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Enhancing the Efficiency of Integrated Energy Systems by the Redistribution of Heat Based on Monitoring Data

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Abstract: Integrated energy systems (IES) for combined power, heat and refrigeration supply achieved a wide application due to high flexibility in matching current loading. So as electricity is easily convertible into any other form of energy, gas engines are widely applied as driving engines characterized by high electrical and overall efficiency of about 45% and 90%, respectively. However, the highest thermal efficiency is achieved at full matching heat generated by the engine and heat transformed. This is often impossible in actual practice, especially if the heat is transformed into refrigeration by the most efficient and widespread absorption lithium-bromide chillers (ACh) and the heat not consumed by the ACh is removed from the atmosphere through an emergency radiator. The unused heat might be transformed by an ejector chiller (ECh) as the simplest and cheapest. So as the thermodynamic efficiency of any combustion engine is influenced essentially by the sucked air temperature, the excessive refrigeration produced by the ECh, is used for IES cooling to generate additional electricity and increase the electrical and overall efficiency of the engine. Such a redistribution of heat enables the enhancement of the efficiency of IES with an absorption-ejector chiller (AECh). The modified criteria for the comparative estimation of thermodynamic efficiency of innovative IESs with AEChs without overgenerated heat lost against a typical IES with an ACh and heat lost are proposed. In contrast to well-known electrical and heat efficiency, it considers the magnitude of heat loss and enables us to compare the heat efficiency of any version of transforming heat to refrigeration with an ideal basic version of IES based on a highly efficient ACh, transforming all the heat removed from the engine without heat loss. Some alternative scheme decisions for heat recovery systems have been developed based on monitoring data. They might be easily implemented into a typical IES with ACh.

Keywords: integrated energy supply; gas engine; heat transformation; overgenerated heat; refrigeration

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1. Introduction

Integrated energy systems (IES) [1,2] for combined refrigeration, heat and power supply [3,4] gained a wide application due to the high flexibility of heat flows to match current loading [5,6]. The application of IES makes it possible to increase COP by about 50% against different kinds of separate energy generation and increase yearly operation times practically twice compared to cogeneration [7,8]. This makes them very prosperous in many branches of industries, including building and district combined energy supply [9,10], to substitute or to save energy in vapor compression machines [11,12] with electrically driven refrigeration compressors.

Various combustion engines are applicable as prime movers for IES: internal combustion engines [13,14], gas turbines [15,16] and gas engines (GE) [17,18]. So as electricity is the most liquid form of energy, easily transformed into any other, gas engines (GE) are mostly applied as drive engines, characterized by high electrical and overall efficiencies of about 45% and 90%, respectively [19,20].

However, with rising intake air temperature, the thermodynamic efficiency of any combustion engine drops: power output falls, and gas fuel heat rises.

The heat removed from GE is usually transformed to refrigeration by absorption lithium-bromide chillers (ACh) as the most efficient heat transformer with a high coefficient of performance (COP) of 0.7–0.8 [21,22]. Ammonia-water absorption chillers have a bit lower COP of about 0.6 and found wide application too [23,24] as well as adsorption chillers [25,26].

The cogenerative GE modules are equipped with heat exchangers [1,27,28], and their extracting and transforming exhaust heat circuits involve many heat exchangers [29,30]. The jet devices [31,32], such as ejector chillers (ECh) [33,34] and thermopressors [35,36], are the simplest in design, mainly also consist of heat exchangers [37,38] and are well adapted for engine cyclic air cooling.

The efficiency of chillers and the whole heat transforming systems can be improved due to the intensification of two-phase flow heat transfer in evaporators [39–41] and condensers [42] through the application of innovative contours [43], deep exhaust heat utilization [44–46] with low-temperature condensation [47,48] that provides increasing heat to be converted for cyclic air engine cooling [49–53].

The application of highly efficient mini-channel heat exchangers enables us to apply intermediate auxiliary coolant circuits to reduce the refrigerant charge [54,55]. Their heat [56,57] and hydrodynamic [58,59] efficiency might be improved by the intensification of heat transfer [60,61] and mitigating the maldistribution of refrigerant flows [62,63].

The COP of EChs, as the most simple and accordingly well adopted for easy implementation in IES, is significantly less than in an ACh: about 0.3 against 0.7–0.8. Therefore an ECh can be applied as a booster chiller to transform the rest heat not consumed by highly efficient AChs. The application of such an absorption-ejector chiller (AECh) transforms all the heat removed from the GE for engine intake air deep cooling [64,65] and increases the thermodynamic engine efficiency as a result.

Many methodological approaches and methods are used to enhance the thermodynamic and operational efficiency of cogeneration [66,67] and trigeneration [68,69] systems to follow actual loads [70–72] and to optimize the loads on the systems of exhaust heat utilization and cooling air in order to follow actual loads and achieve a maximum effect [73,74].

Various criteria were proposed to estimate the operation [75–77] and thermodynamic efficiency of IES [78–80] and used as indicators to follow current needs according to thermal demand management (TDM) [81,82] and primary energy saving (PES) management providing a high level of IES loading [83,84]. Multi-criteria analysis for the assessment of environmentally relevant installations and synthesis of the trigeneration plant were conducted [69,84–87]. The thermal load profiles were analyzed to cover yearly cooling needs [88,89] and enhance engine output due to sucked air cooling [69,90].

Most of the widespread concepts to enhance the operation and thermodynamic [80–82] efficiency of combined energy generation and transformation, including engine-sucked air cooling by the ACh [78,79], are based on the approach that all the heat generated by the engine is transformed to refrigeration without taking into account the heat lost to the atmosphere through the radiator. However, such an assumption is not generally correct in real practice. This leads to some excessive heat source and refrigeration potential unrealized and extracted from the return of hot water from the ACh to the environment [91].

In major cases of IES operation, the range of hot water temperature depression optimal for AChs is usually less than the available value. The last condition is satisfied by removing heat, not transformed by the ACh, to the atmosphere by the radiator, which leads to an inevitable heat loss of over 25–35%.

The aim of this research is to improve the thermodynamic efficiency of integrated energy systems by the redistribution of heat, initially lost through removal to the atmosphere by a radiator, that is caused by mismatching the heat generated by GE and heat transformed to refrigeration by the ACh.

2. Materials and Methods

2.1. General Assumptions and Hypothesis

The mismatching heat generated and transformed leads to inevitable excess heat typically lost through dissipation to the surroundings. In major cases, to overcome heat mismatching and compensate for refrigeration, requires the application of a booster thermotransformer to recover lost excessive heat is needed. Moreover, it must be easily implemented into the existing typical heat transforming system and combined perfectly with the ACh to boost overall output. A refrigerant ejector chiller (ECh) can be applied as the simplest and cheapest booster thermotransformer.

So as the thermodynamic efficiency of combustion engines is affected essentially by a sucked air temperature, the additional refrigeration capacity gained is reasonable to use for cooling air to provide the efficient stabilized performance of IESs.

A new concept of two-stage transforming the heat lost has been realized by applying an ECh as a booster heat transformer to cool engine-sucked air and enhance the overall electric and heat efficiency of the IES.

The heat and corresponding refrigeration potential was evaluated by processing the monitoring data.

A new modified criterion, $\eta_{h.IAECh}$, for comparative estimation of thermodynamic efficiency of innovative IESs with AEChs, is proposed. It is based on well-known criteria such as electrical, $\eta_{el} = P_{el}/Q_{gas}$, and heat efficiency, $\eta_h = Q_h/Q_{gas}$, and overall electrical and heat efficiency, $\eta_{el+h} = (P_{el} + Q_h)/Q_{gas}$, of IESs. This criterion, $\eta_{h.IAECh}$, enables us to compare the heat efficiency of any version of transforming engine heat, Q_h, to refrigeration, for instance, by the ACh as in typical IES, or a modified combined version of IES including ECh as a booster chiller, with a version when all the heat removed from GE is transformed to refrigeration by the ACh accepted as an ideal basic one. The criterion is quite suitable for the primary estimation of any modification of basic IES due to the comparative evaluation of IES thermodynamic efficiency.

A general methodological novelty of the research consists of developed criteria for evaluation of heat efficiency and overall heat and electrical efficiency of recovering the heat removed from GE in comparison with the ideal variant of IES with full recovering by the chiller with a high COP, for instance, by an ACh.

The advantages of the improved criteria in the applied aspect are quite evident from their applicability for the primary step-by-step estimation of innovative solutions implemented into an existing typical IES with an ACh.

2.2. Calculation Procedure

A method for reducing the monitoring data on consumed fuel, electrical power and heat output and refrigeration generation in dependence on the engine-sucked air temperatures was presented in [29]. The generalized correlations of the method, measuring devices, their measurement ranges and accuracy were presented in [67].

The accuracy of reducing the experimental results was determined considering the accuracy of measurements, including measuring devices, as well as methodological and systematic errors and was 5–7% [67].

The main rated characteristics of gas engine JMS 420 applied as driving one at ISO parameters (air temperature $T_{in.ISO}$ = 298.15 K and relative humidity φ_{ISO} = 30%) are the following: electrical power $P_{el.ISO}$ = 1420 kW, specific gas fuel consumption $b_{e.ISO}$ = 167.76 g/kWh.

The heat of gas fuel, Q_{gas}, used to generate electric power P_{el} and heat Q_h of hot water, was calculated by using the monitoring data on volumetric fuel transforming B_f. In a typical basic IES, only part of gas fuel heat, Q_{gas}, is transformed to refrigeration capacity by the ACh, whereas in developed innovative IES, the heat, Q_{lost}, lost in the basic one, is used by the ECh to generate additional refrigeration used for cooling engine sucked air.

The heat removed from the GE with hot water, Q_h, that transformed by the ACh, $Q_{h.IACh}$, and heat lost, Q_{lost}, as remaining heat dissipated into the atmosphere through the emergency radiator, was calculated according to the measured water flow rate G_w and temperatures of water. Their values were used to estimate the thermodynamic efficiency of IES and to reveal and realize the reserves for IES improvement.

