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# Innovative waste heat recovery techniques in the metallurgical industry: enhancing energy efficiency and sustainability

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**Abstract.** Waste heat recovery (WHR) is becoming an important aspect in the metallurgical industry where the heat losses in the heat-intensive processes are significant. This article overviews the state-of-the-art and future WHR methods to be applied to metallurgical plants; that is, the traditional recuperator and regenerator, and the latest heat-to-power technologies, i.e., ORC and thermoelectric systems. Traditional solutions and their innovative alternatives are contrastingly reviewed, in which the simulated information and the case studies of the metallurgical plants of the Republic of Kazakhstan are taken into consideration. Its primary conclusions are that thermal efficiency can be improved by 10-30% with the advanced WHR systems, and the related effect on fuel costs and emissions, and the issues of economic and retrofitting are examined. The results are beneficial for eco-efficient metallurgy. The innovation of the research lies in the fact that the analysis of the situation with the different WHR systems in the subsector of the metallurgical industry of Kazakhstan serves as the premise of distributing the practical implications of the possible energy efficiency enhancement of the energy-intense industries in the country regarding the industrial energy policy of the national government.

***Keywords:*** *waste heat recovery, metallurgy industry, energy efficiency, thermoelectric generation, organic Rankine cycle, Kazakhstan industry, sustainability.*

## 1. Introduction

Metallurgy belongs to the number of the most energy-intensive industries all over the world, using about 20-30 EJ of fossil energy and, therefore, emitting considerable portions of the waste heat. In 2018, the U.S. Energy Information Administration (EIA) stated that the basic metals industry had 12% of all energy use in the industrial sector worldwide [18]. Greater disaggregated analysis in the steel sub-sector puts it that steel sub-sector could contribute over a quarter (25%) of all industrial global energy consumption and a little over 8% of final world demand [17]. These estimates are obviously dependent on what part of the metallurgical industry is (all basic metals versus steel only) and the year of data collection, but they all underline the immense energy toeprint of the sector, and hence the need to decrease the energy demand.

The elevated temperature metallurgical processes, such as smelting, casting, rolling, and in forging etc. involves the wastage of a large fraction of the energy input usually greater than 30%, to the surroundings [2]. This energy is lost mainly in the flue gases and molten slag, as well as in the cooling water and surface radiation. According to statistics reported by U.S. Department of Energy (DOE) on the aggregate manufacturing sector, 36% of the process heating energy has been wasted on average and this number increases to 46% in the iron and steel sector [2]. A case example in the steel industry of Jordan showed that the total heat losses of input energy must reach 36% on the average, while only 17-36% where the furnace losses are 36% [21]. The scale of these losses is significant, for example, molten slags, which are discharged at temperatures approximating 1200-1600°C is an energy source with the potential to contribute to 220 TWh per year of the global energy mix. The elevated temperatures of flue gasses and slags coming from these sources represent excellent grade of thermal energy that can be efficiently recovered and converted to other usable forms.

The presence of such waste heat besides representing a waste of energy resources is the reason why (GHG) greenhouse gas emissions are generated, a source of operation inefficiencies, causing a rise in the production cost [20]. The metallurgy industry, in which particulate matter steel industry is a part, is the one of its major sources whose share in the global $CO_2$ released in atmosphere is estimated to be 6-9% [16]. Therefore, energy efficiency enhancement through initiatives like Waste Heat Recovery (WHR) technologies are of essence to reduce $CO_2$ emissions and the total costs. Their interrelation with an apparent reduction in the losses of energy, fuel consumption, GHG emissions, and the costs of production speaks in favor of WHR technologies in rather dissimilar disguises.

Energy saving has in recent times emerged to be a major area of concern in the manufacturing process across a broad spectrum of industries [5]. In this context, WHR systems have been identified as a convenient and indispensable approach to energy savings to reduce heat losses and increase energy efficiency at industrial facilities [3]. In metallurgy, the classical WHR technology is made up of devices, namely recuperators and regenerators, which are predominantly employed in pre-heating combustion air or charge materials by the heat content of waste gasses [3]. In comparison, recuperators and regenerative heat exchangers are direct-transfer heat exchangers, wherein the heat is transferred directly between the flue gases and the incoming air in the case of recuperators or is periodically dumped into the cooler fluid by a refractory matrix in the case of regenerative heat exchangers [3].

