Water accumulators of energy and heat pumps for solar power plants on the walls of high-rise buildings

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Abstract

The article examines the energy and economic characteristics of solar power plants that can be built on the walls of multi-story residential and office buildings. Each such station on the walls will be able to provide consumers with a significant reduction in energy consumption from the network by 40-50%. Equipping the stations with innovative water accumulators of energy turns solar power plants into a source of 24-hour electricity. The flexible use of this adjustable 24-hour energy source provides significant benefits for both the consumer and the grid.

Solar power plants on the walls of multi-story residential and office buildings bring generation sources closer to energy consumers, which reduces the load on power grids and reduces the need to build new power lines. The Complex delivers 224,000 kWh of power to the consumer annually, including 151,000 kWh during the day and
73,000 kWh during non-sunny times of the day.

The system in question combines solar panels, water accumulators of energy, and heat pumps and expanders. This system is 10-20 times cheaper than electrochemical batteries of equivalent energy capacity, offers twice the service life and is environmentally friendly. The proposed combination of equipment achieves an efficiency similar to that of pumped storage power plants.

The system's capital expenditure (CAPEX) is approximately: US$ 32/kWh or US$ 500/kWh, and the night energy price is 1.4 ¢/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. 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

The Electricity Authority presented in 2020 a Review of the Possibility of Increasing Renewable Energy to 30% of Annual Consumption [1]. Solar panels are recognized as the main source of renewable electricity for Israel.

To achieve this goal, 29 terawatt-hours of renewable electricity must be produced in 2030. According to actual production data in the country, each kilowatt of installed panels produces 1,500...1,843 kWh per year. According to the review, photovoltaics should therefore have a peak capacity of about 16,000 MW. Based on the regulations of recent years, 1 megawatt requires 9...11 dunams of land. To obtain such a capacity of 16,000 MW, the peak must be allocated to 160 km^2 of Israel's economic territory. The solution for ground-based installations is to use the land resource and damage the territories. According to the Survey on the possibilities of increasing renewable energy to 30% of annual consumption [1], construction on roofs or dual use of installations will require an additional 4 billion shekels.

During midday hours, large amounts of solar energy can begin to exceed demand or the grid's ability to receive it. The energy then needs to be either stored for later use or not used, which reduces the efficiency of solar panels. In China, for example, up to 25% of renewable energy is wasted due to insufficient storage capacity.

- Solar energy is only produced during the daytime. The intermittency of solar and wind energy can only be addressed with energy storage. Average capital costs as of May 2024 [1] for thermal energy storage and compressed air storage were

US$ 232 /kWh and US$ 293 /kWh, respectively. In 2023, average capital costs for lithium-ion systems were US$ 304 /kWh for systems with a four-hour storage duration, i.e., typically for shorter storage periods.

Currently, electrochemical batteries, battery inverters and solar charge controllers are mainly used. Lithium-ion (Li-Ion) and lithium-iron-phosphate (LiFePO4) batteries are most often used. Cyclic battery operation modes with periodic or constant deep discharges dramatically reduce the service life of batteries. Therefore, the discharge depth 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 Israel, the main consumers of electricity - industrial and residential complexes - are located in the center and north of the country. Huge reserves of space for solar power plants are located in the south of the country. In order to transmit large amounts of solar electricity during the daytime from south to north, it is necessary to build sufficiently powerful new power transmission lines, which will simply stand idle during non-sunny times and thereby reduce the efficiency of solar energy. Solar power plants on the walls of multi-story residential and office buildings bring generation sources closer to energy consumers, which reduces the load on power grids and reduces the required capacity of new power transmission lines.
- According to a press release [31] from December 10, 2025, according to the Ministry of Energy's plan, new buildings will no longer have solar and electric boilers as backup systems. The entire roof of an apartment building will be dedicated to the installation of solar panels, and a heat pump will be installed in each apartment as both the primary and backup system. However, during non-sunny hours of the day, solar panels do not produce energy, and therefore all building equipment must receive power from the grid.
- 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 installations in thermodynamic cycles convert low-energy heat into electric power 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 easily and simply adjusted. Pneumatic motors operate on compressed air or water vapor. The industry produces various piston steam engines. But sometimes it is cheaper to convert automobile and tractor diesel engines into steam piston engines.
- By 2025, solar power plants with a total capacity of over 1,400 GW are operational worldwide, but by 2030, only 345 GW of energy storage capacity is projected. Therefore, the market for this energy storage technology is very relevant and amounts to 1,000 GW.

2. The purpose of the presented theoretical study: The purpose of the study is to consider a Complex of solar panels on the walls of buildings,

supplemented by water energy accumulators and heat engines, as an alternative to electrochemical batteries and as an autonomous controlled source of both night and day round-the-clock generation, located near the consumer.

3. Economic sense

- The studied Equipment Complex turns solar photovoltaic panels into an autonomous controlled source of both night and day round-the-clock generation. The consumer receives 79% of the panels' electric energy, providing an "energy return" no worse than that of a pumped storage power plant or electrochemical batteries. The studied water energy accumulators are 10-20 times cheaper than energy storage devices on electrochemical batteries of the same capacity and also have a twice as long service life. The capital cost of the system is approximately CAPEX = US$ 32/kWh or

US$ 500/kWh and the night energy price is 1.4 ¢/kWh.

.As an autonomous controlled source of round-the-clock generation in a decentralized energy system, the Complex increases the stability of electricity supply to consumers in the network.

- Solar power plants on the walls of multi-story residential and office buildings bring generation sources closer to energy consumers, which reduces the load on power grids and reduces the required capacity of new power transmission lines.

4. **Solar panels on the walls of buildings**.

4.1. Most of the sites suitable for solar panels in Israel are located in the south, while the demand areas are in the center and north. Dust and dirt can be a real problem for existing solar panels, as it interferes with their operation, especially in particularly dusty or desert areas. High-pressure washers or tractors with hydraulic brushes are commonly used to clean solar panels, but they waste a lot of water. Window and vertical glass wall cleaning and washing technology is widely used and is significantly cheaper than tractors for washing inclined rows of solar panels.

4.2. Let us consider the installation of solar panels on the walls of buildings. Fig. 1 shows such a building, in which the entire wall is covered – faced with solar panels. [23]

Fig. 1 [23]

Researchers from the Leipzig University of Applied Sciences claim that installing solar panels facing east and/or west will produce more renewable electricity and reduce one of the side effects of traditional solar farms - an abundance of electricity at midday and a shortage in the morning or afternoon. Their study was published in the August 2022 issue of the journal Smart Energy. By installing panels facing east or west, most of the electricity is generated in the morning and evening. This will reduce the need for electricity storage and therefore save a lot of valuable land area needed for electricity production.

Figure 2 shows a diagram provided by the Leipzig University of Applied Sciences. [24] The diagram shows typical solar energy production with a conventional orientation (black curve), a vertical east-west orientation (green), a south orientation (blue) and a combination of orientations. The east-west orientation starts producing electricity many hours earlier and continues producing energy many hours later than a conventional solar farm. There is a large drop in output during midday hours. The energy produced by the vertical panels facing south is the area below the blue curve in the graph and the energy produced by the panels facing east (or west) is the area below the green curve in the graph. As a first approximation, these areas are equal, so in this study it can be assumed that almost the same energy can be produced from south, east and west walls.

