. Therefore, it is assumed that the thermodynamic efficiencies of the expander match those of the compressor, with the following values:

- Indicator efficiency coefficient ηi = 0.8.
- Effective efficiency coefficient ηeff=0.95
- Electrical efficiency ηel=0.95
- Analysis of data from operating steam piston engines shows that the typical efficiency (ηi) ranges from 0.75 to 0.85, while the effective coefficient (ηeff) ranges from 0.90 to 0.95.

In non-sunny times, compressor 3 is de-energized, and the expander circuit 4 converts the accumulated heat into electrical energy for the consumer. The transformation occurs from hot water 11 with a temperature in the middle of the cycle

Th =90 oC=363 K to the temperature in the radiator 1 at night in the middle of the cycle Tx=25 oC=298 K. The efficiency coefficient is 18 %:

Kp = τ = (Th - Tc) / Th =(363–298)/363=0.179.

From the energy Eh=8.5 MJ/m^2, obtained during the day for 8.5 hours by water 11 (see section 6.7), it is theoretically possible to obtain work

$E=Eh*\tau=1.52\ MJ/m^2\ (=8.5*0.179)=0.423\ kWh/m^2$.
Taking into account the total efficiency=0.722 of the thermodynamic cycle, expander 5 will produce work and transfer to the consumer in 15.5 hours of non-solar time energy Ew=0.3 kWh/m^2 (=0.722*0.423) with an average power of 0.02 kW/m^2 (=0.3/15.5).
- A radiator in non-solar times emits energy of 7 MJ/m2 (=8.5 - 1.5), which is equal to the energy of 8.5 MJ/m2 received by hot water, minus the energy theoretically converted into work (1.52 MJ /m2). Radiator 1 must dissipate energy in the amount of 7 MJ/m2 during the evening and night so that the cold refrigerant in the radiator has a temperature of 25 °C or lower by morning.

The inverter receives a power of 0.065 kW/m2, which produces energy of
0.5525 kWh/m2 (=0.065*8.5) in 8.5 hours, and gives the consumer electricity of 0.525 kWh/m2 (=0.95*0.5525) during the day with an average power of
0.062 kW/m2 (=0.05*0.95).
In non-sunny times, the expander 4 has a capacity of 0.02 kW/m2 and gives the consumer energy of 0.3 kWh/m2.
In total, during the day and night, the consumer receives energy of 0.825 kWh/m2 (=0.525+0.3) with an average capacity of 62 W during the day and 20 W at night.
- If all the energy of the panels is supplied through the inverter, then the consumer would receive energy only during the day 1.045 kWh/m2 (=1.1*0.95).

The system with a compressor and expander-generator gives the consumer 79% of the energy (=0.825/1.045) from the energy of the panels with the inverter. However, in addition, the system also gives energy at night, i.e. turns the panels into an autonomous controlled source of round-the-clock generation. Thus, the consumer receives 79% of the energy, i.e. we have an energy "return" like a pumped storage power plant or batteries.

4. Calculation of tank volume

- The volume of the hot water tank 11 receives energy of Eh =8.5 MJ/m^2 from the compressor circuit during the day and heats the water during a sunny day from 85 °C to 95 °C.

The heat capacity of water is 4212 J/kg*oC, the heat capacity of 1 m^3 of water from
+85 °C to 95°C is $E10 = 1000 * 4212 * 5 = 42\ MJ/m^3$.
The mass of hot water is
$Mh = 1000 * Eh / E10 = 8.5\ MJ/m^2 / 42\ MJ/m^3 = 0.200\ m^3/m^2$.

5. **Heat exchanger capacity**.

- During the day, the heat exchanger gives off 8.5 MJ/m2 of energy from the refrigerant to hot water in 8.5 hours. At night, the heat exchanger gives off 7 MJ/m2 of energy to the refrigerant in 15.5 hours. The heat exchanger capacity is 0.28 kW/m2 (=8.5/8.5*3.6).
- During the day, the radiator must dissipate energy of 6.6 MJ/m2, and at night for 15.5 hours it must dissipate energy of 7 MJ/m2, so that by the morning the refrigerant has a temperature of 25 °C or lower.

The radiator power is 0.22 kW/m2 (=6.6/8.5*3.6).

Application 3

Thermal Machine Price Analysis
1. The total capacity of the compressor motors will be 65 kW.
Prices for compressors for refrigeration units, according to information from the Internet, range widely: from US$ 120 / kW to US$ 900 / kW. Manufacturers are European and Chinese: for example, [5], [6], [7]. If we take a price close to the minimum, for example, US$ 150 / kW, then the cost of compressors for the complex under study will be US$ 10,000.