The monitoring data on daily changes of electrical power output P_{el} and volumetric gas fuel B_{gas} consumed by gas engine JMS 420 were treated for calculation of gas fuel heat Q_{gas} and electrical efficiency $\eta_{el} = P_{el}/Q_{gas}$.

In order to calculate the heat Q_h removed from GE and transformed by the ACh into refrigeration as well as the rest lost heat Q_{lost} of warm water leaving the ACh and dissipated into the atmosphere, the monitoring data on water flow G_w and changes in temperature of hot water were used. These data were also applied for the calculation of heat efficiency, $\eta_h = Q_h/Q_{gas}$, and the overall efficiency, $\eta_{el} + \eta_h$, of the IES.

A modified criterion, $\eta_{el+h.IACh}$, for estimation of thermodynamic efficiency of a typical IES with an ACh proceeding from IES real heat efficiency $\eta_{h.IACh}$ considers the real part of the heat removed from the engine, Q_h, taking into account the heat lost, $Q_{h.lost}$, as their difference, $Q_h - Q_{h.lost}$, transformed to refrigeration. Comparing the values of proposed criteria, $\eta_{el+h.IACh}$ and $\eta_{h.IAECh}$, accordingly with the potentially available values, η_{el+h} and η_h, enables us to reveal the reserves for further improvement of IES operation through minimizing the mismatching engine heat generation and IES transforming.

The following correlations were used for the calculation of heat efficiency of the IES without heat lost ($Q_{h.lost} = 0$) as the ideal basic version:

$$\eta_h = Q_h/Q_{gas}; \tag{1}$$

for transforming the heat, $Q_h - Q_{h.lost}$, by the ACh in the IES:

$$\eta_{h.IACh} = (Q_h - Q_{h.lost})/Q_{gas} \tag{2}$$

or

$$\eta_{h.IACh} = \eta_h - Q_{h.lost}/Q_{gas}; \tag{3}$$

for transforming the heat, $Q_{h.lost}$, by the ECh in the IES:

$$\eta_{h.IECh} = Q_{h.lost}\ (COP_{ECh}/COP_{ACh})/Q_{gas}. \tag{4}$$

A modified criterion, $\eta_{h.IAECh}$, for transforming the heat, $Q_h - Q_{h.lost}$, by the ACh and $Q_{h.lost}$ by the ECh in the IES:

$$\eta_{h.IAECh} = [(Q_h - Q_{h.lost}\ (1 - COP_{ECh}/COP_{ACh})]/Q_{gas}. \tag{5}$$

If $COP_{ECh} = COP_{ACh}$ (without mismatching engine heat generation and IES transforming by the ACh):

$$\eta_{h.IAECh} = \eta_h = Q_h/Q_{gas} \tag{6}$$

or

$$\eta_{h.IAECh} = \eta_{h.IACh} + \eta_{h.IECh},$$

where

$$\eta_{h.IACh} = \eta_h - Q_{h.lost}/Q_{gas} \tag{7}$$

and

$$\eta_{h.IECh} = Q_{h.lost}\ COP_{ECh}/COP_{ACh}/Q_{gas}. \tag{8}$$

The thermodynamic efficiency of transforming the heat generated by the gas engine and transformed to refrigeration by the ACh and ECh for cooling sucked air was analyzed for IES of "Sandora"–"PepsiCo Ukraine" (climatic conditions in Mykolayiv, southern Ukraine). The IES consists of two gas engines, JMS 420 (at ISO air parameters: P_{eISO} = 1400 kW and Q_h = 1500 kW) and AR-D500L2 Century as an ACh (Figure 1).

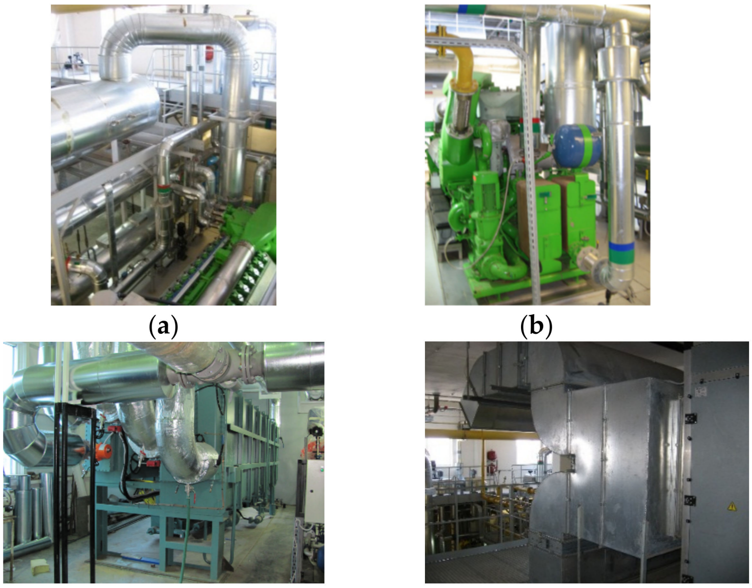

Figure 1. Gas engine module JMS GE Jenbacher including exhaust boiler (**a**) and heat exchangers for extracting heat of lubricating oil and engine jacket high-temperature cooling water (**b**), absorption chiller AR-D500L2 (**c**) and central conditioner for cooling the air coming into engine room (**d**).

A scheme of a typical integrated energy system (IES) of a gas engine heat transforming to refrigeration in the ACh is presented in Figure 2.

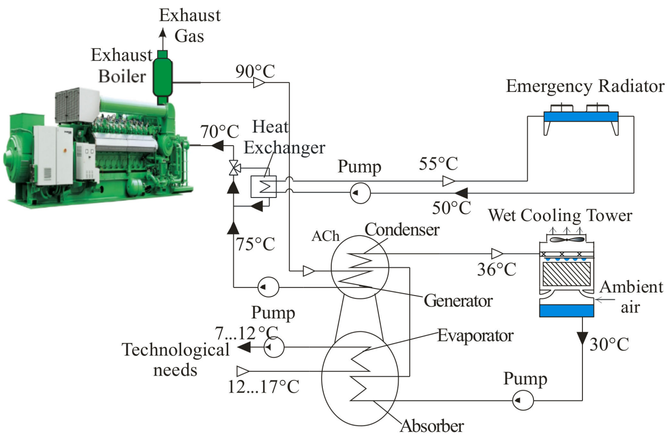

Figure 2. A scheme of a typical integrated energy system with an ACh transforming the heat generated by the GE to refrigeration.

The heat of the water-cooling engine jacket, lubricating oil, charged air-gas mixture and exhaust gas is used to heat water to the temperature of about 90 °C. The heated water is transformed by the ACh to refrigeration to generate chilled water with temperatures of 7–12 °C. The cooled water is used for technological requirements, conditioning the workshops and feeding the central conditioner for processing the air coming into the engine room. The air is sucked from the engine room by a GE turbocharger.

The flow sheet of investigation is presented in the Supplementary Materials.

3. Results and Discussion of Investigation

3.1. Estimation of Heat Lost in Typical IES with an ACh

The monitoring data on the hot water temperatures in a basic engine heat transforming system with an ACh are shown in Figure 3 for the time interval $\tau = 12^{00}$–24^{00} (28 July 2017).

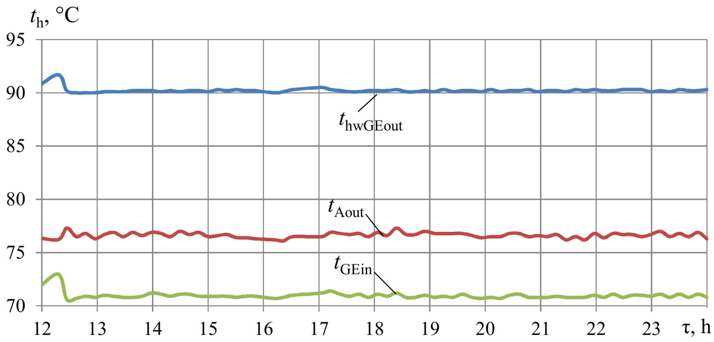

Figure 3. Temperatures of hot water leaving the GE at the entry of ACh $t_{hwGEout}$, return water at the outlet of ACh t_{hwAout} and return hot water cooled in the emergency radiator at the inlet of the GE t_{hwGEin} in the basic variant of IES.

The heat flows Q_h in a typical basic heat transforming system with an ACh were determined proceeding from monitoring data on the water temperatures (Figure 3).

The heat Q_h removed from GE and transformed by ACh into refrigeration as well as the rest lost heat Q_{lost} of warm water leaving ACh and dissipated into the atmosphere were calculated based on the monitoring data on water flow G_w and changes in temperature of water in engine heat utilization circuit.

The heat balance based on the hot water flow rate G_w and hot water temperatures at the GE outlet $t_{hwGEout}$ and inlet t_{hwGEin}, measured during monitoring, is used for calculation of the overall available heat generated by GE: $Q_h = G_w\ c_w\ (t_{hwGEout} - t_{hwGEin})$.

Accordingly, the heat balance compiled from the temperatures of hot water at the outlet of the GE (the inlet of the ACh) $t_{hwGEout}$ and outlet of the ACh t_{hwAout} is used to determine the heat transformed to refrigeration: $Q_{h.ACh} = G_w\ c_w\ (t_{hwGEout} - t_{hwAout})$.

The rest lost heat is calculated as $Q_{h.loss} = G_w\ c_w\ (t_{hwAout} - t_{hwGEin})$.

The overall summarized amount of heat, $Q_{h.GE}$, removed from two GE, the heat transformed by ACh into refrigeration, $Q_{h.ACh}$, and the heat loss, $Q_{h.loss}$, in the basic exhaust heat transforming circuit are presented in Figure 4.