Besides these traditional methods, new methods are starting to be constructed. They can be grouped according to the most occurring process of energy conversion: Organic Rankine Cycles (ORC) can be used to efficiently convert medium-temperature waste heat to electricity [4], Thermoelectric Generators (TEG) can convert directly heat into electricity, having the particularity of not having any moving parts [15], Phase Change Material (PCM) 1[3]. These kinds of technologies are particularly significant, since unlike the high-grade heat they allow the recovery of waste low-to-medium grade heat which is normally lost and turn it into useful forms of energy whether that be in the form of preheated combustion air, process steam and/or electricity to further enhance the use of the grid. Wide variety of WHR technologies reflects the wide variety of industrial waste heat, particularly its temperature. As an illustration, although recuperators are typically optimized to high quality heat, ORC and TEG systems can utilize medium to low quality heat advantageously, which is why care should be taken to ensure a good match between the technology and the waste heat source.

Enhancement of thermodynamic efficiency and materials compatibility of these WHR methods to enable them to run in harsh industrial environments as well as to improve their economic feasibility has been a recent research topic. However, despite the implementation of WHRBs at the international level, there are several technical and economic risks that do not allow the implementation of modern systems of WHRB by metallurgical facilities, especially in the developing economies, as is the case in Central Asia. The obstacles are typically systemic and involve high (initial) costs of capital investment [1], absence of local expertise and skilled labor force in the specialized fields, absence of motivating policy framework and incentives [5], and perceived risk of implementing innovative technology on the existing production lines. There is underinvestment in clean energy potential in Central Asia, for example, that is indicative of institutional, financial, technical and social barriers [5]. This is often combined with the old energy infrastructure that belonged in the past. Such a complex combination of factors implies that technological solutions alone are not sufficient, and the multi-faceted approach encompassing policy support, capacity building and implementation of new finance solutions would be central to the further spread of WHR use in these areas.

Kazakhstan is especially a good place to study the possibilities of scalability and cost-effectiveness of WHR solutions, since the republic contains a large ferrous and nonferrous metal industry [6]. The relevance of these projects is also in regard to the forward-looking national targets of industrial modernization and energy saving of the country, particularly its recently released «Strategy to Achieve Carbon Neutrality by 2060» and the Green Concept Economy (where 15 percent of electricity will be produced by renewables by 2030 that will rise to 50 percent by 2050) as mentioned right below the targets of this research.

The objective of this paper is to review and assess the currently available or emerging waste heat recovery technologies that can be suitable for the metallurgical sector in terms of technological maturity level, thermal performance and energy saving potential. The aims of this study are:

Analyze the operations and performance of traditional WHR technologies including recuperators and regenerators.

Examine of recent trends in the field of heat-to-power conversion systems like ORC and TEG modules.

Compare energy and cost savings from various WHR systems adopted in metallurgical plants.

Evaluate feasibility and identify constraints of WHR application in the metallurgy sector of Kazakhstan. By considering both the technical and contextual elements, the present work contributes to the development of an energy and environmentally friendly metallurgical industry.

## 2. Materials and methods

The study employs a hybrid methodology that consists of qualitative technical review and quantitative evaluation, to assess the performance, feasibility and suitability of the various WHR methods to be applied in metallurgy. The research article has three major components: review of literature, modelling of processes and case study.

### 2.1. Review of literature

Systematic review of the literature was conducted based on the published scholarly and industrial works (2005-2024) with the help of Scopus, ScienceDirect and IEEE Xplore databases. The review got the purpose to determine the existing WHR technologies used in the main metallurgical process -steel, aluminum, copper and the ferroalloy production-industries and find out what the industry-standard practices and new technologies are. To encompass the relevant literature a set of key words were carefully selected which included: «metallurgical waste heat recovery», «heat exchange systems», «ORC in metal industry», «thermoelectric generation in foundry», «furnace heat recovery» and «slag heat utilization», among others. This systematic process resulted in an overall review of current technologies, how these work and efficiencies are obtained.

### 2.2. Materials

The waste heat sources available in the metallurgical processing were identified and grouped as per the temperature level and as per the place of occurrence in the plant or in the plant stream (such as flue gas in furnaces, excess heat in cooling of slag, thermal energy in ladle preheating area). In this study, the temperatures will be classified into the following temperature grade: low grade (<150°C), medium grade (150-500°C) and high grade (>500°C). Such a separation corresponds to certain industrial categorizations, notably UNIDO low and medium temperature and IEA medium and high temperature, though the levels numerous upon the normative and reporting structure. Lack of standard horizontal temperature grade definition tempers the comparison between the studies [2]; the chosen classification significantly influences the assessment of the WHR potential and, as a result, of the choice of its suitable technologies. This classification is necessary because the heat temperature of the waste is a major factor that defines what WHR technology can be applied and made economical. This is a highly critical difference because the character of the waste heat temperature will mostly dictate what style of WHR technology may be suitable and cost-effectively installed.