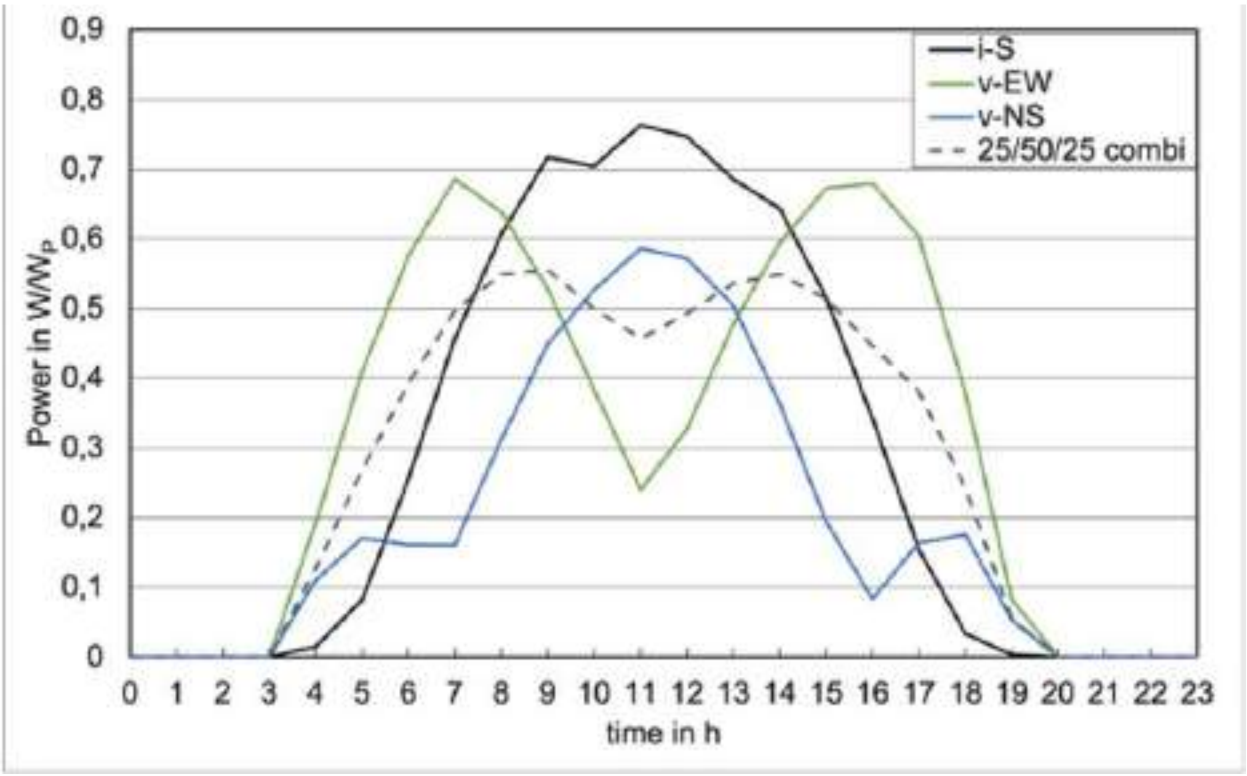


Fig.2 [24]

5. Let's look at the energy obtained from vertical panels in Jerusalem, Israel.

5.1. The data above were obtained at the latitude of Leipzig. The February 2020 Estimating the Optimum Tilt Angles for South-Facing Surfaces in Palestine Report [2] examined the energy potential of solar panels, particularly in Jerusalem. (See Tables 15, 16, 17, 18 in Appendix 1).

Let's look at an analysis of Tables 15, 16, 17, and 18 from the report:

- Tables 17 and 18 contain data on the amount of energy obtained (in kWh) for each month from 5 kW panels with the panels in **a horizontal** position (facing south).

- In this study, we are interested in the data on the amount of energy received (in kWh) from 5 kW panels with a **vertical** position of the panels (facing south). The tables do not contain such data, but the tables do contain information on the intensity of solar radiation (in kWh/m^2*day) with the vertical position of the panels.
- The ratio of the amount of energy received (in kWh) from 5 kW panels with a horizontal position of the panels (facing south) to the intensity of solar radiation (in kWh/m^2*day) for 48 measurements is 117.5 kWh/kWh/m^2*day.
- Based on this ratio, from Tables 15 and 16, it is possible to calculate the amount of energy received (in kWh) from panels with a capacity of 5 kW with a **vertical** position of the panels (facing south):
- Per year, with a **vertical** position of the panels (at an angle of 90o), the intensity of solar radiation (in kWh/m^2*day) for 4 measurements is (Tables 15 and 16) on average per month 3.46 in kWh/m^2*month (=(3.53+3.26+3.55+3.50/4)=13.84/4).
- Taking into account the above ratio (117.5 kWh/kWh/m^2*day), the energy received per year per 1 square meter of panels with a **vertical** position of the panels (facing south) is 176 kWh/m^2*year (=117.5*3.46*12*0.18/5).
- From Tables 15 and 16 it is clear that with a **vertical** position of the panels (angle 90o), the highest intensity of solar radiation (in kWh/m^2*day) is observed in October and November and is 4.52+4.63+4.49+4.12 (Table 15) +4.71+4.63+4.54+4.54 (Table 16).
- On average, for these 8 measurements, the highest intensity of solar radiation in October - November is 4.52 kWh/m^2*day (=36.18/8). Taking into account the above ratio (117.5 kWh/kWh/m^2*day), the highest amount of energy received (in kWh) in October and November from 5 kW panels with a **vertical** position of the panels (facing the south) is 531 kWh per month (=117.5*4.52). Thus, with a **vertical** position of the panels (facing the south), the highest amount of energy received (in kWh) on sunny days in October and November is 106 kWh/kW per month (=531/5) and 3.48 kWh/kW each day.

5.2. The peak power of most solar photovoltaic panels is 0.18 kW peak per 1 m^2 of panel area. Therefore, on the sunniest days in October – November we have the highest amount of energy received per 1 m2 of panel area 0.626 kWh/m^2*day (=3.48*0.18).

- With an average duration of sunny daylight in these months of 8 hours, we have an average panel power of 0.0783 kW/m^2 (=0.626 /8). On the sunniest days, the maximum panel power will be higher and will be no less than 0.08 kW/m^2.

In this study, based on the above information, we assume that the panels have a maximum power of 0.08 kW/m^2 (per 1 m^2 of panel) and produce 0.64 kWh/m^2 of energy during the day in 8 hours (=0.08*8).

5.3. According to the graph obtained by the Leipzig University of Applied Sciences [24], the energy obtained from vertical panels facing south is the area on the graph under the blue curve, and the energy obtained from panels facing east (or west) is the area on the graph under the green curve. As a first approximation, these areas are equal, therefore, in this study it can be assumed that from the southern, eastern and western walls the energy received per year per 1 square meter of panels with the panels in a vertical position is 176 kWh/m^2*year. And on the sunniest days, the maximum power of the panels will be no less than 0.08 kW/m^2.As shown above, with the panels in a vertical position, it can be roughly assumed that the same energy can be obtained from southern, eastern, and western walls.

5.4. To continue the study, let us consider a residential building, which is faced with square tiles, which allows us to visually estimate the area of the walls. See Fig. 3. The tiles are 1 m by 1 m in size (in reality, they are somewhat larger).