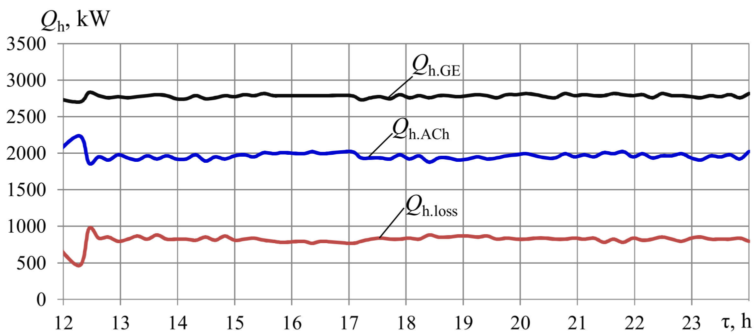

Figure 4. Values of the overall amount of heat $Q_{h.GE}$ removed from two GEs, the heat transformed by ACh to refrigeration, $Q_{h.ACh}$, and the heat loss $Q_{h.loss}$ in the basic IES with ACh.

As Figure 4 shows, the overall summarized heat of hot water with a temperature, t_h, of 90 °C from two GE $Q_{h.GE}$ is about 2800 kW, accordingly 1400 kW from one GE. The heat transformed in the ACh to refrigeration $Q_{h.ACh}$ is about 2000 kW for two GE and 1000 kW for one engine. The rest loss (excess) of heat dissipated into the surroundings by the emergency radiator, $Q_{h.loss}$, is about 800 kW for two and 400 kW for one engine.

Thus, the heat loss, $Q_{h.loss}$, in a typical IES with an ACh reaches 25–30% of the overall available amount $Q_{h.GE}$ generated by GE.

3.2. Estimation of Thermodynamic Efficiency of a Typical IES by Traditional Method

The results of monitoring data on daily changes of electrical power P_{el}, volumetric gas fuel transforming, B_{gas}, the heat of gas fuel, Q_{gas}, of a JMS 420 gas engine with temperatures of ambient air, t_{amb}, and sucked air, t_{in}, at the inlet of the engine turbocharger, t_{in}, (1 June 2019, Mykolayiv, southern Ukraine) are presented in Figure 5.

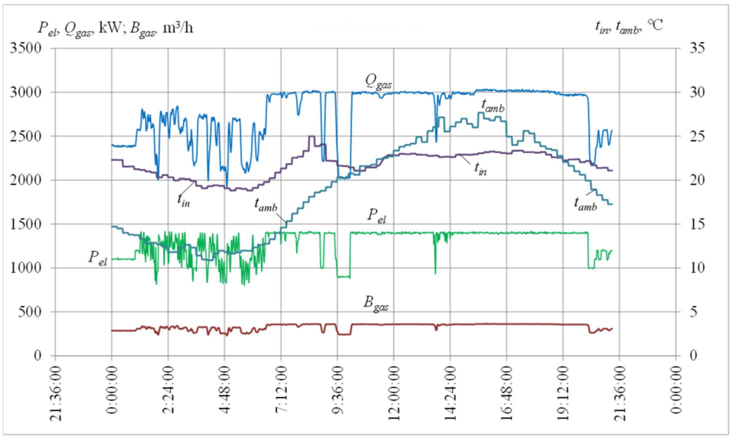

Figure 5. Daily changes of electrical power, P_{el}, volumetric gas fuel transforming, B_{gas}, the heat of gas fuel, $Q_{\mathrm{ga,s}}$ of gas engine JMS 420 with temperatures of ambient, t_{amb}, and sucked air at the inlet t_{in} of engine turbocharger.

Monitoring data on electrical power, P_{el}, the heat of gas fuel, Q_{gas}, and calculated electrical efficiency $\eta_{\mathrm{el}} = P_{\mathrm{el}}/Q_{\mathrm{gas}}$ of gas engine JMS 420 are presented in Figure 6.

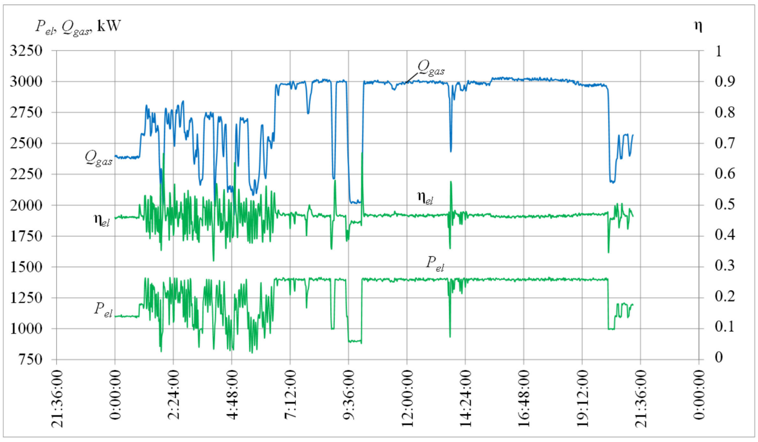

Figure 6. Daily changes in electrical power P_{el}, the heat of gas fuel, Q_{gas}, and the electrical efficiency, $\eta_{el} = P_{\mathrm{el}}/Q_{\mathrm{gas}}$, of gas engine JMS 420.

As it is seen, the electrical efficiency, η_{el}, of gas engine JMS 420 is about 0.47.

Monitoring data on fuel heat, Q_{gas}, heat removed from the engine, Q_{h}, and heat efficiency, $\eta_{\mathrm{h}} = Q_{\mathrm{h}}/Q_{\mathrm{gas}}$, of gas engine JMS 420 are presented in Figure 7.

As Figure 7 shows, the heat efficiency, η_{el}, of gas engine JMS 420 is about 0.5.

The values of overall electrical and heat efficiency, $\eta_{\mathrm{el+h}} = (P_{\mathrm{el}} + Q_{\mathrm{h}})/Q_{\mathrm{gas}}$, are calculated according to monitoring data on electrical power, P_{el}, the heat of gas fuel, Q_{gas}, and the heat removed from the engine Q_{h} (Figure 8).

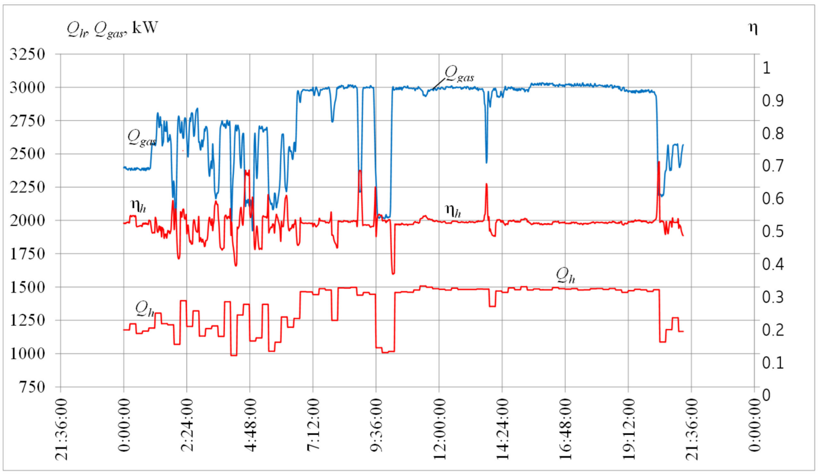

Figure 7. Daily changes of fuel heat Q_{gas}, heat removed from engine (heat capacity) Q_h and heat efficiency $\eta_h = Q_h/Q_{gas}$ of gas engine JMS 420.

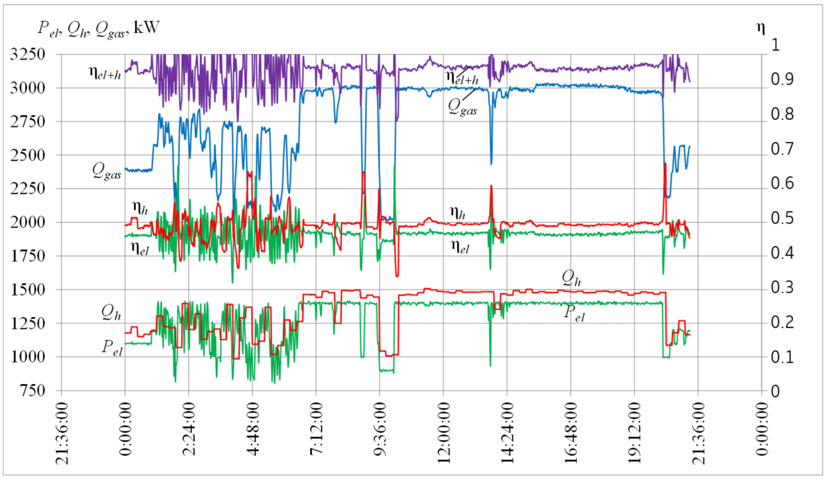

Figure 8. Daily changes of electrical power, P_{el}, the heat of gas fuel, Q_{gas}, heat removed (heat capacity), Q_h, electrical efficiency, $\eta_{el} = P_{el}/Q_{gas}$, heat efficiency, $\eta_h = Q_h/Q_{gas}$, and the overall electrical and heat efficiency, $\eta_{el+h} = (P_{el} + Q_h)/Q_{gas}$, of gas engine JMS 420.

As one can see, the values of overall electrical and heat efficiency $\eta_{el+h} = (P_{el} + Q_h)/Q_{gas}$ of the gas engine are quite close to 1, which proves the high efficiency of gas engine JMS 420 while operation as a cogenerative plant at full electrical and thermal loading. Meantime, for the operation of a cogenerative gas engine module in trigeneration mode, such a traditional method of estimation of IES thermodynamic efficiency needs to be approved, taking into account, firstly, the mismatching of the heat removed from GE and transformed to refrigeration and, secondly, the efficiency of transforming the heat to refrigeration needs. Such an approach to the estimation of the thermodynamic efficiency of IES operation enables us to reveal the reserves of the IES for further improvement.

3.3. Estimation of Thermodynamic Efficiency of a Typical IES by Improved Method

A modified criterion, $\eta_{el+h.IACh}$, for estimation of thermodynamic efficiency of a typical IES with an ACh proceeding from IES real heat efficiency, $\eta_{h.IACh}$, considers the rate of realization of the heat available from the engine (engine heat generation), η_h, taking into account the mismatching generation of heat and IES transforming to refrigeration generation. Comparing the values of proposed criteria, $\eta_{el+h.IACh}$ and $\eta_{h.IAECh}$, accordingly, with the potentially available values, η_{el+h} and η_h, enables us to reveal the reserves for further improvement of IES operation through minimizing the mismatching engine heat generation and IES transforming.