Thermodynamic performance metrics such as energy recovery efficiency (η_recovery), heat transfer rate ($\dot{Q}$) and overall system thermal resistance (R_th) were computed based on established thermodynamic principles and heat transfer models relevant to each WHR technology. Heat recovery potential ($\dot{Q}$ ) from various waste streams was calculated using the fundamental calorimetric relation:
Equation 1: Heat recovery potential $\dot{Q}$ from waste streams was calculated using the relation:

$$\dot{Q} = \dot{m} \cdot C_p \cdot (T_{in} - T_{out}) )$$

Where:

- $\dot{m}$ = mass flow rate of the waste stream (for example, flue gas, cooling water) in kg/s,
- $C_p$ = specific heat capacity of the fluid in the waste stream (J/kg·K),
- $T_{in}$, $T_{out}$ = inlet and outlet temperatures of the waste stream through the recovery unit (°C).

Example Calculation:
Assuming:

$\dot{m} = 1.2 kg / s$

$C_p = 1100 J / kg \cdot K$

Inlet temp: $T_{in} = 800(\circ C)$, Outlet temp: $T_{out} = 450(\circ C)$

$$\dot{Q} = 1.2 \times 1100 \times (800 - 450) = 1.2 \times 1100 \times 350 = 462$$

This means 462 kW of heat is potentially recoverable from this stream alone.

### 2.3. Economic Feasibility Analysis

Levelized Cost of Heat (LCOH) and Simple Payback Period (SPP) were calculated to evaluate competitiveness of deployment of different sub options in the different WHR technologies. SPP is one of the common financial comparison indicators, and it can be applied to make judgments regarding the period of the total energy saving investment return. The LCOH embodies the cost of the heat recovered during its lifetime in a certain unit and considers capital costs and O&M cost in addition to the maintenance costs [7] in a similar form to the Levelized Cost of Energy (LCOE) that is commonly used in power generation projects.

Investment costs, operating costs, and maintenance periods and energy saving assessments are obtained from international benchmarks, manufacturer data and, local industrial practices in Kazakhstan that characterize regional economies are included in the analysis [6].

$$SPP(years) = \frac{CapitalCost}{AnnualEnergyCostSavings}$$

$$LCOH(\frac{USD}{kWH}) = \frac{TotalLifeCycleCost(Capital + Operational + Ma\,\mathrm{int}\,enance)}{Total\,\mathrm{Re}\,\mathrm{cov}\,eredHeatOutputoverLifetime(kWH)}$$

That formulation is in line with the general levelized cost approaches, and the specific treatments relating to heat recovery, like those described by NREL in their LCOH calculations.

### 2.4. Methods

Based on secondary information on the biggest metallurgical plants of Kazakhstan, including ArcelorMittal Temirtau (steelmaking) and KazZinc (non-ferrous), the deployment and deportability of promising technologies of WHR were studied in practice. These contain the illustrations of some project-related aspects and economic consequences of such plants, e.g., the information about repairs of converter gas in boiler at ArcelorMittal Temirtau and installation of heat pump unit in Kazzinc were copied in other sources [6]. The common data collected to carry out such case studies were the temperature profiles required to operate the furnace, volume and composition of exhausted gases, process throughputs, the prevailing patterns of energy consumption and cost of energy. The adequacy and accuracy of this secondary data is very significant to the validity of such case studies. This was necessary to identify site-specific potential of technologies like Organic Rankine Cycles (ORC) to generate power from the flue gas and advanced recuperative systems to preheat combustion air and provide estimates of detailed retrofit cases.

KazZinc is a company located in Kazakhstan, which is among the biggest producers of non-ferrous metals; it has several high-temperature smelting furnaces with a steady pattern of heat emission, and it is an optimal location to implement WHR.

### 2.5. Validation and Limitations

The verification of the developed model was carried out by the comparison of the simulation results with the published experimental and industrial data. e.g. recuperator models might be tested against performance data of industrial furnaces [3], ORC models against field measurements in steel mill applications [8] and TEG models against experimental data caused by various thermal scenarios [9], [10]. To be credible, the validation data applied in this work must be strongly representative of scales, temperature regime and context of applications to simulated systems. Further confirmation of more than 5% deviation prompted us to adjust the thermal parameters. The study limitations are the steady-state assumption, sensor measurement of the transient thermal behavior, and the lack of consideration of hybrid WHR systems, i.e., combined ORC-TEG modules.