Fig. 3

The photograph shows two identical buildings. The building on the left in the photograph has a sunlit western wall, and its southern façade is not illuminated. The building on the right has a sunlit eastern wall in the morning and a sunlit southern wall in the afternoon. On a sunny day, the sun illuminates two walls of each building.

In Israel, building roofs are commonly used to install solar water heaters. When replacing water heaters with solar panels (as per the Ministry of Energy's decision [31]), the area of panels on the roof will be several times smaller than the area of panels on the walls of high-rise buildings.

In the buildings in question, the height of the floor is 3 m, the building has two walls (illuminated by the sun) 20 m long, 6 windows on two walls, 1 m each. The total area of the two walls without windows on each floor is 114 m² (=40*3-6).

On 2 walls on each floor (out of 13) it is possible to install 57 regular panels (with an area of 2 m^2 and a capacity of 0.18 kW peak/m^2) with a total capacity of 20 kW peak (=0.18*114). Above we showed that the panels give off 176 kWh/m^2*year per year. We assume that we receive almost the same energy from the southern, eastern and western walls. In our buildings in Fig. 12 on 6 floors on 2 walls we have a panel area of 684 m^2 (=114*6) and can receive 120 MWh (=176*684) of energy per year.

5.5. The average Israeli family uses 8162 kilowatt-hours per year (2023). [25] In our building, 120,000 kWh of energy can supply 14 average families. (=120,000/8162) There are 24 families living on the 6 floors considered, so the panels on the walls can cut the annual electricity costs of these families in half.

Higher residential buildings are less shaded and solar panels can be installed even on 3 walls and on more floors. See Fig. 4.

Fig. 4

In Fig. 4 we have a photo of a group of high-rise residential buildings. The buildings have 19 floors and are located quite far from each other and therefore do not block the walls from the sun. On these buildings, solar panels can be installed on the 15th…16th floors and on 3 walls. As we have shown above, the panels give
off 176 kWh/m^2*year per year.
The energy from 3 walls is one and a half times more and residents could further reduce their electricity bills.
A significant amount of energy can be obtained from installing solar panels on high-rise office buildings. The return on investment for placing solar panels on the walls of various buildings and structures is determined mainly by the prices that Hevrat Hashmal is willing to pay for solar green energy. In the summer, power grids have problems receiving energy from solar panels, so the problem of intermittent solar and wind energy can only be solved with the help of energy storage devices.
According to the website [29], in 2020, the volume of high-rise housing construction in Israeli cities amounts to hundreds of housing units. High-rise buildings (over 16 floors) account for 17.8% of the total construction volume... buildings 11-15 floors high (14.13%). Each high-rise residential building is several thousand square meters of space for solar panels, several megawatts of peak power, and several megawatt-hours of electricity per day. (See below, item 9)

6. Let's consider the possibilities using water accumulators of energy for solar panels on the walls of residential and office buildings.
- We will examine the efficiency assessment of the Complex of solar panels on the walls of residential buildings, supplemented by water accumulators of energy, using the example of a “field” of solar photovoltaic panels on the walls of the building shown in Fig. 4.

- We will study the efficiency assessment of the Complex of solar panels on the walls of residential and office buildings and water energy storage using the example of a "field" of solar photovoltaic panels on the walls of the building shown in Fig.4. On this building, we will assume that the area of the panels on 2 walls of each floor is also 114 m^2, as in the building in Fig. 4. On 16 unshaded floors on 2 walls, we have a panel area of 1824 m^2 (= 114 * 16). As we showed above (p. 5.1), the panels can produce energy of 176 kWh / m^2 * year per year, and on the sunniest days in October-November, the maximum power of the panels will be at least 0.08 kW / m^2.

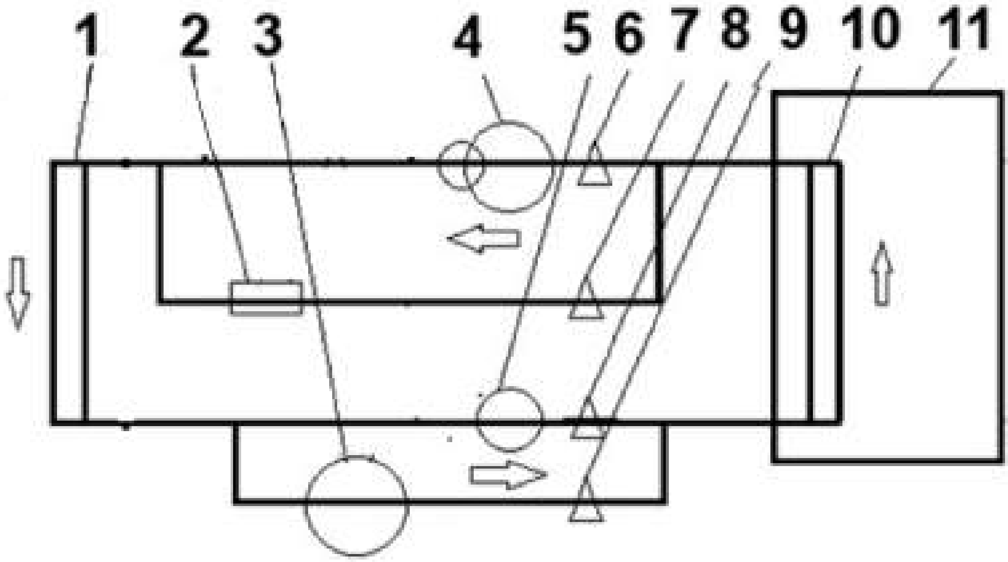
-In further analysis, for clarity, we assume that the total area of the panels is 1800 m^2.

The capacity of the solar photovoltaic panel field is 324 kW peak (= 0.18 * 1800), the productivity is 317,000 kWh per year (= 176 kWh/m^2 * 1800 m^2).

- In this study, based on the above information, we assume that the panels have a maximum power of 0.08 kW/m^2 (per square meter of panel) on the sunniest days in October-November and generate energy of 0.64 kW h/m^2 (= 0.08 * 8) during 8 hours of sunny daylight (in October-November).

7. Description of the Complex Operation

The complex complements the solar power plant and includes water thermal accumulators of energy and thermal machines. The layout of the system is shown in Fig. 5.



15 oC 85-95 oC

Fig. 5

Designations in Fig. 5:

1 - 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 Operation

7.1. During Sunny Time

Solar photovoltaic panels generate electricity during sunny time of day. Part of this electricity is supplied through the inverter directly to the consumer. Solar panels and inverter are not shown in the diagram.

The other part of the electric power goes to the motor of the compressor 3. The refrigeration circuit of the compressor 3 consists of the throttle 2, the radiator 1 and the heat exchanger 10. In the radiator 1, the cold 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 the hot water.

The air cooled in the radiator can be directed to residential, office or industrial premises.

7.2. In non-sunny time of day

In non-sunny time, compressor motor 3 is switched off, valves 7 and 9 are closed, and valves 6 and 8 are opened. Pump 5 and expander-generator 4 are switched on. Expander 4 has an electric generator that gives 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.

7.3. Conversion of electrical energy of panels during solar time

In this study, based on the above information, we assume that the panels have a maximum power of 0.08 kW/m^2 (per 1 m^2 of panel) in October-November and produce energy of 0.64 kWh/m^2 (=0.08*8) during the day in 8 hours.