The values of overall electrical and heat efficiency $\eta_{el+h} = (P_{el} + Q_h)/Q_{gas}$ are calculated according to monitoring data on electrical power, P_{el}, the heat of gas fuel Q_{gas} and engine removed heat Q_h (Figure 9).

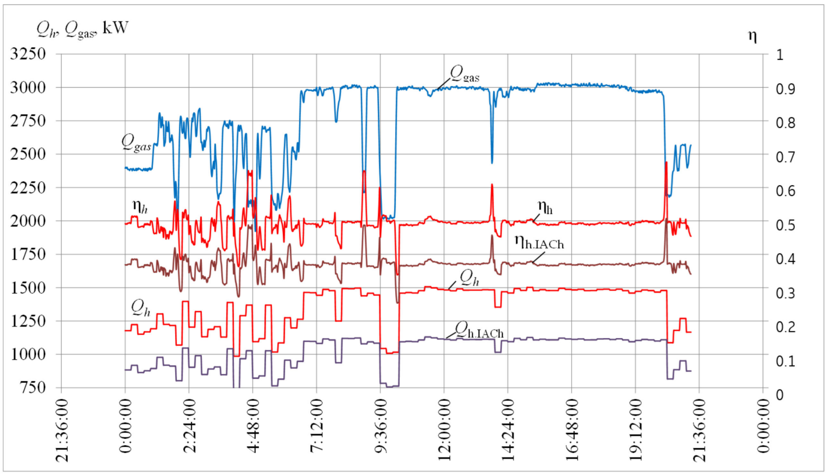

Figure 9. Daily changes in gas fuel heat, Q_{gas}, heat removed from the GE, Q_h, and transformed by the Ach, Q_{hIACh}, the potentially available heat efficiency, η_h, and the real efficiency due to the heat transformed by the Ach, $\eta_{h.IACh}$: $\eta_h = Q_h/Q_{gas}$; $\eta_{h.IACh} = Q_{h.IACh}/Q_{gas}$; $Q_{h.IACh} = Q_{h.ACh} = Q_h - Q_{h.lost}$.

As one can see (Figure 10), the values of overall electrical and heat efficiency $\eta_{el+h} = (P_{el} + Q_h)/Q_{gas}$ of the gas engine are quite close to 1, which proves the high efficiency of gas engine JMS 420 while operation as a cogenerative plant at full electrical and thermal loading.

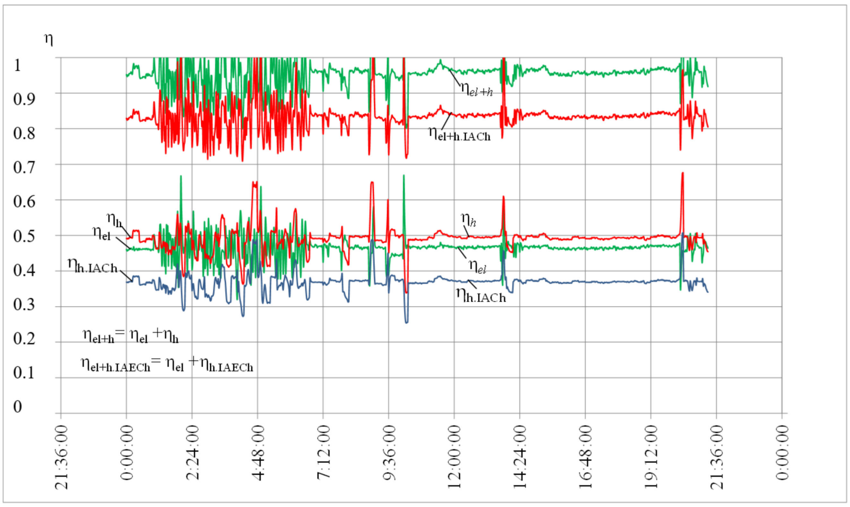

Figure 10. Daily changes in the potentially available, η_h, and real heat efficiency due to the heat transformed by the ACh, $\eta_{h.IACh}$, the potential overall electrical and heat efficiency, η_{el+h}, and the real overall electrical and heat efficiency, $\eta_{el+h.IACh}$: $\eta_h = Q_h/Q_{gas}$; $\eta_{h.IACh} = Q_{h.IACh}/Q_{gas}$; $\eta_{el+h} = (P_{el} + Q_h)/Q_{gas}$; $\eta_{el+h.IACh} = (P_{el} + Q_{h.IACh})/Q_{gas}$.

Meantime, for the operation of a cogenerative gas engine module in the trigeneration mode, such a traditional method of estimation of IES thermodynamic efficiency needs to be approved, taking into account, firstly, the mismatching generation of heat and IES transforming to refrigeration and, secondly, the efficiency of transforming the heat to refrigeration needs, id est. COP.

3.4. Estimation of Thermodynamic Efficiency of Innovative Waste Heat Recovery System by Improved Method

A modified criterion, $\eta_{el+h.IACh}$, for the estimation of thermodynamic efficiency of typical IES with ACh proceeding from IES real heat efficiency, $\eta_{h.IACh}$, considers the rate of realization of the heat available from the engine (engine heat generation), η_h, taking into account the mismatching generation of heat and IES transforming to refrigeration. It is based on well-known criteria such as electrical, $\eta_{el} = P_{el}/Q_{gas}$, and heat efficiency, $\eta_h = Q_h/Q_{gas}$, and the overall efficiency, $\eta_{el+h} = (P_{el} + Q_h)/Q_{gas}$, of the IES. This criterion, $\eta_{h.IAECh}$, enables a comparison of the heat efficiency of any version of transforming engine heat, Q_h, to refrigeration in an IES, for instance, by an ACh and IES modified version including an ECh as a booster chiller, with an ideal basic version without mismatching engine heat generation and IES transforming (Figure 11). The criterion is quite suitable for the primary estimation of any modification of a basic IES due to the comparative evaluation of the IES's thermodynamic efficiency.

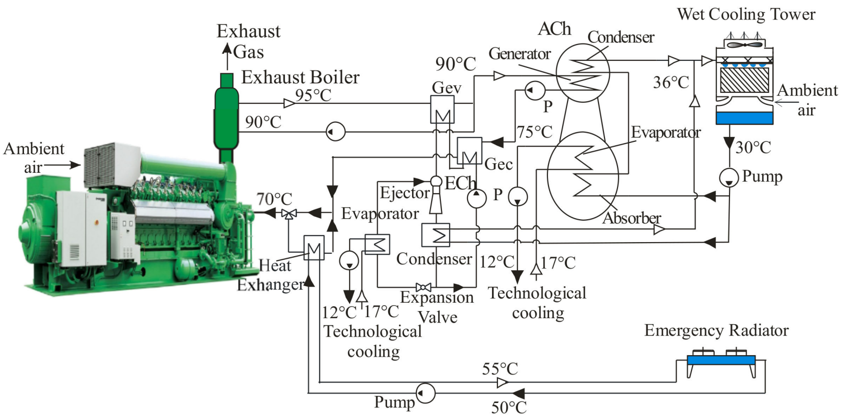

Figure 11. A scheme of developed waste heat recovery system with the ECh transforming the excessive remaining heat in addition to the ACh: G_{ev} and G_{ec}—evaporative and economizer section of a refrigerant generator of the ECh.

A comparably low efficiency (low COP) of the ECh requires matching a combined operation of the basic ACh and booster ECh to off-set lowered COP of the last one, strictly depending on the level of feeding heat flow by using the hot water just leaving the engine with the highest temperature. Therefore, the ECh should use the heat of hot water of the higher potential, id est. of increased temperature, just at the exit of GE.

The daily changes of gas fuel heat Q_{gas}, heat removed from engine Q_h and transformed by the ACh, Q_{hIACh}, and both the ACh and ECh, Q_{hIAECh}, heat efficiency potentially available, η_h, and real due to the ACh, $\eta_{h.IACh}$, and both the ACh and ECh, $\eta_{h.IAECh}$, are presented in Figure 12.

The values of heat efficiency potential available η_h, real values due to the ACh heat transformed, $\eta_{h.IACh}$, and the ECh heat transformed, $\eta_{h.IECh}$, and both the ACh and Ech's, $\eta_{h.IAECh}$, potential overall electrical and heat efficiency, η_{el+h}, real overall electrical and heat efficiency due to the ACh, $\eta_{el+h.IACh}$, due to the ECh, $\eta_{el+h.IECh}$, and due to both the ACh and ECh, $\eta_{el+h.IAECh}$, are presented in Figure 13.

As one can see, the values of overall electrical and heat efficiency, $\eta_{el+h} = (P_{el} + Q_h)/Q_{gas}$, of the gas engine are quite close to 1, which proves the high efficiency of gas engine JMS 420 while operation as cogenerative plant at full electrical and thermal loading. Meanwhile, for the operation of a cogenerative gas engine module in trigeneration mode, such a traditional method of estimation of IES thermodynamic efficiency needs to be approved, taking into account, firstly, the mismatching generation of heat and the IES transforming to refrigeration and, secondly, the efficiency of transforming the heat to refrigeration needs, id est. COP. Such an approach to the estimation of thermodynamic efficiency IES operation enables us to reveal the reserves of further IES improvement.