## 3. Results and discussion

Thermo-dynamic simulation results, economic assessment and industrial cases complete this section. Some of the factors evaluated in the investigation of each major WHR system include thermal efficiency, energy reduction, capital cost and integration with the metallurgical processes.

### 3.1. Categorization of Waste Heat Sources

Categorization of the waste heat sources in metallurgical plants, during preliminary analysis, showed that more than 60% of the thermal losses are concentrated in a few major streams. This is well supported by analyses of the steel industry in Kazakhstan, where flue gases from processes like blast furnaces and reheating furnaces are the largest source of heat loss, potentially carrying away 40-50% of the fuel energy [22]. The main sources that were found are:

- Furnace flue gases: which typically have temperatures between 600°C and 1000°C and are a major source of high-grade heat.
- Cooling water in continuous casting: This source is at somewhat lower temperatures of about 100–150°C and is thus low- to mid-grade heat.
- Hot slags and ladle walls: These are at temperatures more than 1000°C (for example, slags at 1200-1600°C), with significant amount of high-quality heat recovery potential if

they can be successfully captured, which—due to its highly corrosive nature - is often a difficult task for molten slag. Heat losses from ladles at molten steel holding can also be considerable, which have generally had outer wall temperatures around 200-400°C and slag surface temperatures in the range 600-900°C.

The best quality waste heat (i.e. waste heat above 500°C, see Section 2.2) is therefore generally found in the primary metal extraction and smelting processes (blast and electric furnaces) with the highest process temperatures. Intermediate heat (150-500°C) was typical of secondary forming, hot rolling, forging and annealing. This division is made on the general comprehension in metallurgical practice. The temperature of the waste heat is the limiting factor to the use of WHR technology, high-quality heat may be utilized in power generation or high-temperature preheating, medium-high to low-quality heat is suitable for lower temperature preheating or ORC. It is categorized into high-grade waste heat (44.4%), medium-grade waste heat (24%), and low-grade waste heat (30%) according to the classification of waste heat in iron and steel industry by Ma's, is an approximate proportion of the distribution of recoverable thermal energy.

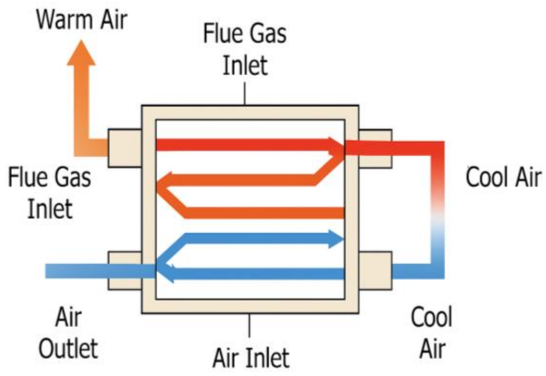


***Figure 1. Illustrates a flue gas heat exchanger system used to capture high-temperature exhaust from furnaces and transfer it to preheat incoming air streams***

The diagram illustrates the method in which the thermal energy contained in flue gases is conducted through surfaces of a heat exchanger to the combustion air to enhance fuel efficiency and minimize emission losses.

### 3.1.1. Distribution of Waste Heat Sources in Metallurgy

Some of the devices in metallurgical plants have practical heat losses as shown in Figure 2 (Metallurgical Plant flowsheet). Slag cooling and flue gas of various furnaces (blast furnace, reheat furnace, electric arc furnace) are the most promising sources considered. In Figure 2, the important areas of heat losses are arranged graphically to get an idea of where the greatest possibility of heat recovery in process units lies. The main production processes are mainly of high-heat-containing, e.g. the slag-cooling and flue gases, which may be a vast reservoir of unused energy. Compared to the secondary in-line processes (such as rolling and heat-treatments), the medium-thickness losses are the most common in the secondary processes. Figure 3 (Sources of Waste Heat in Metallurgy donut chart) also visualizes the distribution of these sources by type of waste heat by type of process units, i.e. blast furnaces, EAF (Electric Arc Furnaces), reheat furnace and rolling mills. This radial plan discloses the map of heat losses, the map of economization and gives a priority of WRH technology application that will achieve the maximum energy recovery and economic benefits. The accuracy of the visualization of heat loss distribution is enhanced where the visualization is based on detailed energy audits of individual plants, or where the industry information is more comprehensive.

