SATBAYEV UNIVERSITY
Journal of Energy, Mechanical Engineering and Transport
Volume 2 (2025), Issue 2, 22-27

https://doi.org/10.51301/jemet.2025.i2.04

Combined installations based on renewable energy sources (control, generation of electric and thermal energy)

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Abstract. In recent decades, humanity has been actively looking for sustainable and environmentally friendly ways to meet its growing energy needs. Renewable energy sources (RES) such as solar, wind, hydropower, biogas, and geothermal energy are the main focus of these efforts. In this regard, combined installations based on renewable energy sources are being actively introduced, which make it possible to simultaneously generate electrical and thermal energy, increasing the efficiency and stability of energy systems. Combined installations powered by renewable energy sources represent an innovative and efficient approach to energy generation, combining several systems of its production and use into a single cycle. These systems optimize the use of renewable energy to generate electricity and heat, ultimately improving overall energy efficiency and stability. The main concept is cogeneration, the process of simultaneous production of two types of energy: electric and thermal. In the case of renewable energy sources, this process typically uses solar, wind, biomass, and geothermal resources. For example, photovoltaic-thermal (PVT) solar systems combine solar photovoltaic panels to generate electricity with solar thermal collectors to generate heat. Similarly, biomass power plants and geothermal installations are capable of producing both electrical and thermal energy, meeting the needs of the industrial, residential and agricultural sectors.

Keywords: *renewable energy sources (RES), cogeneration, energy efficiency, electric energy, thermal energy, solar energy, wind energy, biomass, geothermal energy*.

1. Introduction

In today's world, growing electricity demand and mounting environmental challenges compel society to seek alternatives to traditional energy sources. Thermal power plants (TPPs) and other fossil-fuel facilities have limited efficiencies (30–42% for TPPs) and produce significant carbon-dioxide emissions. By contrast, renewable energy sources (RES)—notably solar and wind generation—offer promising efficiency figures, reaching 15–22% for photovoltaic panels and 35–50% for wind turbines [3].

The chief obstacle for RES remains output variability: solar power is available only during daylight, and wind strength fluctuates. To boost overall performance, hybrid RES systems—combining solar panels, wind turbines, biogas units and pumped-storage batteries—smooth production swings and raise total system efficiency to 50–70% [3].

A primary advantage of combined energy installations is their ability to generate electricity and heat simultaneously, dramatically increasing overall energy efficiency. In conventional generation, a large share of energy is lost during conversion and transmission. Combined plants instead capture surplus heat created during electricity production and use it to warm buildings or meet industrial needs, markedly reducing total energy consumption and improving resource utilization.

The core control principle for such systems is to synchronize the various generators and balance real-time demand for electricity and heat. A typical energy complex may therefore integrate photovoltaic panels, wind turbines, biomass boilers, geothermal units and solar-thermal collectors, whose joint operation provides a more stable and rational energy supply.

2. Materials and methods

Combined installations based on renewable energy sources (RES) are sophisticated energy complexes that employ several generation and control technologies simultaneously. This approach increases resource-use efficiency, lowers energy costs and minimises the impact of fluctuations in any single source. The key components are: Hybrid generators – parallel operation of different RES units that together meet the demand for both electricity and heat. Intelligent (automated) control system – balances load, manages energy storage and minimises losses. Energy-storage system – smooths the variability inherent in RES generation.

Extensive research is under way in this field, and scientists continue to make significant advances. Typical combinations now under investigation are summarised in Tables 1 and 2.

Analysis of the tables shows that the solar-wind pairing and the wind-hydro pairing deliver the highest performance indices. At the Department of Energy, Satbayev University (43.25° N, 76.95° E), ongoing research focuses on precisely these configurations. The experimental system incorporates PV modules, inverters, a pyranometer, a weather station and devices for monitoring operating parameters.