7.4. For example, half of this power 0.04 kW/m2 is received by the inverter, which produces energy of 0.32 kWh/m2 (=0.04*8) in 8 hours, and gives the consumer electricity of 0.304 kWh/m2 (=0.95*0.32) during sunny hours with an average power of 0.038 kW/m2 (=0.304/8). The inverter has an efficiency of 0.95.

The remaining part of the panels' power 0.04 kW/m2 (out of 0.08 kW/m²) is directed to the compressor motor to accumulate energy for non-solar times.

7.5. The power ratio for the inverter and compressor pump may be different depending on the average statistical needs of the building. Reducing the share of energy for the compressor reduces the amount of energy generated during non-solar times.

8. Analysis of the efficiency of the studied complex, including solar panels, a water thermal energy accumulators and thermal machines - compressors and expanders.

8.1. We will evaluate the Complex's efficiency using the example of solar photovoltaic panels on walls with an area of 1,800 m^2. The solar photovoltaic panel field capacity is 324 kW peak, and the annual output is 317,000 kWh. (See Section 6).

From solar panels in October-November, the consumer receives 547 kWh of electricity per day (=0.304 kWh/m^2*1800 m^2) with an average power of
68 kW (=0.038 *1800) - see section 7.4.

During non-sunny times in October-November, the consumer receives 324 kWh of energy (=0.18 kWh/m^2*1800 m^2) from the expander over 16 hours per day from the Complex with an average power of 18 kW (=281/16) -see section 9.2.

- The panels produce 317,000 kWh per year, half of which (via the inverter) goes directly to the consumer, 151,000 kWh (=317,000*0.5*0.95), and the expander gives the consumer 46% of the other half, 73,000 kWh (=317,000*0.5*0.46). In total, the Complex gives the consumer 224,000 kWh of energy per year (=151,000+73,000).

If all the energy from the panels were fed through the inverter, the consumer would receive energy (but only during sunny hours) of 301,000 kWh (=317,000 * 0.95). Therefore, the Complex's annual energy return is 74% (=224,000/301,000).

9. Thermodynamic calculations

9.1. Thermodynamic calculations were performed for the sunniest days in October-November. In the calculations, it was assumed that the ambient air temperature during the day is 20 °C, and the temperature of the refrigerant in the radiator in the compressor circuit due to heat removal is 15 °C.

During non-sunny periods, the ambient air temperature is 10 °C. The temperature of the coolant in the expander circuit in the radiator is 15 °C due to the removal of heat 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.

9.2. The following results of thermodynamic calculations were obtained for a panel area of 1800 m^2:

- The refrigeration coefficient in the refrigeration cycle is εк = 3.264.
- During an 8-hour sunny day in October-November, the compressor circuit in heat pump mode receives 2.73 GJ of energy per day from the panels (=0.04*8*3.6*1800), but takes 4.52 GJ of energy from the ambient air through the radiator (=2.51* MJ/h*m^2*1800 m^2)-
- During these 8 hours in October-November, the hot water accumulates 6.6 GJ of energy (= 3.66 MJ/h*m^2*1800 m^2) due to the operation of the heat pump, which received only 2.73 GJ from the panels

.- In non-solar times, the conversion of heat into work in the expander circuit has a theoretical efficiency coefficient of Kp= τ=0.2066.

- The expander produces work and will transfer to the consumer, over 16 hours of non-solar time per day in October-November, energy of 1.01 GJ (=0.562 MJ/m2 *1800 m2) with an average power of 18 kW (=0.0097 kW/m^2 *1800 m^2)

9.3. During the day and night in October-November, the consumer receives 828 kWh of energy (=547 +281) with an average power of 68 W during the day and 18 W at night.

10. **The panels produce** 317,000 kWh annually, half of which (via the inverter) goes directly to the consumer: 151,000 kWh (=317,000*0.5*0.95), and the expander gives the consumer 46% of the other half: 73,000 kWh (=317,000*0.5*0.46). In total, the Complex gives the consumer 224,000 kWh of energy per year (=151,000+73,000).

If all the energy from the panels were fed through the inverter, the consumer would receive energy (but only during sunny hours) of 301,000 kWh (=317,000 x 0.95). Therefore, the Complex has an annual energy return of 74% (=224,000/301,000).

- It is important to emphasize that the Complex also provides consumers with energy at night, turning solar panels into a completely autonomous, controllable 24-hour energy source.

11. Main characteristics of the Complex:

- Solar panels have a total area of 1800 m^2,
- Installed capacity: 324 kW peak,
- Annual energy production by panels: 317,000 kWh.
- Annual energy production during daylight hours: 151,000 kWh
- Annual energy production during non-solar hours: 73,000 kWh
- Daytime energy: 547 kWh per day in October-November
- Useful returned (night) energy: 281 kWh per day in October-November.
- Capital expenditure (CAPEX) = $32/kWh or $500/kWh, the price of night energy is 1.4 ¢/kWh – see item 13.5.

Compressor motor power must be at least 70 kW.

- Expander generator power must be at least 20 kW.
- Hot water tank capacity must be at least 160 m^3.
- Heat exchanger power must be at least 230 kW.
- Radiator power must be at least 190 kW.
- Energy recovery efficiency is 74 % - see item 10.
- Required capacity of alternative battery: 864 kW h – see item 13.7.

12. Estimation of the capacity of an alternative storage battery

We will study a system containing solar panels, an inverter and a storage 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, 0.32 kWh/m^2 (= 0.04*8), and the remaining energy 0.32 kWh/m^2 (= 0.04*8) is stored in an electrochemical battery for use in non-sunny periods, then:
- The consumer will receive 0.304 kWh/m^2 during the day (= 0.32*0.95) and 0.243 kWh/m^2 in non-sunny periods (= 0.32*0.8*0.95).
- Here we assume that the inverter operates with an efficiency of 95%, and the battery (including controller losses) has an energy recovery efficiency of 80%
- A system containing only an inverter would supply the consumer with energy of 0.608 kWh/m^2 (=0.08*8*0.95) during the day.
- A system containing an inverter and a battery will supply the consumer with a total of 0.547 kWh/m^2 (=0.304+0.243) during the day and night, which is 90% (=0.547/0.608) of the energy generated by a system using only an inverter.
- An alternative storage battery should return this stored energy of 0.32 kWh/m^2 every night, but modern batteries can only be discharged by 80%. Therefore, the battery should have a capacity of at least 0.4 kWh/m^2 (=0.32/0.8). It is known that electrochemical batteries lose their capacity by 10-20% during operation. To prevent intensive loss of battery capacity during its nightly discharge, the battery capacity should be increased by at least 20% and be at least 0.48 kWh/m^2 (=0.4*1.2).

13. Cost of capital equipment and materials for a solar panel array with a total area of 1800 m^2.

In this section we will calculate the cost of the capital equipment used in the solar panel system, including compressors, expanders and their alternatives. The prices are based on available information and assumptions, such as the use of compressors and expanders made from repurposed automobile and tractor diesel engines.

13.1. The analysis of prices for heat engines is given in Appendix 3.

The analysis showed that for further research in the Solar Panel Complex with an area of 1800 m^2 on the walls of buildings, it is advisable to use converted autotractor diesel engines as compressors and expanders. Their average price is US$ 50/kW. The total capacity of the compressors is 72 kW and the cost is US$ 3500 (= 50 * 70). The total capacity of the expanders is 20 kW and the cost is US$ 1000 (= 50 * 20).