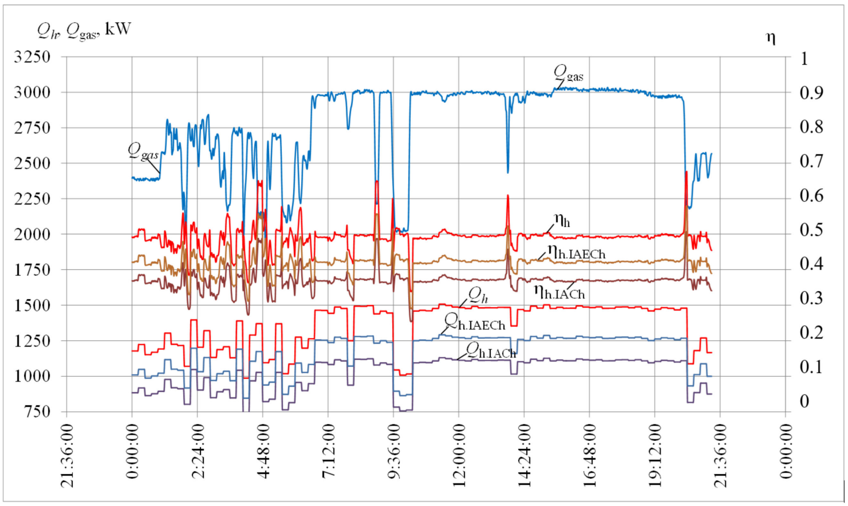

Figure 12. Daily changes of gas fuel heat, Q_{gas}, heat removed from the engine, Q_h, and transformed by the ACh, Q_{hIACh}, and both the ACh and ECh, Q_{hIAECh}, heat efficiency potential available, η_h, and real due to the ACh $\eta_{h.IACh}$ and both the ACh and ECh $\eta_{h.IAECh}$: $\eta_h = Q_h/Q_{gas}$; $\eta_{h.IAECh} = Q_{h.IAECh}/Q_{gas}$; $\eta_{h.IACh} = Q_{h.IACh}/Q_{gas}$; $Q_{h.IAECh} = [(Q_h - Q_{h.lost}\,(1 - COP_{ECh}/COP_{ACh})]$.

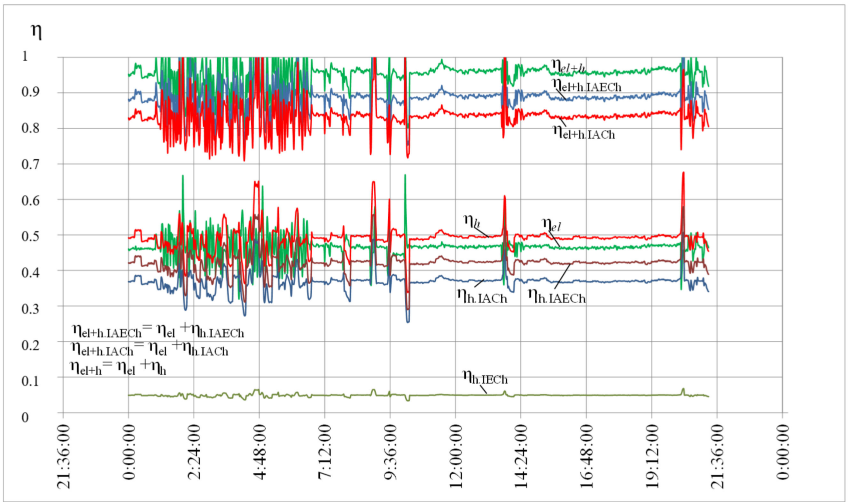

Figure 13. Daily changes of available heat efficiency potential η_h, real values due to the ACh heat transformed, $\eta_{h.IACh}$, the ECh heat transformed, $\eta_{h.IECh}$, and both the ACh and ECh, $\eta_{h.IAECh}$, the potential overall electrical and heat efficiency, η_{el+h}, real overall electrical and heat efficiency due to the ACh, $\eta_{el+h.IACh}$, due to the ECh, $\eta_{el+h.IECh}$ and due to both the ACh and ECh, $\eta_{el+h.IAECh}$: $\eta_h = Q_h/Q_{gas}$; $\eta_{h.IACh} = Q_{h.IACh}/Q_{gas}$; $\eta_{h.IECh} = [Q_{h.lost}\ COP_{ECh}/COP_{ACh}]/Q_{gas}$; $\eta_{el+h} = (P_{el} + Q_h)/Q_{gas}$; $\eta_{el+h.IACh} = (P_{el} + Q_{h.IACh})/Q_{gas}$; $\eta_{el+h.IECh} = (P_{el} + Q_{h.IECh})/Q_{gas}$; $\eta_{el+h.IAECh} = (P_{el} + Q_{h.IAECh})/Q_{gas}$.

3.5. Estimation of Thermodynamic Efficiency of Innovative IES with Cooling Engine Sucked Air

The waste heat recovery system with ECh converting the excessive remaining heat not transformed by the ACh and used for cooling engine sucked air was developed (Figure 14).

Daily changes of electrical efficiency of basic IES η_{el} and IES with cooling engine sucked air, $\eta_{el.inc}$, heat efficiency potential available, η_h, real values due to the ACh heat transformed, $\eta_{h.IACh}$, and with engine intake air cooling air ECh, $\eta_{h.IACh.inc}$, are presented in Figure 15.

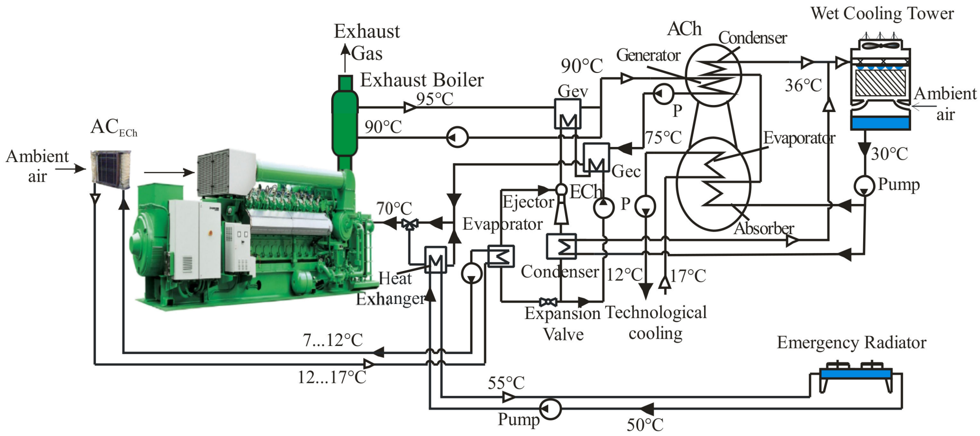

Figure 14. A scheme of developed waste heat recovery system with ECh converting the excessive remaining heat not transformed by the ACh and used for cooling engine sucked air: AC_{Ech}—air cooler fed by ECh; G_{ev} and G_{ec}—evaporative and economizer sections of the refrigerant generator of the ECh.

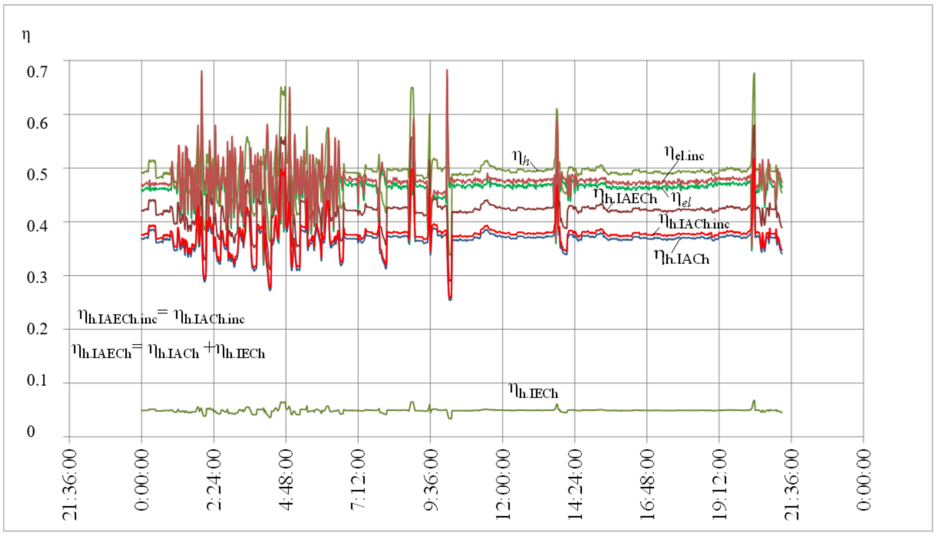

Figure 15. Daily changes of electrical efficiency of the basic IES, η_{el}, and the IES with cooling using engine-sucked air, $\eta_{el.inc}$, the heat efficiency potentially available, η_h, real values due to the heat transformed by the ACh, $\eta_{h.IACh}$, and for engine intake air cooling by the ECh, $\eta_{h.IACh.inc}$: $\eta_h = Q_h/Q_{gas}$; $\eta_{h.IACh} = Q_{h.IACh}/Q_{gas}$; $\eta_{h.IECh} = Q_{h.IECh}/Q_{gas}$; $Q_{h.IECh} = Q_{h.lost}\ COP_{ECh}/COP_{ACh}$; $\eta_{h.IAECh.inc} = Q_{h.IACh}/Q_{gas.inc}$; $\eta_{h.IACh.inc} = Q_{h.IACh}/Q_{gas.inc}$; $\eta_{el} = P_{el}/Q_{gas}$; $\eta_{el.inc} = P_{el}/Q_{gas.inc}$.

Daily changes in the real overall electrical and heat efficiency due to the ACh heat transformed without intake air cooling, $\eta_{el+h.IACh}$, and with engine intake air cooling in the ECh, $\eta_{el.inc+h.IACh.inc}$, due to both the ACh and ECh without intake air cooling, $\eta_{el+h.IAECh}$, are presented in Figure 16.

When the excess heat, transformed by ECh to refrigeration, is used for lowering the GE sucked air temperature to generate additional electricity and boost electrical, $\eta_{el.inc}$, and overall efficiency, $\eta_{el.inc+IECh}$, the heat efficiency, $\eta_{h.IAECh.inc}$, remains the same because the excess heat is used for cooling inlet air and is already considered in increased electrical efficiency (Figure 16).