Photovoltaic modules (PV) convert solar energy into electricity via the photovoltaic effect. The basic element is the solar cell, a semiconductor junction that releases electrons when struck by light, thereby producing current. Several module types exist, differing in materials, manufacturing techniques and applications [5]. This variety reflects efforts to raise conversion efficiency and reduce manufacturing cost.

Table 1. Average performance of popular RES combinations

RES combination	Average efficiency, %	System reliability
Solar + Wind	85	High
Solar + Biomass	80	Medium
Wind + Hydropower	90	High
Solar + Geothermal	85	High

Table 2. Energy outputs and applications of selected hybrid options

RES combination	Electrical output	Thermal output	Typical applications
Photovoltaic panels (PV) + solar-thermal collectors	Electricity via PV modules	Water/air heating via collectors	Homes, greenhouses
Geothermal energy (ORC plants)	Electricity via Organic Rankine-Cycle turbines	Hot water/steam from geothermal wells	District heating, industry
Small hydropower + heat exchangers	Turbine electricity	Heat extraction from water via exchangers	Heating of buildings near rivers and lakes
Wind energy + heat pumps	Electricity from wind turbines	Conversion of electricity to heat by heat pumps	District-scale heating

Figure 1. CHN250-60P

The 250 W CHN250-60P module from Chinaland Solar Energy is a popular choice for private homes, small businesses and small-scale solar plants because it balances cost and performance.

Cell type Poly-crystalline cells (lower price than mono-crystalline at slightly lower efficiency)
Maximum power 250 W
Efficiency 17–18%
Dimensions 1650 mm × 990 mm × 35 mm
Weight 18–20 kg
Temperature coefficient 0.40% / °C
Short-circuit current (I_{sc}) 8.8 A
Open-circuit voltage 30.5 V

The 550 W RSM144-9-550M module from Risen is a high-efficiency product for commercial and residential PV plants. It belongs to Risen's mono-crystalline line and uses advanced cell technology for higher efficiency and longer service life.

Cell type Mono-crystalline PERC (Passivated Emitter and Rear Cell)
Maximum power 550 W
Efficiency 21.2%
Dimensions 2278 mm × 1134 mm × 35 mm
Weight 27.5 kg
Temperature coefficient –0.34% /C
Short-circuit current (I_{sc}) 15.48 A
Open-circuit voltage 41.4 V
Number of cells 144 mono-crystalline cells (standard for ≈500 W modules)

Figure 2. RSM144-9-550M

An *inverter* converts the direct current (DC) supplied by PV modules, batteries or other sources into alternating current (AC) suitable for household and industrial loads. Stand-alone inverters – operate without a grid connection, together with batteries. Grid-tied inverters – connect to the utility grid and can export surplus energy. Hybrid inverters – combine both modes, working with or without the grid and with batteries.

Technical data of inverters used in the project: Model MEX-3000-24 *Operating temperature range* –20…55C.

Mode	**Parameter**	**Value**
Inverter	Nominal power	3000 VA / 2400 W
	DC input	24 V DC, 100 A
	AC output	230 V AC, 50/60 Hz, 13 A, 1-phase
AC charger	AC input	230 V AC, 50/60 Hz, 20.8 A, 1-phase
	DC output	27 V DC, 60 A
Solar charger	Rated power	1000 W
	System voltage	24 V DC
	Max. PV open-circuit voltage (Voc)	100 V DC

Model SFB-5500-48 *Operating temperature range* –10…50 C

Mode	**Parameter**	**Value**
Inverter	Nominal power	5500 W
	DC input	48 V DC, 119 A
	Power factor	0.9
	AC output	230 V AC, 50/60 Hz, 21.7 A
AC charger	AC input	230 V AC, 50/60 Hz, 41.7 A
	DC output	54 V DC, max 80 A (default 30 A)
Solar charger	Maximum PV power	6000 W
	Max. PV current	18 A
	Max. MPPT charge current	100 A
	Optimal PV voltage range	240–430 V DC
	Operable PV voltage range	120–430 V DC
	Max. PV open-circuit voltage (Voc)	500 V DC

A *rechargeable battery* is a device designed to store electrical energy and later release it as a power source [5]. Modern batteries operate on the principle of repeatedly converting chemical energy into electricity, allowing them to be charged and discharged many times. Rechargeable batteries come in numerous types, classified by capacity, voltage, manufacturing technology and other parameters.