13.2. Compressor electric motors cost US$ 1 /kW [12]. 70 kW electric motors cost US$ 70.

Expander electric generators cost US$ 2 /kW [13]. 20 kW electric generators cost US$ 40.

13.3. The total capacity of the heat exchangers and radiator is 400 kW. According to the Internet, the prices of heat exchangers range from US$ 1.3/kW [14] to US$ 10 /kW [15]. Their average price is US$ 5/kW. The cost of a heat exchanger and radiator for a Solar Panel Complex is about US$ 2000 (=5*400).

13.4. Cost of insulated tank

The cost of insulated tank is calculated in Appendix 4.

The cost of materials and concrete work is US$ 3060.
The cost of insulation – foamed polyethylene – is US$ 550.
13.5. **The total cost** of the main equipment and materials for a 1800 m^2 solar panel field on the walls of buildings is approximately:
The total cost is US$ 10,220, including 3500 (compressors) + 1000 (expanders) + 70 (electric motors) + 40 (generators) + 2000 (heat exchangers) + 3060 (concrete) + 550 (insulation).
The useful stored (night) energy is 324 kWh/day
Capital expenditure (CAPEX) is $32/kWh (=10,220/324) or $500/kW (=$10,220/20/kW).
The share of equipment cost in the annual nighttime energy price
CAPEX is 1.4 ¢/kWh (=$10,220/73,000*10). Here:
- equipment cost is $10,220,
- annual nighttime energy production is 73,000 kWh,
- the service life of the refrigeration equipment is 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 (2024) is $0.02/kWh = 2¢ /kWh [30]
13.6 Average capital costs as of May 2024 [1] for thermal energy and compressed air storage were US$ 232 /kWh and US$ 293 /kWh, respectively. In 2023, average capital costs for lithium-ion systems were US$ 304 /kWh for systems with a four-hour storage duration, i.e., typically for shorter storage periods.
13.7. An alternative electrochemical battery for the studied Solar Panel Complex with a total area of 1800 m^2 on the walls of buildings should have a capacity of at least 864 kWh (=0.48*1800) - see item 11.
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 studied Complex should be at least
US$ 130,000 (=151*864), and the price of LiFePO4 batteries would be at least
US$ 250,000 (=290*864).

14. Results

14.1. Comparison of the cost of the complex
- The cost of the equipment complex for solar panels (including compressor, expander, heat exchanger, concrete work and thermal insulation) is US$ 10,320.
- This cost is 10-20 times less than the cost of alternative batteries (US$ 130,000 or US$ 250,000) required to store the same amount of electricity. The capital cost (CAPEX) is US$ 32/kWh or $500/kW and the night energy price is 1 ¢/kWh..

14.2. Environmental Considerations
- The solar panel system in question uses water and coolants circulating in closed circuits that are not exposed to the atmosphere, making it environmentally friendly.
- The refrigeration units and coolants 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.

14.3. **Construction features**. Cost of cladding buildings. - The price of solar panels has remained at about $ 0.2 per Watt peak in recent years. The panels are, for example, 1 by 2 m, with a power of 360 W peak. The panel costs $ 72 and has an area of 2 m^2, i.e. the price of cladding a wall with panels is $ 36 per square meter (excluding the cost of installation work).
- The cost of stone tiles for external cladding of buildings under construction is $10.00-$ per square meter. [26]

Installing stone tiles on walls costs between $70 and $250 per square meter. [27]

- Installing glass curtain walls on office buildings costs between $2,000 and $6,000 per s meter. Although these glass walls are not load-bearing, they are usually part of a wall s and have a lightweight metal frame such as aluminum. This means that they require c installation on adjacent structural members. [28]
- So, we see that facing buildings with stone tiles costs about $ 100 per square meter, f buildings with glass units costs thousands of dollars per square meter. And the price of panels for wall cladding is $ 36 per square meter.

15. Conclusion

15.1. Advantages of the complex

- The solar panel equipment complex, consisting of refrigeration compressors, expanders and water accumulators, offers a highly profitable and environmentally friendly alternative to electrochemical batteries.
- The total capital cost of the complex is significantly lower than when 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.
- As an autonomous, controlled source of round-the-clock generation in a decentralized energy system, the Complex increases the sustainability of electricity supply to consumers in the network.
- Solar power plants on the walls of multi-story residential and office buildings bring generation sources closer to energy consumers, which reduces the load on power grids and reduces the required capacity of new power transmission lines.
- Solar power plants on the walls of multi-story buildings can be built on any already constructed and operating building.

15.2 Presentation of the Study

This study 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.

Links

[1] Source: Capex for energy storage technologies as of May 2024. https://www.ess-news.com/2024/05/31/ldes-poised-to-outcompete-lithium-ion-batteries/

[2] https://www.researchgate.net/publication/342903106_Estimating_the_Optimum_Tilt_Angles_for_South-Facing_Surfaces_in_Palestine

[3] Determination of the energy efficiency of devices, installations and systems PhD A.V. Martynov. http://www.energosovet.ru/stat616.html

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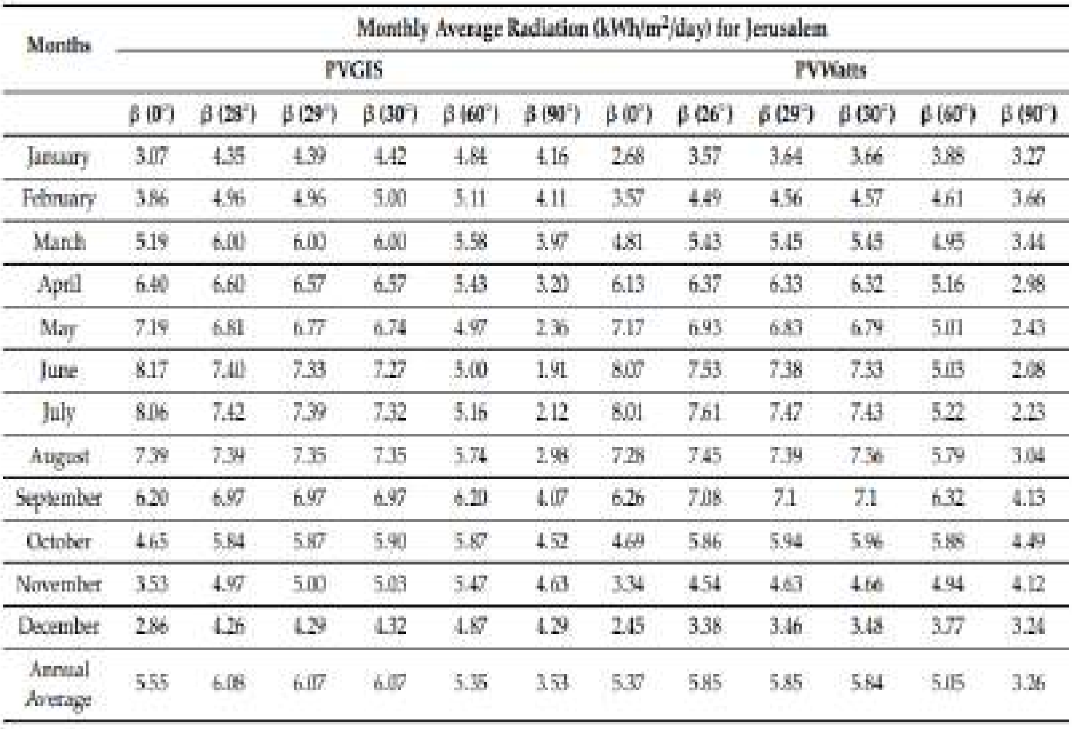
Application 1