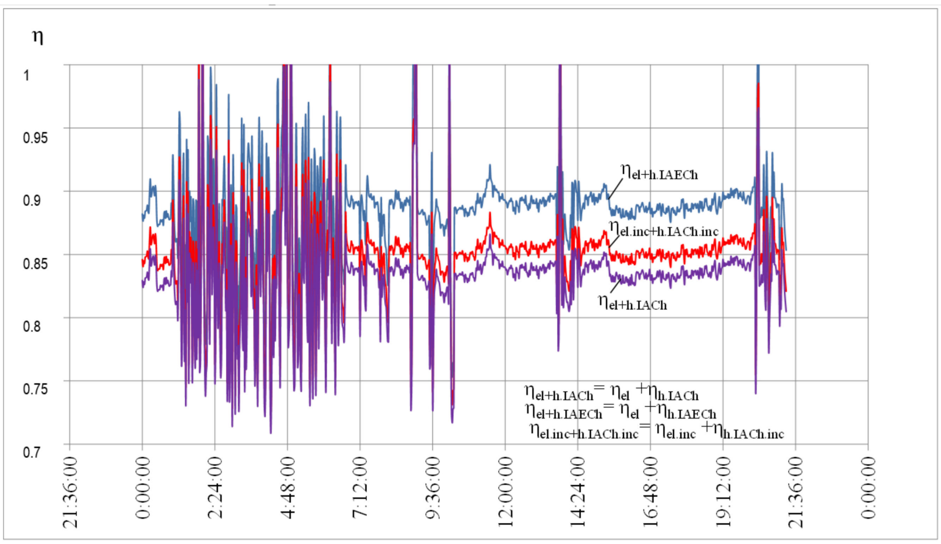

Figure 16. Daily changes of real overall electrical and heat efficiency due to the ACh heat transformed without intake air cooling, $\eta_{el+h.IACh}$, and with engine intake air cooling in the ECh, $\eta_{el.inc+h.IACh.inc}$, due to both the ACh and ECh without intake air cooling, $\eta_{el+h.IAECh}$: $\eta_{h.IACh} = Q_{h.IACh}/Q_{gas}$; $\eta_{el.inc+h.IAECh.inc} = (P_{el} + Q_{h.IAECh.inc})/Q_{gas.inc}$; $Q_{h.IAECh.inc} = Q_{h.IACh}$.

4. Conclusions

Overgenerated heat, removed from GE above the value, transformed into refrigeration by ACh in typical IES, leads to inevitable heat lost conventionally dissipated by the emergency radiator into the atmosphere.

Based on the monitoring data, the magnitude of the excessive heat is evaluated as about 25% of its overall value released from the GE and constitutes the reserve for enhancing the thermodynamic efficiency of IES through its transforming into refrigeration by booster chiller. The ECh is considered the simplest and cheapest thermotransformer.

So as the fuel efficiency of combustion engines is influenced essentially by sucked air temperature, the excessive refrigeration capacity has been used for cooling air to reduce fuel consumption and generate additional electricity and increase the electrical and overall efficiency of engines.

Such a redistribution of heat by transforming the rest left from the ACh in a booster ECh chiller enables us to enhance the efficiency of the IES due to minimizing the overgenerated heat lost.

The modified criteria for the comparative estimation of the thermodynamic efficiency of an innovative IES with an AECh without overgenerated heat against a typical IES with an ACh and heat loss were proposed. In contrast to well-known electrical and heat efficiency, they consider the magnitude of heat lost and the efficiency of its transforming to refrigeration evaluated by COP. The latter enables us to compare the heat efficiency of any transformation of engine heat to refrigeration with the ideal version of the IES, based on a high-efficiency ACh transforming all the heat removed from the engine without heat loss.

Some alternative scheme solutions of heat recovery systems focused on reducing the heat, not transformed by the ACh, are developed based on monitoring a hot water circuit.

The results presented reveal the opportunities for further investigation of GE cyclic air cooling, including scavenging air, by applying a proposed method of comparative estimation of IES thermodynamic efficiency.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15228774/s1. Flow sheet of investigation.

Author Contributions: Conceptualization, A.R. and M.R.; Methodology, A.R. and H.K.; Software, A.R.; Validation, R.R.; Formal analysis, H.K. and S.F.; Data curation, R.R.; Writing—review & editing, M.R.; Supervision, M.R. and H.K.; Project administration, A.R. and M.R. All authors have read and agreed to the published version of the manuscript.

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Nomenclature

AC	air cooler	
ACh	absorption lithium-bromide chiller	
AECh	absorption-ejector chiller	
COP	coefficient of performance	
ECh	ejector chiller	
LHV	Low Heat Value	kJ/kg
Symbols and unIES		
d_{amb}	ambient air absolute humidity	g/kg
G_{a}	air mass flow rate	kg/s
P_e	power output	kW
Q_0	overall cooling capacity	kW
q_0	specific cooling capacity—per unit air mass flow rate	kW/(kg/s) or kJ/kg
t	temperature	°C
t_{amb}	ambient air temperature	°C
t_{a2}	outlet air temperature	°C
t_0	refrigerant boiling temperature	°C
ξ	specific heat ratio of the overall heat (latent and sensible) related to sensible heat	
τ	time interval	h
φ_{amb}	ambient air relative humidity	%
Δt	air temperature decrease	K, °C
Subscripts		
a	air	
amb	ambient	
max	maximum	
opt	optimal	
rat	rational	

References

1. DFIC—Dr. Fromme International Consulting. *Cogeneration & Trigeneration—How to Produce Energy Efficiently: A Practical Guide for Experts in Emerging and Developing Economies*; Zellner, S., Burgtorf, J., Kraft-Schäfer, D., Eds.; Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH: Eschborn, Germany, 2016; p. 144.
2. Gluesenkamp, K.; Hwang, Y.; Radermacher, R. High efficiency micro trigeneration systems. *Appl. Therm. Eng.* **2013**, *50*, 6. [CrossRef]
3. Fahad, A. Al-Sulaiman; Ibrahim Dincer; Feridun Hamdullahpur Thermoeconomic optimization of three trigeneration systems using organic Rankine cycles: Part I—Formulations. *Energy Convers. Manag.* **2013**, *69*, 199–208.
4. Maraver, D.; Sin, A.; Royo, J.; Sebastián, F. Assessment of CCHP systems based on biomass combustion for small-scale applications through a review of the technology and analysis of energy efficiency parameters. *Appl. Energy* **2013**, *102*, 1303–1313. [CrossRef]
5. Popli, S.; Rodgers, P.; Eveloy, V. Trigeneration scheme for energy efficiency enhancement in a natural gas processing plant through turbine exhaust gas waste heat utilization. *Appl. Energy* **2012**, *93*, 623–636. [CrossRef]
6. Rocha, M.; Andreos, R.; Simões-Moreira, J.R. Performance tests of two small trigeneration pilot plants. *Appl. Therm. Eng.* **2012**, *41*, 84–91. [CrossRef]
7. Khaliq, A.; Dincer, I.; Sharma, P.B. Development and analysis of industrial waste heat based trigeneration for combined generation of power heat and cold. *J. Energy Inst.* **2010**, *83*, 79–85. [CrossRef]