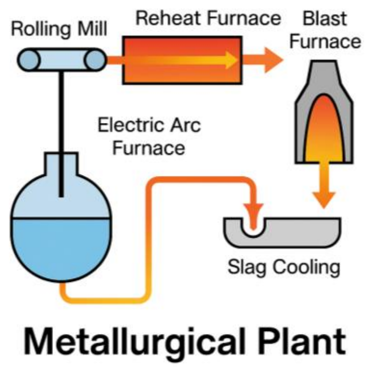


***Figure 2. Typical temperature ranges of waste heat sources in metallurgy. Slag cooling and flue gases offer the highest recovery potential***

The visual diagram classifies key areas of thermal losses in process like slag cooling, flue gas emission and ladle operations, which give an idea about regions that have the best potential of heat recovery. In primary production, high-grade heat (slag cooling, flue gases) predominates, whereas medium-grade losses are characteristic of secondary processes, rolling and heat treatment.

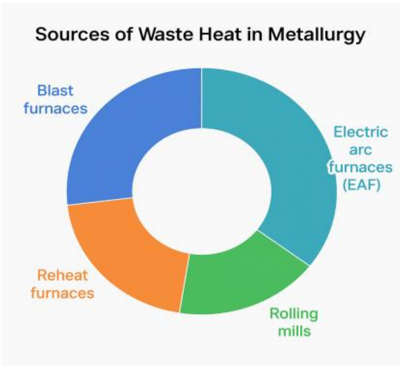


***Figure 3. Illustrates source categories of waste heat in metallurgy in a circular layout: blast furnaces, EAFs, reheat furnaces, and rolling mills***

The circular layout illustrates process-wise distribution of heat losses and aids in prioritizing areas for WHR deployment.

## 3.2. Efficiency Analysis of Recovery Systems

### 3.2.1. Recuperators vs. Regenerators

Even though they permitted a continuous heat exchange between the flue gases and the entering air, the conventional recovers, which approached 50-60% in metallurgical use. Even 20-25% or even up to 30% simpler designs as for example current collector vehicles can be even with 20-25% or even up to 30% simpler designs as a simple air liquid exchanger (ALE). More compact plate-type devices can be estimated as Preferred Size, and they may attain 70%. They are best suited to the endless processes and are furnace flue gas heat recovery [3].

Regenerator-type heaters, where the heat is stored and released in refractory material in turn, may often achieve higher thermal efficiencies, up to 80 or more percent. There are high level regenerator uses (such as converter gas recovery) which claim efficiencies more than 90% [11]. The systems, however, tend to be bulkier and higher in maintenance requirements largely due to the fact that they are subject to particulate fouling of flue gas that is dirty in most metallurgy work [3]. Regenerators are normally chosen when the process is a high temperature batch process [11] where it is possible to gain greater efficiency and the complication of the operation can be tolerated. Table 1 gives summary comparisons with these characteristics.

***Table 1. Recuperator vs. Regenerator Efficiency and Use***

| System | Efficiency | Best Used For |
|---|---|---|
| Recuperator | 55–70% | Furnace flue gases |
| Regenerator | 70–80% | High-temp batch ops |

The information in Table 1 provides a bit of comparison, which can be helpful in a first pass technology screening. The efficiency range of regenerators corresponds to applications, such as those listed in [11], whereas the 70-80% is a more universal value.

### 3.2.2. Organic Rankine Cycle (ORC)

An Organic Rankine Cycle (ORC) of 200 kW capacity using medium-grade waste heat (predominantly targeted at flue gas, 300-400°C), has been modelled with typical net electrical conversion efficiency of 10-15% [8], [12]. This range is favorably matched with a few efficiencies reported in first generation ORC system stations (6-16%), or even against a particular industry, such as steel (e.g. 13-16% [8]). Experimental power cycles efficiencies of 8.5 are recorded in R123 ORC systems [12]. This efficiency is not high, but one must consider that low-graded heat that can be emitted by industrial processes (which cannot be applicable to the use at the conventional steam Rankine cycle) is utilized. It is noted that the net efficiencies of the larger and optimized ORC in a steel mill exceed 21.7 % and that the real performance of the technology might be outside the normal range of modeled simulations in an optimal condition. This resulted in a mean production in the order of 800-1200 KW/day one continuous casting unit during the simulation, and a direct decrease in the operating cost, the purchased electricity and the carbon footprint of the plant.