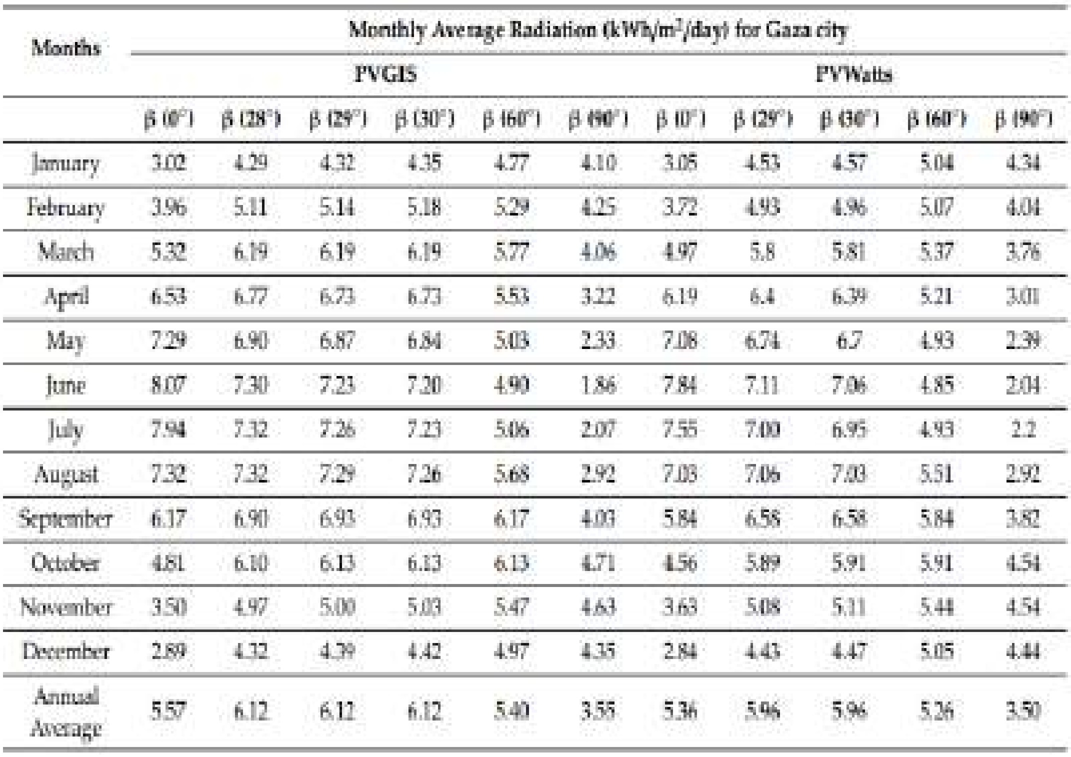
Tables 15, 16, 17, 18 from the report Estimating the Optimum Tilt Angles for South-Facing Surfaces in Palestine dated February 2020 [2]

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



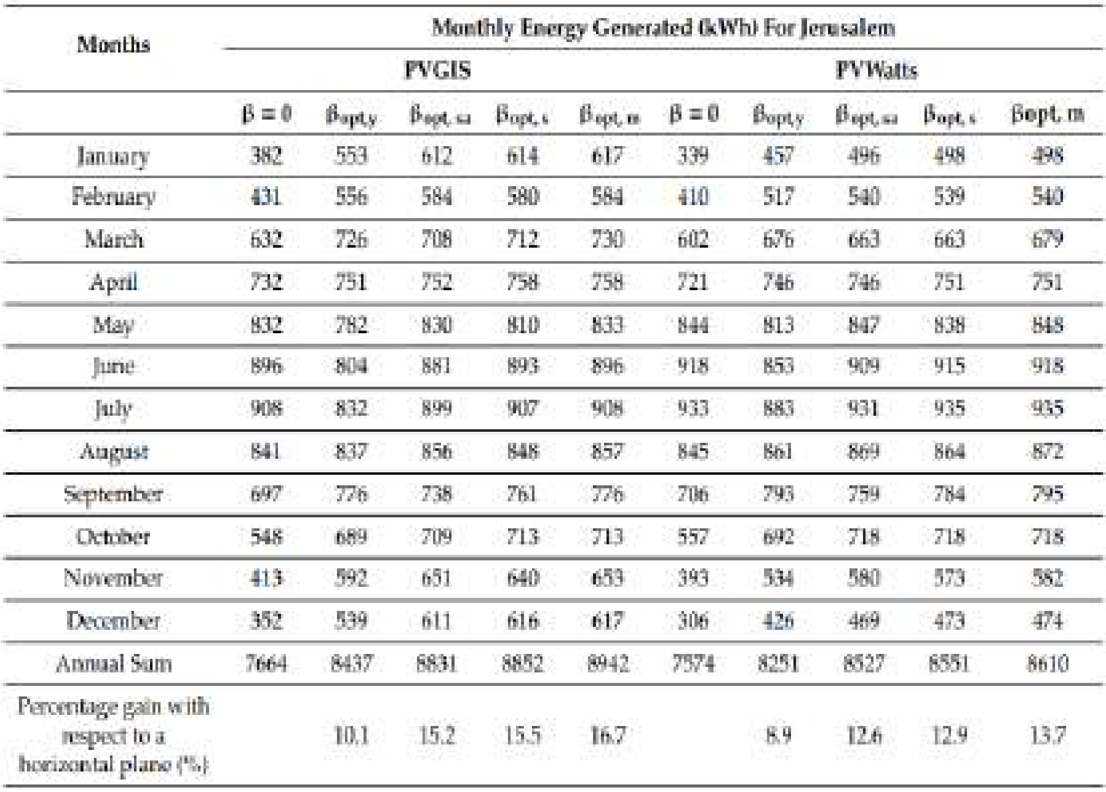
Months	Monthly Average Radiation ($\text{kWh/m}^2\text{/day}$) for Jerusalem											
	PVGIS						PVWatts					
	β (0°)	β (28°)	β (29°)	β (30°)	β (60°)	β (90°)	β (0°)	β (26°)	β (29°)	β (30°)	β (60°)	β (90°)
January	3.07	4.35	4.39	4.42	4.84	4.16	2.68	3.57	3.64	3.66	3.88	3.27
February	3.86	4.96	4.96	5.00	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).