8. Abusaa, G.; Issa, K. Performance Improvements of Power Generation Using Waste Heat Hybrid Cooling Plant. Kingdom Trigeneration Summit 29 September 2013; p. 24. Available online: http://www.adcenergysystems.com/images/Downloads/Tri-Gen%202013%Performance%20Improvements%20of%20Power%20Generation%20--%20K.Issa,%20ADC.pdf (accessed on 20 February 2020).
9. Oktay, Z.; Coskun, C.; Dincer, I. A new approach for predicting cooling degree-hours and energy requirements in buildings. *Energy* **2011**, *36*, 4855–4863. [CrossRef]
10. Ullah, I.; Hussain, I.; Rehman, K.; Wróblewski, P.; Lewicki, W.; Kavin, B.P. Exploiting the Moth–Flame Optimization Algorithm for Optimal Load Management of the University Campus: A Viable Approach in the Academia Sector. *Energies* **2022**, *15*, 3741. [CrossRef]
11. Shukla, A.K.; Sharma, A.; Sharma, M.; Mishra, S. Performance Improvement of Simple Gas Turbine Cycle with Vapor Compression Inlet Air Cooling. *Mater. Today Proc.* **2018**, *5*, 19172–19180. [CrossRef]
12. Barreto, D.; Fajardo, J.; Caballero, G.C.; Escorcia, Y.C. Innovative exergy and exergoeconomic analysis of a gas power system with steam injection and air cooling with a compression refrigeration machine. *Energy Technol.* **2021**, *9*, 2000993. [CrossRef]
13. Radchenko, R.; Pyrysunko, M.; Kornienko, V.; Scurtu, I.-C.; Patyk, R. Improving the Ecological and Energy Efficiency of Internal Combustion Engines by Ejector Chiller Using Recirculation Gas Heat. In *Lecture Notes in Networks and Systems*; Nechyporuk, M., Pavlikov, V., Kritskiy, D., Eds.; Integrated Computer Technologies in Mechanical Engineering—2020; ICTM 2020; Springer: Cham, Switzerland, 2021; Volume 188, pp. 531–544.
14. Radchenko, M.; Mikielewicz, D.; Andreev, A.; Vanyeyev, S.; Savenkov, O. Efficient Ship Engine Cyclic Air Cooling by Turboexpander Chiller for Tropical Climatic Conditions. In *Integrated Computer Technologies in Mechanical Engineering—2020*; Nechyporuk, M., Pavlikov, V., Kritskiy, D., Eds.; ICTM 2020; Lecture Notes in Networks and Systems; Springer: Cham, Switzerland, 2021; Volume 188, pp. 498–507.
15. Farouk, N.; Sheng, L.; Hayat, Q. Effect of Ambient Temperature on the Performance of Gas Turbines Power Plant. *Int. J. Comput. Sci.* **2013**, *10*, 439–442.
16. Patel, V.R.; Chaudhari, K.V.; Pathak, B.C.; Shekh, A.A. Evaluation of output and heat rate of the simple cycle gas turbine during the base load condition. *Int. J. Adv. Res. Eng. Sci. Technol.* **2015**, *2*, 2394–2444.
17. CIMAC Position Paper Gas Engine Aftertreatment Systems by CIMAC WG 17, Gas Engines, May 2017. Available online: https://www.cimac.com/cms/upload/Publication_Press/WG_Publications/CIMAC_WG17_2017_Aug_Position_Paper_Gas_Engine_Aftertreatment_Systems.pdf (accessed on 5 March 2019).
18. Jenbacher. Available online: http://www.intma.ru/energetica/power_stations/thermal_ps_trigeneration_ru.html (accessed on 5 March 2019).
19. Radchenko, N.; Trushliakov, E.; Radchenko, A.; Tsoy, A.; Shchesiuk, O. Methods to determine a design cooling capacity of ambient air conditioning systems in climatic conditions of Ukraine and Kazakhstan. *AIP Conf. Proc.* **2020**, *2285*, 030074. [CrossRef]
20. Pavlenko, A.M.; Koshlak, H. Application of Thermal and Cavitation Effects for Heat and Mass Transfer Process Intensification in Multicomponent Liquid Media. *Energies* **2021**, *14*, 7996. [CrossRef]
21. Al-Ibrahim, A.M.; Varnham, A. A review of inlet air-cooling technologies for enhancing the performance of combustion turbines in Saudi Arabia. *Appl. Therm. Eng.* **2010**, *30*, 1879–1888. [CrossRef]
22. Radchenko, A.; Radchenko, N.; Tsoy, A.; Portnoi, B.; Kantor, S. Increasing the efficiency of gas turbine inlet air cooling in actual climatic conditions of Kazakhstan and Ukraine. *AIP Conf. Proc.* **2020**, *2285*, 030071. [CrossRef]
23. Liang, X.; He, G.; Zhou, S.; Hao, Z.; Cai, D. Absorption characteristics of NH3/NaSCN working pair in an adiabatic absorber with structured packing. *Appl. Therm. Eng.* **2021**, *185*, 116325. [CrossRef]
24. Al-Tahaineh, H.A. Cooling of compressor air inlet of a gas turbine power plant using ammonia-water vapor absorption system. *Int. J. Energy Eng.* **2013**, *3*, 267–271.
25. Umberto, L. Adsorber efficiency in adsorbtion refrigeration. *Renew. Sustain. Energy Rev.* **2013**, *20*, 570–575.
26. Sur, A.; Das, R.K.; Sah, R. Influence of initial bed temperature on bed performance of an adsorption refrigeration system. *Therm. Sci.* **2018**, *22*, 2583–2595. [CrossRef]
27. Forduy, S.; Radchenko, A.; Kuczynski, W.; Zubarev, A.; Konovalov, D. Enhancing the fuel efficiency of gas engines in integrated energy system by chilling cyclic air. In *Grabchenko's International Conference on Innovative Manufacturing Process*; InterPartner-2019. Lecture Notes in Mechanical Engineering; Tonkonogyi, V., Ed.; Springer: Cham, Switzerland, 2020; pp. 500–509. [CrossRef]
28. Blecich, P. Experimental investigation of the effects of airflow nonuniformity on performance of a fin-and-tube heat exchanger. *Int. J. Refrig.* **2015**, *59*, 65–74. [CrossRef]
29. Dizaji, H.S.; Hu, E.J.; Chen, L.; Pourhedayat, S. Using novel integrated Maisotsenko cooler and absorption chiller for cooling of gas turbine inlet air. *Energy Convers. Manag.* **2019**, *195*, 1067–1078. [CrossRef]
30. Radchenko, R.; Radchenko, N.; Tsoy, A.; Forduy, S.; Zybarev, A.; Kalinichenko, I. Utilizing the heat of gas module by an absorption lithium-bromide chiller with an ejector booster stage. *AIP Conf. Proc.* **2020**, *2285*, 030084. [CrossRef]
31. Radchenko, M.; Radchenko, A.; Radchenko, R.; Kantor, S.; Konovalov, D.; Kornienko, V. Rational loads of turbine inlet air absorption-ejector cooling systems. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2021**, *236*, 450–462. [CrossRef]
32. Konovalov, D.; Kobalava, H.; Maksymov, V.; Radchenko, R.; Avdeev, M. Experimental Research of the Excessive Water Injection Effect on Resistances in the Flow Part of a Low-Flow Aerothermopressor. In *Advances in Design, Simulation and Manufacturing III (DSMIE 2020)*; Lecture Notes in Mechanical Engineering; Ivanov, V., Ed.; Springer: Cham, Switzerland, 2020; pp. 292–301.

33. Butrymowicz, D.; Gagan, J.; Śmierciew, K.; Łukaszuk, M.; Dudar, A.; Pawluczuk, A.; Łapiński, A.; Kuryłowic, A. Investigations of prototype ejection refrigeration system driven by low grade heat. *HTRSE-2018 E3S Web Conf.* **2018**, *70*, 7. [CrossRef]
34. Smierciew, K.; Gagan, J.; Butrymowicz, D.; Karwacki, J. Experimental investigations of solar driven ejector air-conditioning system. *Energy Build.* **2014**, *80*, 260–267. [CrossRef]
35. Konovalov, D.; Radchenko, M.; Kobalava, H.; Kornienko, V.; Maksymov, V.; Radchenko, A.; Radchenko, R. Research of characteristics of the flow part of an aerothermopressor for gas turbine intercooling air. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2022**, *236*, 634–646. [CrossRef]
36. Yang, Z.; Konovalov, D.; Radchenko, M.; Radchenko, R.; Kobalava, H.; Radchenko, A.; Kornienko, V. Analyzing the efficiency of thermopressor application for combustion engine cyclic air cooling. *Energies* **2022**, *15*, 2250. [CrossRef]
37. Korze'n, A.; Taler, D. Modeling of transient response of a plate fin and tube heat exchanger. *Int. J. Therm. Sci.* **2015**, *92*, 188–198. [CrossRef]
38. Taler, D. Mathematical modeling and control of plate fin and tube heat exchangers. *Energy Convers. Manag.* **2015**, *96*, 452–462. [CrossRef]
39. Pavlenko, A. Energy conversion in heat and mass transfer processes in boiling emulsions. *Therm. Sci. Eng. Prog.* **2020**, *15*, 100439. [CrossRef]
40. Pavlenko, A. Change of emulsion structure during heating and boiling. *Int. J. Energy A Clean Environ.* **2019**, *20*, 291–302. [CrossRef]
41. Konovalov, D.; Kobalava, H.; Radchenko, M.; Scurtu, I.-C.; Sviridov, V. Determination of the evaporation chamber optimal length of a low-flow aerothermopressor for gas turbines. In Proceedings of the Lecture Notes in Mechanical Engineering, Innovative Manufacturing Processes II, Selected Papers from the 2nd Grabchenko's International Conference on Innovative Manufacturing Processes (InterPartner-2020), Odessa, Ukraine, 8–11 September 2020; Tonkonogyi, V., Ed.; Springer: Cham, Switzerland, 2021; pp. 654–663.
42. Kruzel, M.; Bohdal, T.; Dutkowski, K.; Radchenko, M. The Effect of Microencapsulated PCM Slurry Coolant on the Efficiency of a Shell and Tube Heat Exchanger. *Energies* **2022**, *15*, 5142. [CrossRef]
43. Kruzel, M.; Bohdal, T.; Dutkowski, K.; Kuczyński, W.; Chliszcz, K. Current Research Trends in the Process of Condensation of Cooling Zeotropic Mixtures in Compact Condensers. *Energies* **2022**, *15*, 2241. [CrossRef]
44. Yang, Z.; Korobko, V.; Radchenko, M.; Radchenko, A.; Radchenko, R. Improving thermoacoustic low temperature heat recovery systems. *Sustainability* **2022**, *14*, 12306. [CrossRef]
45. Radchenko, A.; Trushliakov, E.; Tkachenko, V.; Portnoi, B.; Prjadko, O. Improvement of the Refrigeration Capacity Utilizing for the Ambient Air Conditioning System. In *Innovative Manufacturing Processes II. InterPartner 2020*; Lecture Notes in Mechanical Engineering; Tonkonogyi, V., Ed.; Springer: Cham, Switzerland, 2021; pp. 714–723.
46. Radchenko, N.; Radchenko, A.; Tsoy, A.; Mikielewicz, D.; Kantor, S.; Tkachenko, V. Improving the efficiency of railway conditioners in actual climatic conditions of operation. *AIP Conf. Proc.* **2020**, *2285*, 030072. [CrossRef]
47. Yang, Z.; Kornienko, V.; Radchenko, M.; Radchenko, A.; Radchenko, R.; Pavlenko, A. Capture of pollutants from exhaust gases by low-temperature heating surfaces. *Energies* **2022**, *15*, 120. [CrossRef]
48. Fan, C.; Pei, D.; Wei, H. A novel cascade energy utilization to improve efficiency of double reheat cycle. *Energy Convers. Manag.* **2018**, *171*, 1388–1396. [CrossRef]
49. Kornienko, V.; Radchenko, R.; Stachel, A.; Andreev, A.; Pyrysunko, M. Correlations for pollution on condensing surfaces of exhaust gas boilers with water-fuel emulsion combustion. In *Grabchenko's International Conference on Innovative Manufacturing Process. InterPartner-2019*; Lecture Notes in Mechanical Engineering; Tonkonogyi, V., Ed.; Springer: Cham, Switzerland, 2020; pp. 530–539. [CrossRef]
50. Kornienko, V.; Radchenko, R.; Bohdal, Ł.; Kukiełka, L.; Legutko, S. Investigation of condensing heating surfaces with reduced corrosion of boilers with water-fuel emulsion combustion. In *Integrated Computer Technologies in Mechanical Engineering—2020. ICTM 2020. Lecture Notes in Networks and Systems*; Nechyporuk, M., Pavlikov, V., KrIESkiy, D., Eds.; Springer: Cham, Switzerland, 2021; Volume 188, pp. 300–309.
51. Kornienko, V.; Radchenko, R.; Radchenko, M.; Radchenko, A.; Pavlenko, A.; Konovalov, D. Cooling cyclic air of marine engine with water-fuel emulsion combustion by exhaust heat recovery chiller. *Energies* **2022**, *15*, 248. [CrossRef]
52. Yang, Z.; Kornienko, V.; Radchenko, M.; Radchenko, A.; Radchenko, R. Research of Exhaust Gas Boiler Heat Exchange Surfaces with Reduced Corrosion when Water-fuel Emulsion Combustion. *Sustainability* **2022**, *14*, 11927. [CrossRef]
53. Radchenko, R.; Kornienko, V.; Pyrysunko, M.; Bogdanov, M.; Andreev, A. Enhancing the Efficiency of Marine Diesel Engine by Deep Waste Heat Recovery on the Base of IES Simulation Along the Route Line. In *Integrated Computer Technologies in Mechanical Engineering (ICTM 2019)*; Advances in Intelligent Systems and Computing; Nechyporuk, M., Pavlikov, V., Krieskiy, D., Eds.; Springer: Cham, Switzerland, 2020; Volume 1113, pp. 337–350. [CrossRef]
54. Mikielewicz, D.; Klugmann, M.; Wajs, J. Flow boiling intensification in minichannels by means of mechanical flow turbulising inserts. *Int. J. Therm. Sci.* **2013**, *65*, 79–91. [CrossRef]
55. Dąbrowski, P.; Klugmann, M.; Mikielewicz, D. Channel Blockage and Flow Maldistribution during Unsteady Flow in a Model Microchannel Plate heat Exchanger. *J. Appl. Fluid Mech.* **2019**, *12*, 1023–1035. [CrossRef]
56. Dąbrowski, P.; Klugmann, M.; Mikielewicz, D. Selected studies of flow maldistribution in a minichannel plate heat exchanger. *Arch. Thermodyn.* **2017**, *38*, 135–148. [CrossRef]