For our system we selected *Challenger AGM* batteries rated at 12 V and 120 Ah. They deliver stable performance, accept a 15 A charge current and are maintenance-free, which makes them a convenient solution for autonomous energy systems.

A *pyranometer* (from Greek pyr – fire, ano – above, metron – measure) is a type of actinometer designed to measure solar radiation incident on a surface. It delivers the irradiance (W m^{-2}) arriving from the whole upper hemisphere [5].

The *CMP6* pyranometer is intended for standard measurements of global solar irradiance on a horizontal surface. It complies with ISO 9060:2018 (spectral class B) and contains 64 thermocouple junctions connected in series. The sensing surface is coated with a highly stable, inorganic carbon layer that provides excellent spectral absorption and long-term stability.

The instrument needs no external power, producing its own low-voltage output (0–30 mV) proportional to irradiance (0–1500 W m^{-2}). If required, the signal can be converted to 4–20 mA or a higher-voltage range.

A *weather station* is a specialised device—or a suite of instruments—designed to monitor meteorological parameters both indoors and outdoors. These units collect and analyse data on changing atmospheric conditions, including wind speed and direction, solar-radiation levels, precipitation and other variables.

Key functions of a weather station: Measurement of temperature; Determination of humidity level; Monitoring of atmospheric pressure; Types of weather stations; Analogue — used mainly for decorative purposes yet still providing basic functionality; Digital — precise instruments equipped with numerous sensors and additional features

Our system employs a *Davis Vantage Pro 2 6152CEU* weather station, which delivers high-accuracy readings and enables effective analysis of weather conditions.

3. Results and discussion

On the basis of the data described above we developed both structural and circuit diagrams and installed a pyranometer together with the weather station. These instruments provide the foundation for the subsequent analysis (Figure 3).

The investigation examined weather-station and pyranometer records for December, January and February. Particular attention was paid to the parameters that determine the performance of combined renewable-energy installations—namely wind speed, air temperature, humidity, atmospheric pressure, precipitation and solar insolation.

$$E_{solar} = U_{emf} / (S) \tag{1}$$

where: H — solar irradiance (W m^{-2}); U — output voltage (mV); η — efficiency of the PV panel; S — sensor sensitivity (mV / (W m^{-2})).

$$1W / m^2 = \frac{1}{67.65} mV = 0.01478 mV$$

Weather-station data for three days in December

Table 3. Meteorological parameters (weather station)

Date	Time	Temperature (°C)	Humidity (%)	Pressure (hPa)	Wind speed (m s^{-1})
01 Dec 2024	00 : 30	3.5	91	1018.6	0.0
01 Dec 2024	06 : 00	2.9	94	1019.3	0.4
01 Dec 2024	12 : 00	3.3	92	1019.1	0.4
02 Dec 2024	00 : 00	1.6	92	1022.5	0.0
02 Dec 2024	06 : 00	1.6	89	1022.7	0.4
02 Dec 2024	12 : 00	3.4	82	1022.7	1.3
03 Dec 2024	00 : 00	2.5	68	1022.9	0.9
03 Dec 2024	06 : 00	2.2	67	1023.6	0.9
03 Dec 2024	12 : 00	5.8	48	1024.3	2.7

Pyranometer readings and calculated solar power density.