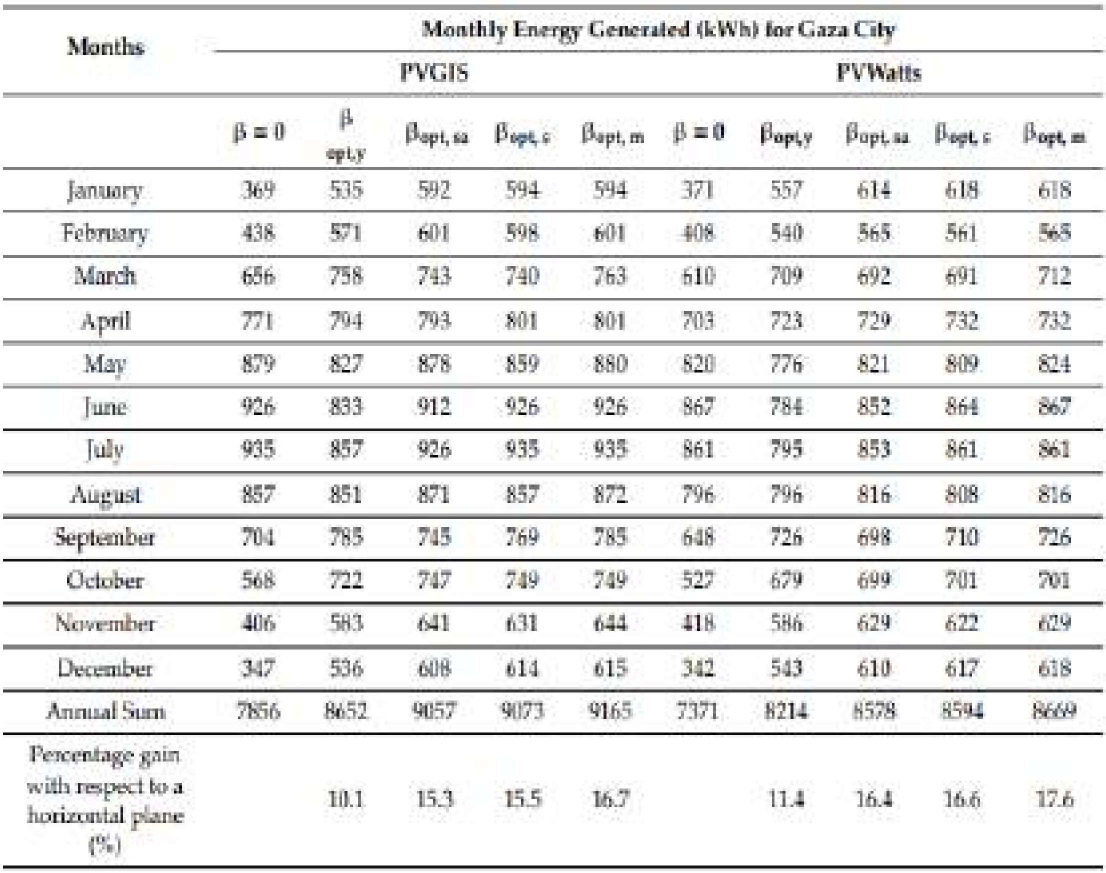
Months	Monthly Average Radiation (kWh/m^2/day) for Gaza city										
	PVGIS						PVWatts				
	β (0°)	β (28°)	β (29°)	β (30°)	β (60°)	β (90°)	β (0°)	β (29°)	β (30°)	β (60°)	β (90°)
January	3.02	4.29	4.32	4.35	4.77	4.10	3.05	4.53	4.57	5.04	4.34
February	3.96	5.11	5.14	5.18	5.29	4.25	3.72	4.93	4.96	5.07	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				
	β = 0	$\beta_{opt,y}$	$\beta_{opt,sa}$	$\beta_{opt,s}$	$\beta_{opt,m}$	β = 0	$\beta_{opt,y}$	$\beta_{opt,sa}$	$\beta_{opt,s}$	βopt, 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				
	$\beta = 0$	$\beta_{opt,y}$	$\beta_{opt,sa}$	$\beta_{opt,c}$	$\beta_{opt,m}$	$\beta = 0$	$\beta_{opt,y}$	$\beta_{opt,sa}$	$\beta_{opt,c}$	$\beta_{opt,m}$
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 ηi = 0.8, the effective coefficient - ηeff = 0.95, the electric efficiency - ηel = 0.95 were adopted in the calculations.

Based on the analysis of the proposed Equipment Complex (see Fig. 5), which was performed by Chat GPT Plus, the efficiency was clarified as follows: indicator efficiency ηi = 0.78, effective efficiency ηeff = 0.9, electrical efficiency –ηel = 0.95, and it was also recommended to reduce the theoretical COP by 15%. The total efficiency product is
ηi·ηeff·ηel = 0.78 * 0.9 * 0.95 = 0.6669.

2. Electricity from the panels during sunny periods is accumulated in a water tank 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 0.08 kW/m^2 (per square meter of the panel) and generate during the day (in October-November) for 8 hours energy of 0.64 kW h/m^2 (= 0.08 * 8) - see paragraph 5.2.

- For example, half of this power 0.04 kW/m^2 is received by the inverter, which produces energy 0.32 kWh/m^2 (=0.04*8) in 8 hours, and gives the consumer electricity during the day 0.304 kWh/m^2 (=0.95*0.32) with an average power of
0.038 kW/m^2 (=0.304/8). The inverter has an efficiency of 0.95.
The remaining part of the panels' power 0.04 kW/m^2 (out of 0.08 kW/m^2) is sent 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 statistical needs of consumers and the network. Reducing the share of energy for the compressor reduces the amount of energy generated in non-sunny times.

3. Thermodynamic processes occur as follows.
3.1. Conversion of electrical energy from panels during solar time
- Half of the electrical energy from solar panels goes to the compressor, for example, 0.04 kW h/m^2*h from 0.08 kW h/m^2*h. Here and further in Appendix 2, all calculations are performed for 1 square meter of solar panel.
- The total real power going to the compressor is
Nk=N/ ηi *ηeff*ηel = 0.04 kW/m^2. See [4]
- The efficiency factors are specified in point 1 and their product is
0.6669 (=ηi * ηeff * ηel = 0.78 * 0.9 * 0.95).
- The theoretical compressor power N in the thermodynamic cycle at these efficiencies is N = Qo / εк = Nk * ηi * ηeff * ηel = 0.04 * 0.6669 = 0.0267 kW / m^2.
- In the hot tank, the temperature in the middle of the cycle is Tg = 90 oC = 363 K.
- The temperature of the refrigerant in the radiator during the day (in October-November) in the middle of the cycle Tc = 15 oC = 288 K (outside air with a temperature of 20 oC, refrigerant temperature up to 15 oC).
- The cooling coefficient is εk = Tc / (Th - Tc), where Tc and Th are the absolute temperatures of the cold refrigerant in the radiator and hot water:
εk = Tc / (Th - Tc)) = 288/(363-288)=3.84. We accept the real COP as 15% less than the theoretical εк=3.264 (=0.85*3.84) - see point 1.
- Cooling energy, i.e. cooling capacity is per hour
Eo=Qo= N*εк =0.0267 *****3.264**=**0.0871 kWh/h *m^2=0.314 MJ/h*m^2. During 8 hours of average solar time (in October-November), the compressor circuit takes energy
of 2.51 MJ/m^2 (=0.314 *8) from the air through the radiator
The heated hot water in the compressor circuit received energy Eg per hour during the day, which is equal to the energy of the thermodynamic cycle Eo = Qo (which the radiator received from the surrounding air) plus energy Ep (which the compressor pump received):
Eh=Eo+Ep=0.0871 kWh/m^2+0.04 kWh/m^2=0.1271 kWh/m^2=0.458 MJ/h*m^2.
Eo=Qo= N*εк =0.0267 *****3.264**=**0.0871 kWh/h *m^2=0.314 MJ/h*m^2
The energy consumed by the compressor pump in 1 hour Ep=0.04 kWh/m^2.
For 8 hours of average solar time, the hot water received energy
3.66 MJ/m^2. (=0.458*8)

3.2. Conversion of electrical energy of panels in non-solar time
- In the studied Complex, the compressor and expander are the same thermal piston machines, which structurally differ only in the valve drive.
Based on the analysis of the proposed Equipment Complex (see Fig. 5) performed by Chat GPT Plus, the efficiency of the expander was refined as follows: indicator efficiency ηi = 0.85, effective efficiency ηeff = 0.92, and electrical efficiency ηel = 0.95. The total efficiency product ηi·ηeff·ηel is 0.743 (= 0.85*0.92*0.95).See paragraph 1.
Analysis of data on operating steam piston engines also shows that the indicated efficiency

(ηi) is in the range of 0.75-0.85, and the effective efficiency (ηeff) is in the range of 0.90-0.95.