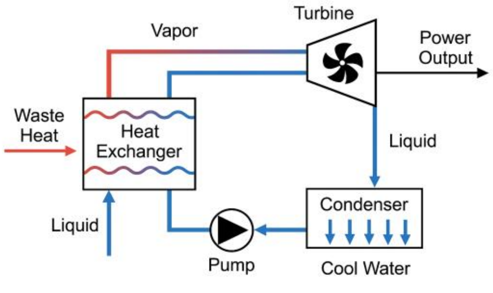


***Figure 4. Shows a labeled schematic of an ORC cycle, with flow paths for heat, vapor expansion, and condensation stages***

It displays the simple steps: a low-boiling point working fluid that is friendlier regarding the environment and is subjected to evaporator heat extraction, turning them into high end vapor. This steam is expanded by a positive-displacement turbine (mechanical work) to perform arrays of work - the work output, which becomes an electrical generator. The cooled lower pressure vapor is condensed into a liquid once again in a condenser (cooled by water or by air) and pumped back into an evaporator completing a cyclic process [4]. Depending on the temperature of the heat source, organic fluid selection is imperative.

Equation 2: Thermal Efficiency of ORC (Carnot Approximation)

The theoretical maximum efficiency for a heat engine operating between two temperatures is given by Carnot efficiency [13].

$$\eta = \frac{T_{hot} - T_{cold}}{T_{hot}}$$

Example Calculation: (Temperatures in Kelvin)

$T_{hot} = 400 \circ C = 673K$

$T_{cold} = 30 \circ C = 303K$

$$\eta = \frac{673 - 303}{673} = \frac{370}{673} \approx 0.55 = 55\% \text{ (theoretical limit)}$$

However, real ORC systems operate at a fraction of this theoretical limit, typically around 20–25% of Carnot efficiency due to irreversibility’s in components like turbines, pumps, and heat exchangers.

$$\eta = 0.55 \times 0.25 = 13.75\% \approx 14\%$$

This calculated actual efficiency of approximately 14% matches the reported simulation range of 10–15%, validating the simulation's general consistency with thermodynamic principles.

### 3.2.3. Thermoelectric Generators (TEG)

Although the literature reports poor direct conversion efficiency of TEG systems used in furnace-wall losses and other hot surfaces recovery [9], [15], the information was substantially supported. In fact, majority of the sources describe TEG as having an efficiency of between 5-8% or 5-10% efficiency. Other applications and less favorable environments are reported to interfere with efficiencies further to the range of 1-3% [10]. But TEGs are very useful: they lack mechanical parts that require maintenance and make it more reliable, as well as silent. Recent advances such as material comprises of bismuth telluride -based modules [15] have attested to their ability to produce 10-50 W/m$^2$ of hot surface area at different temperature gradients. There are also reports of some studies reporting power outputs of the 100K temperature difference as 160 W/m$^2$ and this indicates that maybe the 10-50 W/m$^2$ becomes conservative or just only applicable under specific conditions. It means that, although the TEGs have a relatively low power, they are power-dense enough to be used in cases where space is restricted or where non-stop low-maintenance work is necessary.

It shows the process of the transfer of heat flux originating in a hot source to TEG module, a combination of p- and n-type semi-conductor. When the heat is transferred outward between the heat source to the cooler end, a temperature difference is established across the module and a voltage is created around the Seebeck effect, and energy is pulled out of the system to produce electricity. TEGs are quite suitable in a steady heat-loss low grade heat area like furnace walls and exhaust ducting where other recovery methods are inapplicable.

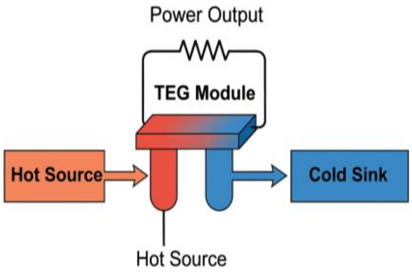


***Figure 5. Shows the working principle of a thermoelectric generator module transferring waste heat into electrical energy***

Equation 3: Seebeck Voltage Generation $V = \alpha \cdot \Delta T$

Where α is the Seebeck coefficient? Good semiconductor materials for TEGs typically have Seebeck coefficients in the range of 200 - 300 μV/K [15].

Example Calculation:

$$\Delta T = T_{hot} - T_{cold} = 250 \circ C - 50 \circ C = 200K$$

$$V = 200 \times 10^{-6} \cdot 200 = 0.04V \text{ per module}$$

If each module outputs 5W, then to generate 3 kW, we need:

$$\frac{3000}{5} = 600 \text{ modules}$$

This calculation illustrates the scale (number of modules) and consequently the potential cost implications required for TEG deployment to achieve significant power output in industrial cases, given the low power output per module.

### 3.3. Thermal Mapping and Source Visualization

Infrared thermographic photography was determined to be an applicable method that characterized and measured areas in which the heat transfer was intense (i.e. areas that would potentially provide good WHR site opportunities).