Table 4. Pyranometer output and solar-power density

Date	Time	Voltage (mV)	Power density (kW m^{-2})
29 Nov 2024	13 : 46 : 56	1.2	0.0812
29 Nov 2024	14 : 17 : 13	0.9	0.0603
29 Nov 2024	15 : 02 : 28	0.4	0.0296
10 Dec 2024	11 : 03 : 04	1.4	0.0963
10 Dec 2024	12 : 38 : 36	2.4	0.1650
10 Dec 2024	13 : 43 : 59	2.3	0.1690
10 Dec 2024	15 : 59 : 44	0.1	0.0074
20 Dec 2024	10 : 50 : 56	0.4	0.0296
20 Dec 2024	10 : 56 : 04	0.5	0.0374

Table 5. Key electrical parameters (hybrid inverter)

Date & time	PV voltage (V)	PV power (W)	Battery voltage (V)	Battery SOC (%)	Charge current (A)	Dis charge current (A)	Output voltage (V)	Active power (W)
06 Dec 2024 14 : 41 : 18	127.7	60	26.6	100	4	0	229.8	0
06 Dec 2024 14 : 31 : 21	93.2	0	26.3	100	0	1	229.6	20
06 Dec 2024 14 : 21 : 20	266.8	78	27.0	100	4	0	230.1	21
06 Dec 2024 14 : 11 : 18	280.1	100	27.0	100	4	0	230.6	20
06 Dec 2024 14 : 01 : 14	283.3	129	27.0	100	4	0	230.1	21

The analysis shows that wind speed varied during the study period, peaking on certain days. The average wind speed serves as an indicator of wind-turbine productivity; higher wind activity boosts wind-power output. Air temperature fluctuated month by month, reaching its lowest values in January. Low temperatures can benefit PV performance because panel efficiency rises as temperature falls. Humidity varied with weather conditions; high humidity and snowfall can reduce PV output by decreasing surface transmittance. Atmospheric pressure changed throughout the observation period, reflecting passing cyclones and anticyclones—information that is useful for predicting weather conditions affecting energy production.

Solar irradiance. Pyranometer data show that solar-radiation maxima occur at midday, while morning and evening values drop sharply. In December and January, irradiance was lower because of seasonal factors and frequent cloud cover.

Overall, the data confirm that hybrid RES installations can operate efficiently when solar and wind resources are properly balanced. During winter the primary energy source tends to be the wind turbine (higher wind speeds), whereas in summer the main load is carried by PV modules owing to stronger irradiance.

The electrical energy generated by the PV array is calculated using

$$E = S \cdot \eta \cdot H \cdot PR \tag{2}$$

where: S – is the panel area (m²), η – the module efficiency, H_i – the incident solar-energy density and (kW·h/m²), PR – the performance ratio.

Thus, during the summer period the value of HiH_iHi rises sharply, boosting solar-energy production, while in winter wind generation becomes the dominant contributor.

The findings confirm the need for *battery-storage systems* to smooth fluctuations in power output: energy accumulated during periods of low solar activity (winter) or weak wind (summer) can be deployed to maintain a stable supply. Weather factors such as humidity and precipitation also demand routine maintenance of PV modules to preserve efficiency; snow cover and surface soiling can markedly reduce energy yield. Figure 3.2 shows the resulting plot.

Overall, *hybrid renewable installations* possess high potential for autonomous power supply but require careful consideration of local climate and skilful management of energy flows.

Almaty offers significant solar potential. The average daily incident short-wave solar energy varies through the year:

January ≈ 2.3 kWh m^{-2}
May ≈ 6.8 kWh m^{-2}
July ≈ 7.6 kWh m^{-2}
October ≈ 3.8 kWh m^{-2}
December ≈ 2.0 kWh m^{-2}

Peak solar activity occurs in summer, favouring efficient PV utilisation in that season. By contrast, the mean wind speed in Almaty is about *0.7 m s^{-1},* well below the ≥ 4 m s^{-1} typically required for efficient wind-turbine operation, so wind power must be assessed carefully against local conditions.