- 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 conversion occurs from hot water 11 with a temperature in the middle of the cycle Th = 90 oC = 363 K to the temperature of the refrigerant in the radiator 1 at night in the middle of the cycle Tc = 15 oC = 288 K.

The efficiency coefficient τ will be 20%:

τ = (Th - Tc) / Th = (363 - 288) / 363 = 0.2066.

From the energy Eh=3.66 MJ/m^2, obtained during the day for 8 hours with hot water, it is theoretically possible to obtain work

E=Eh* τ =0.756 MJ /m^2 (=3.66 *0.2066)=0.21 kWh/m^2.

Taking into account the efficiency=0.743 of the thermodynamic cycle, the expander will produce work and transfer it to the consumer in 16 hours of non-solar time

Ew=0.156 kWh/m^2 (=0.21*0.743) with an average power of 0.0097 kW/m^2 (=0.156/16).

3.3. The radiator in non-solar time emits energy of 2.9 MJ/m^2 (=3.66-0.756), which is equal to the energy of 4.35 MJ/m^2 received by hot water, minus the energy theoretically converted into work (0.756 MJ /m^2).

Radiator 1 must dissipate energy of 2.9 MJ/m^2 during the evening and night, so that the refrigerant in the radiator by morning has a temperature of 15 oC or lower.

3.4. **During sunny** hours, the inverter receives a power of 0.004 kW/m2, which in 8 hours receives energy of 0.32 kWh/m2 (=0.04*8), and gives the consumer electricity during the day of 0.304 kWh/m2 (=0.95*0.32) with an average power of 0.038 kW/m2 (=0.04*0.95). The efficiency of the inverter is 0.95.

4. In non-sunny time, the expander 4 has a capacity of 0.0097 kW/m^2 and gives the consumer energy of 0.156 kWh/m^2.

- In total, during the day and night in October-November, the consumer receives 0.46 kWh/m^2 (=0.304+0.156) of energy with an average power of 38 W/m^2 during the day and 10 W/m^2 at night.

If all the energy from the panels were supplied through the inverter, the consumer would receive 0.608 kWh/m^2 (=0.64*0.95) of energy during the day only.

- A system with a heat pump, compressor, and expander-generator delivers 75% (0.46/0.608) of the energy from the inverter-equipped panels to the consumer in October-November. However, the system also delivers energy at night, transforming the panels into an autonomous, controllable source of 24-hour generation. Thus, the consumer receives 75% of the energy from the system, providing an energy "return" similar to that of a pumped storage power plant or batteries.

5. Calculation of the hot water tank volume

- The volume of the hot water tank 11 receives energy Eh=3.66 MJ/m^2 from the compressor circuit during the day.

The heat capacity of water is 4212 J/kg*oC, the heat capacity of 1 m^3 of water from +85 oC to 95 oC is E10=1000*4212*10=42 MJ/m^3.

The mass of hot water is

Mh = 160 m^3 (=1800 * 1000 * Er / E10 = 1800 m^2 * 3.66 MJ / m^2 / 42 MJ / m^3).

6. Equipment capacity:

- Compressor motor capacity must be at least 68 kW (=0.038 kW/m^2 * 1800 m^2).
- Expander capacity must be at least 18 kW (=0.0097 kW/m^2 * 1800 m^2).

- Heat exchanger capacity: The heat exchanger transfers 3.66 MJ/m² of energy from the refrigerant to hot water over 8 hours during the day. At night, the heat exchanger transfers 3.66 MJ/m² of energy to the refrigerant over 16 hours. The heat exchanger capacity must be at least 230 kW (=1800 * 3.66/8 * 3.6).
- Radiator capacity: The radiator must dissipate 2.51 MJ/m² of energy during the day and 2.9 MJ/m² of energy over 16 hours at night to ensure the refrigerant temperature reaches 15°C or lower by morning.

The radiator capacity must be at least 160 kW (=1800 * 2.51/8 * 3.6).

Appendix 3

Analysis of prices for heat machines

- The total capacity of the compressor motors will be 70 kW.

According to the Internet, prices for compressors for refrigeration units vary 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$ 11,000 (= 150 * 72).

- The total capacity of the expanders will be 20 kW. Prices for expanders for refrigeration devices 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$ 41,000 (= 280000 * 1.1 * 20/150).
- We are exploring alternative options for expanders and compressors.
- The industry produces a range 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 diesel engines for the manufacture of piston steam engines. [8] Compressors for refrigerants can also be manufactured on the basis of 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 - slightly exceeds the cost of the diesel engine on which they are based. The price of automotive and tractor diesel engines, due to their mass production, is quite low and amounts to, for example, from US$ 30/kW [10] to US$ 70/kW [11].

- Summary of Heat machines Costs

Equipment Capacity	Cost US$ per kW	Total Cost US$
Compressor (Internet option) 70 kW	150	11,000
Expander (Internet option) 20 kW	2,090	41,000
Compressor (Air Motor) 70 kW	135	10,000
Expander (Air Motor) 20 kW	135	2,700
Compressor (Diesel Engine Based) 70 kW	50	3,500
Expander (Diesel Engine Based) 20 kW	50	1,000

- From the above we see that using diesel engine based compressors and expanders (with a price of US$ 50 /kW) will result in the lowest cost of both compressors and expanders, a total of US$ 4600 for both. This option is particularly attractive due to the low cost of US$ 50 /kW and the 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$ 52,000.

The air motor option is in the middle, offering a total cost of US$ 12,700 for compressors and expanders.

By choosing diesel engine-based components, the system can achieve significant cost savings while still providing the required performance for the solar panel array.

- For further research, we assume that in the Solar Panel Complex with an area of 1800 m^2, we use converted autotractor diesel engines as compressors and expanders. Their average price is US$ 50/kW. The total capacity of the compressors is 70 kW and the cost is US$ 3500 (= 50 * 70). The total capacity of the expanders is 20 kW and the cost is US$ 1000 (= 50 * 20).

Appendix 4

Calculation of the cost of a heat-insulated tank

-The thickness of the heat insulation and the thickness of the concrete walls, bottom and floors of the tank are adopted 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 Mg = 160 m^3.

The hot water tank has internal dimensions of 18 m in length, 6 m in width, 2 m in depth and is made as a concrete box with a concrete floor. The thickness of the walls at the bottom is 0.2 m, at the top 0.1 m, the floor and bottom are 0.1 m each.

The volume of concrete is no more than 36 m^3.

- The area of 1 layer of thermal insulation with a total thickness of thermal insulation of 0.025 m (5 layers of 0.005 m) is 330 m^2 and the area of 5 layers will not exceed 1700 m^2. This is 35 rolls of 50 m^2.

- The cost of materials and concrete work is US$ 3,060 (= 85x36) at a price of US$ 85/m^3 (= 300 shekels per cubic meter) [17].

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