2. The total capacity of the expanders will be 20 kW. Prices for expanders for refrigeration units according to information from the Internet, for example, an Austrian steam piston machine manufactured by Fördertechnik GmbH, providing 150 kW of electricity at the output, costs €280 thousand, i.e. 1900 € / kW (= 280000/150) [8]. If we accept this price, then the cost of expanders for the complex under study will be about US$ 50,000 (= 280000 * 1.1 * 20/150).

3. We study alternative options for expanders and compressors.
- Ukraine produces a line of pneumatic motors of different power P8-12, P12-12, P13-16, P16-25, DAR-14. Price US$ 135 / kW (= 1078/8) [9].
- As many scientists and authors believe, it is advisable to use the main units and parts of automobile and tractor internal combustion engines and diesel engines for the production of a piston steam engine. [8] Compressors for refrigerants can be manufactured on the basis of the same automobile and tractor diesel engines. The designs of piston internal combustion engines and diesel engines are so well developed that their mechanical losses do not exceed 10%. The same low losses will be in piston steam engines and compressors manufactured on their basis.
- The cost of such piston machines - expanders and compressors - not much more than the cost the cost of the diesel engine on the basis of which they are manufactured. The price of automobile and tractor diesel engines, due to their mass production, is quite low and amounts, for example, from US$ 30/kW [10] to US$ 70/kW [11].

4. Summary of costs for thermal machines
Here's a breakdown of the costs for the thermal machines:

Equipment	**Capacity**	**Cost per kW** (US$)	**Total Cost** (US$)
Compressor (standard option)	65 kW	150	10,000
Expander (standard option)	20 kW	2090	50,000
Compressor (pneumatic motor)	65 kW	135	9,000
Expander (pneumatic motor)	20 kW	135	2,700
Compressor (diesel engine-based)	65 kW	50	3,250
Expander (diesel engine-based)	20 kW	50	1,000

5. From the above analysis, we see that using diesel engine-based compressors and expanders (with a price of US$ 50/kW) would result in the lowest cost for both compressors and expanders, totaling US$ 4,250 for both. This option is particularly attractive because of the low cost of US$ 50/kW and the availability of readily available components from the automotive and agricultural sectors.
On the other hand, using standard compressors and expanders (with prices of US$ 150/kW for compressors and US$ 2090/kW for expanders) would be significantly more expensive, totaling US$ 59,000. This option would likely be more suitable for more specialized applications or where high efficiency and reliability are required.

6. The pneumatic motor option falls in between, offering a total cost of US$ 11,700 for compressors and expanders.
By selecting the diesel engine-based components, the system can achieve significant cost savings while still providing the necessary performance for the solar panel complex.

7. For further research, we assume that in the Solar Panel Complex with a peak capacity of 180 kW we use converted automobile and tractor diesel engines as compressors and expanders. Their average price is US$ 50/kW. The total capacity of the compressors is 65kW and the cost is US$ 3 250 (= 50 * 65). The total capacity of the expanders is 20 kW and the cost is US$ 1000 (= 50 * 20).

Application 4

Calculation of the cost of thermally insulated tank

The thickness of the thermal insulation and the thickness of the concrete walls, bottom and ceilings of the tanks are taken based on the experience of building seasonal heat accumulators [16], taking into account the features of the Complex under study.

The volume of the hot water tank is $Mh = 0.200\ m^3/m^2 \times 1000\ m^2 = 200\ m^3$.

The hot water tank has the following dimensions: length 18 m, width 6 m, depth 2 m, made as a concrete box with a concrete floor and ceiling. The thickness of the walls at the bottom is 0.2 m, at the top 0.1 m, the ceiling and the bottom are 0.1 m each. The volume of concrete is 36 m^3 .

The area of 1 layer of thermal insulation with a total thermal insulation thickness of 0.025 m (5 layers of 0.005 m) is 330 m^2 and the area of 5 layers will be 1700 m^2. This is 35 rolls of 50 m2.

The cost of materials and concrete work is US$ 3060 (=85x36) at a price of US$ 85/m^3 (=300 shekels per cubic meter) [17].

Foamed polyethylene in the form of a roll, thickness 5 mm, width 1.05 m, length 50 running meters, the price is US$ 15 per roll. [18] The cost of 35 rolls of thermal insulation - foamed polyethylene is US$ 550 (=15x35)