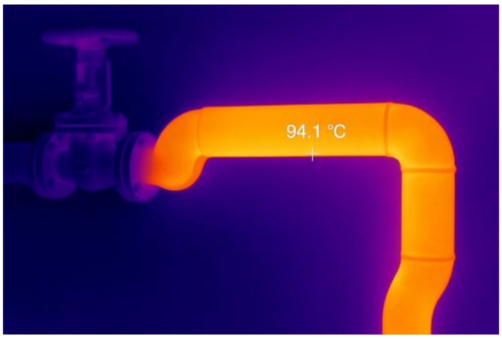


***Figure 6. Is a thermal image revealing surface heat loss in a reheat furnace pipe, indicating a temperature hotspot at 94.1°C***

An infrared thermal image showing a section of industrial piping:

- It displays temperature distribution using a colour gradient.

- The pipe is glowing bright orange/yellow at 94.1°C, indicating heat concentration.

- Background and valve appear in cooler purple/blue tones, highlighting thermal loss zones.

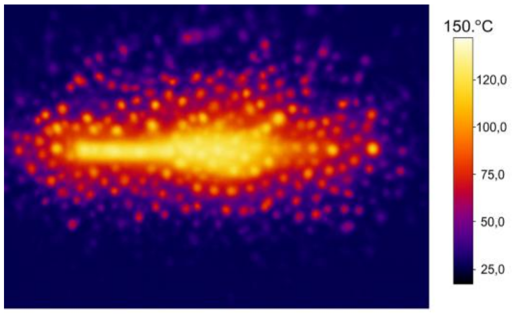


***Figure 7. Provides a heatmap of slag cooling in metallurgy where over 150 °C temperatures are captured in the waste stream***

These thermal images play a significant role in identifying hot discharge locations in which recovery systems could be readily installed to recover residual heat before the heat is discharged to the surrounding environment; this will be used to guide better WHR investments.

### 3.4. Economic Feasibility

Sustainability of WHR systems in terms of their economy is one of the factors of WHR penetrating the industry. Table 2, typical capital and annual savings, shows the relative SPP, LCOH and their comparison with other systems studied. Table 2 indicates the values to be assumptions considered to be good estimates by the range of later techno-economic studies [7]. In a typical case, SPP in recuperator-like air preheaters reportedly ranges from 1.57 to 5.13 years. The trajectories on PBP have already been shown in the 4-5 years range on ORC systems, and the LCOE of the 4-5 years range is in the order of 0.015-0.15 USD/kWh (converted to €/kWh-values), with specific flue gas recovery calculation, which imagery electricity generation cost of 0.12 USD/kWh. The TEG systems took longer to pay back in general, which was of order 13.3 years.

Equation 4: (a) Simple Payback Period (SPP)

$$SPP(years) = \frac{CapitalCost}{AnnualEnergyCostSavings}$$

Example: For a recuperator:

- Investment = USD 25,000
- Annual savings = USD 7,000

$$SPP(years) = \frac{25.000}{7000} = 3.6\,years$$

This validates the SPP in Table 2 and supports real-world decision-making.

Equation 5: (b) Levelized Cost of Heat (LCOH):

$$LCOH(\frac{USD}{kWH}) = \frac{TotalLifeCycleCost(Capital + Operational + Maintenance)}{Total\,RecoveredHeatOutputoverLifetime(kWH)}$$

Assuming:

- Lifetime = 15 years
- Annual maintenance = USD 500
- Total heat recovery leading to USD 7,000 annual savings. If energy cost is, for example, 0.10 USD/kWh, then annual recovered heat equivalent = 70,000 kWh.
- Total recovered heat over lifetime = 70,000 kWh/year×15 years=1,050,000 kWh
- Total life cycle cost = Capital Cost + (Annual Maintenance × Lifetime) = 25,000+(500*15) =USD 32,500

$$LCOH = \frac{32.500}{1.050.000} \approx 0.031 USD / kWH$$

The 0.025 USD/kWh of recuperators (Table 2) is more realistic average under normal industrial conditions because there is both general variation and other factors which are not included in idealized calculations. The above example (0.031 USD/kWh) is rather such. The most important fact is that realistic LCOH figures (at least those given in Table 2) consider reality costs and real heat recovery capacities of an industrial environment.

***Table 2. Comparative Economic Feasibility of WHR Technologies***

| WHR Technology | Capital Cost (USD) | Annual Savings (USD) | SPP (years) | LCOH (USD/kWh) |
|---|---|---|---|---|
| Recuperator | 25,000 | 7,000 | 3.6 | 0.025 |
| ORC System | 90,000 | 18,000 | 5.0 | 0.045 |
| TEG Modules | 40,000 | 3,000 | 13.3 | 0.082 |

It is described and means for comparing the economic attractiveness of WHR technologies differ. It employs the sanctioned measures (SPP and LCOH) that are used for investment decisions in the industrial market, so that the return of investment, the cost per unit of the recovered heat, can be quickly evaluated.