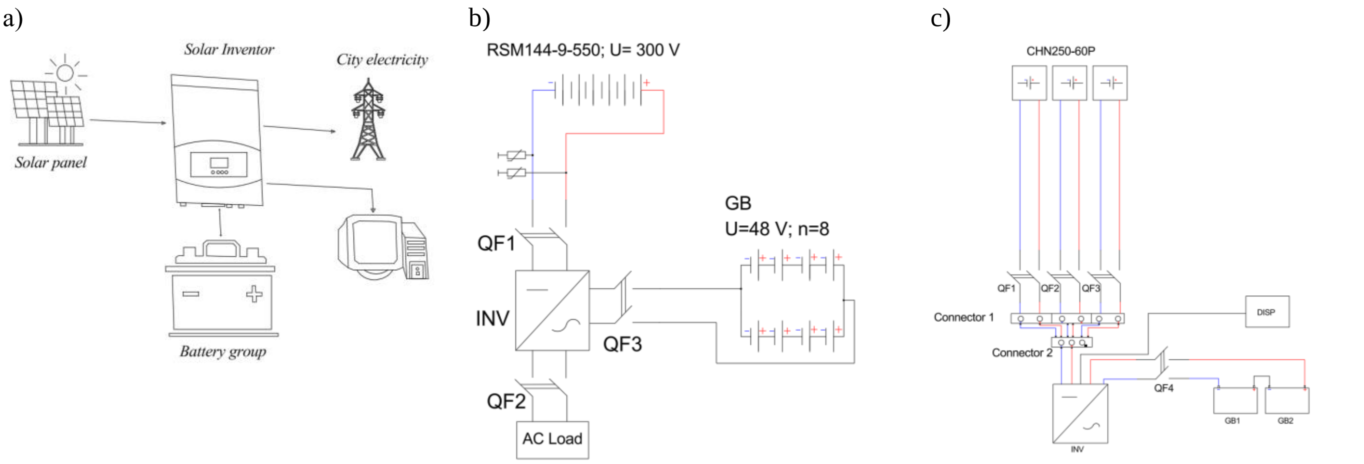

Figure 3. (a) Structural diagram of the PV module; (b) schematic of the RSM144-9-550M PV module; (c) schematic of the CHN250-60P PV module

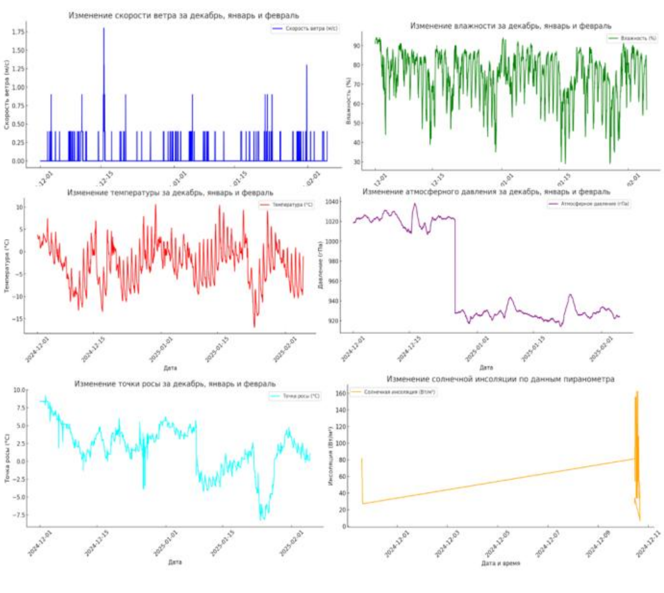

Figure 4. Weather-trend graph

4. Conclusions

Hybrid installations based on renewable energy sources (RES) are a promising solution for decentralised and autonomous energy systems. Integrating multiple RES technologies minimises reliance on conventional fuels, cuts the carbon footprint and enhances energy resilience. Ongoing advances in intelligent control, generation forecasting and adaptive load management are making these systems increasingly effective. Energy-storage integration is vital, as it smooths production fluctuations and stabilises power supply. Looking ahead, hybrid systems that harness artificial intelligence and blockchain to optimise grid operation are expected to gain wide adoption.