57. Kumar, R.; Singh, G.; Mikielewicz, D. A New Approach for the Mitigating of Flow Maldistribution in Parallel Microchannel Heat Sink. *J. Heat Transf.* **2018**, *140*, 72401–72410. [CrossRef]
58. Kumar, R.; Singh, G.; Mikielewicz, D. Numerical Study on Mitigation of Flow Maldistribution in Parallel Microchannel Heat Sink: Channels Variable Width Versus Variable Height Approach. *J. Electron. Packag.* **2019**, *141*, 21009–21011. [CrossRef]
59. Khan, M.G.; Fartaj, A. A review on microchannel heat exchangers and potential applications. *Int. J. Energy Res.* **2011**, *35*, 553–582. [CrossRef]
60. Bohdal, T.; Sikora, M.; Widomska, K.; Radchenko, A.M. Investigation of flow structures during HFE-7100 refrigerant condensation. *Arch. Thermodyn.* **2015**, *36*, 25–34. [CrossRef]
61. Wajs, J.; Mikielewicz, D.; Jakubowska, B. Performance of the domestic micro ORC equipped with the shell-and-tube condenser with minichannels. *Energy* **2018**, *157*, 853–861. [CrossRef]
62. Kuczyński, W.; Kruzel, M.; Chliszcz, K. A Regressive Model for Periodic Dynamic Instabilities during Condensation of R1234yf and R1234ze Refrigerants. *Energies* **2022**, *15*, 2117. [CrossRef]
63. Kuczyński, W.; Kruzel, M.; Chliszcz, K. Regression Model of Dynamic Pulse Instabilities during Condensation of Zeotropic and Azeotropic Refrigerant Mixtures R404A, R448A and R507A in Minichannels. *Energies* **2022**, *15*, 1789. [CrossRef]
64. Yang, Z.; Radchenko, M.; Radchenko, A.; Mikielewicz, D.; Radchenko, R. Gas turbine intake air hybrid cooling systems and a new approach to their rational designing. *Energies* **2022**, *15*, 1474. [CrossRef]
65. Radchenko, A.; Scurtu, I.-C.; Radchenko, M.; Forduy, S.; Zubarev, A. Monitoring the efficiency of cooling air at the inlet of gas engine in integrated energy system. *Therm. Sci.* **2022**, *26*, 185–194. [CrossRef]
66. Marques, R.P.; Hacon, D.; Tessarollo, A.; Parise, J.A.R. Thermodynamic analysis of trigeneration systems taking into account refrigeration, heating and electricity load demands. *Energy Build.* **2010**, *42*, 2323–2330. [CrossRef]
67. Chacartegui, R.; Jiménez-Espadafor, F.; Sánchez, D.; Sánchez, T. Analysis of combustion turbine inlet air cooling systems applied to an operating cogeneration power plant. *Energy Convers. Manag.* **2008**, *49*, 2130–2141. [CrossRef]
68. Lozano, M.; Ramos, J.C.; Serra, L.M. Cost Optimization of the Design of CHCP (Combined Heat, Cooling and Power) Systems under Legal Constraints. *Energy* **2010**, *35*, 794–805. [CrossRef]
69. Mohapatra, A.K. Comparative analysis of inlet air cooling techniques integrated to cooled gas turbine plant. *J. Energy Inst.* **2015**, *88*, 344–358. [CrossRef]
70. Sandhaas, A.; Kim, H.; Hartmann, N. Methodology for Generating Synthetic Load Profiles for Different Industry Types. *Energies* **2022**, *15*, 3683. [CrossRef]
71. Radchenko, A.; Trushliakov, E.; Kosowski, K.; Mikielewicz, D.; Radchenko, M. Innovative turbine intake air cooling systems and their rational designing. *Energies* **2020**, *13*, 6201. [CrossRef]
72. Jamaluddin, K.; Wan Alwi, S.R.; Abdul Manan, Z.; Hamzah, K.; Klemeš, J.J. Development of numerical trigeneration system cascade analysis with transmission and storage energy losses consideration. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *884*, 012019. [CrossRef]
73. Fumo, N.; Mago, P.J.; Smith, A.D. Analysis of combined cooling, heating, and power systems operating following the electric load and following the thermal load strategies with no electricity export. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2011**, *225*, 1016–1025. [CrossRef]
74. Radchenko, M.; Radchenko, A.; Mikielewicz, D.; Radchenko, R.; Andreev, A. A novel degree-hour method for rational design loading. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2022**, *35*, 2455–2460. [CrossRef]
75. Pavlenko, A.M. Force interaction of boiling dispersed emulsion particles. In Proceedings of the 4th Thermal and Fluids Engineering Conference, Las Vegas, NV, USA, 14–17 April 2019; pp. 1051–1059. [CrossRef]
76. Yang, Z.; Radchenko, R.; Radchenko, M.; Radchenko, A.; Kornienko, V. Cooling potential of ship engine intake air cooling and IES realization on the route line. *Sustainability* **2022**, *14*, 15058. [CrossRef]
77. Suamir, I.N.; Tassou, S.A. Performance evaluation of integrated trigeneration and CO_2 refrigeration systems. *Appl. Therm. Eng.* **2013**, *50*, 1487–1495. [CrossRef]
78. Ortiga, J.; Bruno, J.C.; Coronas, A. Operational optimization of a complex trigeneration system connected to a district heating and cooling network. *Appl. Therm. Eng.* **2013**, *50*, 1536–1542. [CrossRef]
79. Pedro, A.R.; Rodriguez-Hidalgo, M.d.; José, I. Nogueira, Antonio Lecuona, María del Carmen Veneg. *Dist. Heat. Cool. Bus. Build. Madr. Appl. Therm. Eng.* **2013**, *50*, 1496–1503.
80. Freschi, F.; Giaccone, L.; Lazzeroni, P.; Repetto, M. Economic and environmental analysis of a trigeneration system for food-industry: A case study. *Appl. Energy* **2013**, *107*, 157–172. [CrossRef]
81. Canova, A.; Cavallero, C.; Freschi, F.; Giaccone, L.; Repetto, M.; Tartaglia, M. Optimal energy management. *IEEE Ind. Appl. Mag.* **2009**, *15*, 62–65. [CrossRef]
82. Cardona, E.; Piacentino, A. A methodology for sizing a trigeneration plant in mediterranean areas. *Appl. Therm. Eng.* **2003**, *23*, 15. [CrossRef]
83. Giaccone, L.; Canova, A. Economical comparison of CHP systems for industrial user with large steam demand. *Appl. Energy* **2009**, *86*, 904–914. [CrossRef]
84. Carvalho, M.; Lozano, M.A.; Serra, L.M. Multicriteria synthesis of trigeneration systems considering economic and environmental aspects. *Appl. Energy* **2012**, *91*, 245–254. [CrossRef]

85. Geldermann, J.; Rentz, O. Multi-criteria analysis for the assessment of environmentally relevant installations. *J. Ind. Ecol.* **2020**, *9*, 127–142. [CrossRef]
86. Kavvadias, K.C.; Tosios, A.P.; Maroulis, Z.B. Design of a combined heating, cooling and power system: Sizing, operation strategy selection and parametric analysis. *Energy Convers Manag.* **2010**, *51*, 833–845. [CrossRef]
87. Pavlenko, A.; Koshlak, H. Heat and Mass Transfer During Phase Transitions in Liquid Mixtures. *Rocz. Ochr. Srodowiska* **2019**, *21*, 234–249.
88. Kalhori, S.B.; Rabiei, H.; Mansoori, Z. Mashad trigeneration potential–An opportunity for CO_2 abatement in Iran. *Energy Conv. Manag.* **2012**, *60*, 106–114. [CrossRef]
89. Forsyth, J.L. Gas turbine inlet air chilling for LNG. *IGT Int. Liq. Nat. Gas Conf. Proc.* **2013**, *3*, 1763–1778.
90. Komuro, T.; Ito, E.; Sonoda, T.; Tomita, Y.; Hidaka, K.; Shibutani, S. Power output augmentation of gas turbine combined cycle by inlet-air cooling system of chiller type under high ambient air temperature. *MIESubishi Heavy Ind. Tech. Rev.* **2010**, *47*, 33–39.
91. Radchenko, A.; Radchenko, M.; Mikielewicz, D.; Pavlenko, A.; Radchenko, R.; Forduy, S. Energy saving in trigeneration plant for food industries. *Energies* **2022**, *15*, 1163. [CrossRef]