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Жаңартылатын энергия көздеріне негізделген біріктірілген қондырғылар (басқару, электр және жылу энергиясын өндіру)

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Аңдатпа. Соңғы онжылдықтарда адамзат өсіп келе жатқан энергетикалық қажеттіліктерін қанағаттандырудың тұрақты және экологиялық таза жолдарын белсенді түрде іздеуде. Жаңартылатын энергия көздері (ЖЭК) – күн, жел, су, биогаз және геотермалдық энергия – бұл ізденістердің басты бағыты болып табылады. Осыған байланысты электр және жылу энергиясын бір уақытта өндіруге мүмкіндік беретін, энергетикалық жүйелердің тиімділігі мен тұрақтылығын арттыратын жаңартылатын энергия көздеріне негізделген біріктірілген қондырғылар белсенді түрде енгізілуде. Жаңартылатын энергия көздері арқылы жұмыс істейтін біріктірілген қондырғылар – бұл энергия өндірудің инновациялық әрі тиімді тәсілі, мұнда бірнеше жүйе бір циклде біріктіріліп, энергияны өндіру мен пайдалану жүзеге асады. Мұндай жүйелер жаңартылатын энергияны тиімді пайдаланып, электр және жылу энергиясын өндіреді, нәтижесінде жалпы энергетикалық тиімділік пен тұрақтылық артады. Негізгі ұғым – когенерация, яғни электр және жылу энергиясын бір мезгілде өндіру процесі. ЖЭК жағдайында бұл процесс әдетте күн, жел, биомасса және геотермалдық ресурстарды қолданады. Мысалы, фотоэлектрлік-термиялық (ФЭТ) күн жүйелері күн батареяларын электр энергиясын өндіру үшін, ал күн жылу коллекторларын жылу алу үшін біріктіреді. Сол сияқты, биомасса мен геотермалдық қондырғылар да электр мен жылу энергиясын қатар өндіре алады және бұл өнеркәсіп, тұрғын үй және ауыл шаруашылығы салаларының қажеттіліктерін қанағаттандырады.

Негізгі сөздер: *жаңартылатын энергия көздері (ЖЭК), когенерация, энергия тиімділігі, электр энергиясы, жылу энергиясы, күн энергиясы, жел энергиясы, биомасса, геотермалдық энергия.*

Комбинированные установки на основе возобновляемых источников энергии (управление, выработка электрической и тепловой энергии)

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Аннотация. В последние десятилетия человечество активно ищет устойчивые и экологически чистые способы удовлетворения растущих энергетических потребностей. Возобновляемые источники энергии (ВИЭ), такие как солнечная, ветровая, гидроэнергия, биогаз и геотермальная энергия, находятся в центре этих усилий. В этом контексте активно внедряются комбинированные установки на основе ВИЭ, которые позволяют одновременно вырабатывать электрическую и тепловую энергию, повышая эффективность и стабильность энергетических систем. Комбинированные установки на основе возобновляемых источников энергии представляют собой инновационный и эффективный подход к производству энергии, объединяя несколько систем её выработки и использования в единый цикл. Эти системы оптимизируют использование возобновляемой энергии для производства электроэнергии и тепла, тем самым повышая общую энергетическую эффективность и устойчивость. Основной концепцией является когенерация — процесс одновременного производства двух видов энергии: электрической и тепловой. В случае возобновляемых источников энергии этот процесс обычно использует солнечную, ветровую, биомассу и геотермальные ресурсы. Например, фотоэлектротермические (ФЭТ) солнечные системы сочетают солнечные фотоэлектрические панели для выработки электроэнергии с солнечными тепловыми коллекторами для получения тепла. Аналогичным образом, электростанции на биомассе и геотермальные установки способны вырабатывать как электрическую, так и тепловую энергию, удовлетворяя потребности промышленного, жилого и сельскохозяйственного секторов.

Ключевые слова: *возобновляемые источники энергии (ВИЭ), когенерация, энергоэффективность, электрическая энергия, тепловая энергия, солнечная энергия, ветровая энергия, биомасса, геотермальная энергия*.

Received: 19 February 2025
Accepted: 15 June 2025
Available online: 30 June 2025