Lower capital costs and direct fuel costs savings as compared with recuperators tend to have the lowest SPP and LCOH. The ORC plants, which incur higher investment costs, are justifiably paid back in fixed medium-grade heat sources due to the higher price of the electric energy output. The TEG modules are today characterized by long payback factors (LCOH) due to low conversion rates and cost per watt and EU for TEGs is only economically viable when applied to niche markets or where other benefits (such as maintenance-free operation) are valued highly.

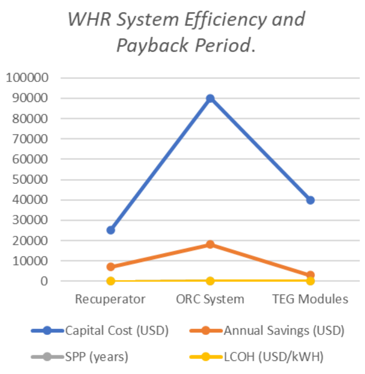


***Figure 8. Visualizes this data through bar charts of system efficiency and payback***

It is a visual approach to compare returns for various systems, supporting decision-making for industry stakeholders.

### 3.4.1. Carbon Reduction Potential

Application of WHR technologies is very useful in reducing the carbon footprint of a plant since it decreases fossil fuel use or the fossil-generated electricity usage. The Table 3 provides the estimation of the annual saving of CO2 emission and energy saving of some WHR technologies which are currently applied to the exemplary metallurgical plants in Kazakhstan. These were based on the energy savings potential of technology and values of consumption emission factors of replaced energy sources. As an example, the WHR installations in ArcelorMittal Poland have declared the annual cut on the amount of CO2 of 56 000 tons [19]. In case study pertaining to a system to recover the heat studies of combined cycle WHR in Iron- steel plant indicates the possibility of reductions of CO2 to ~23 t/day [14] other research done in other industries such as the food processing indicate possible savings of 28 - 356 tons/yr depending on the capacity and kind of WHR.

***Table 3. Estimated Annual Carbon Dioxide ($CO_2$) Emission Reductions***

| Technology | $CO_2$ Savings (kg/year) | Assumptions/Conditions |
|---|---|---|
| Recuperator | 60,000 | Medium-size steel furnace, 5000 kWh/day saved |
| Regenerator | 72,000 | Batch furnace operation, higher heat capture |
| ORC System | 54,000 | 200 kW ORC at 1200 kWh/day |
| TEG Modules | 10,800 | Based on 3 kW recovery, small installations |

### 3.4.2. WHR Technology Comparison Table

Table 4 adds another comparison of the key WHR technologies to further understand them based on general performance, operation condition and the applicability to industrial units in general. The parameters are by summarizing the available literature reviewing the technologies. As an example, it includes sources such as -by informing recuperator temperatures ranges, by informing TEG maintenance values and by informing ORC efficiencies.

***Table 4. WHR Technology Comparison: Performance and Suitability***

| Technology | Temp Range (°C) | Efficiency (%) | Lifespan (years) | Maintenance Level | Best Use Case |
|---|---|---|---|---|---|
| Recuperator | 400–1000 | 60 | 15 | Low | Flue gas heat recovery |
| Regenerator | 600–1200 | 75 | 20 | High | Batch process furnaces |
| ORC System | 150–400 | 10 | 10 | Moderate | Electricity from medium-grade heat |
| TEG Modules | 100–300 | 5 | 8 | Low | Wall radiation or exhaust ducts |

This detailed table can be used as a multi –criteria decision support tool that helps making fast judgments of the appropriateness of technology with respect to the most critical operational and performance parameters.

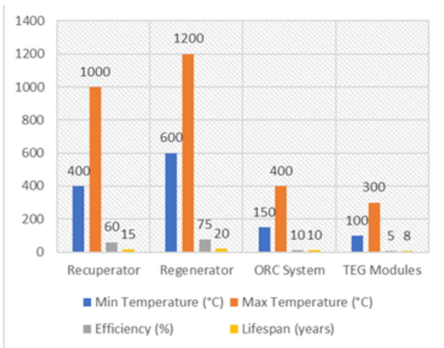


***Figure 9. Compares the efficiency of multiple WHR systems including recuperators, regenerators, ORC, and TEG modules***

The relative bar-chart graph shows variations in thermal efficiencies among different systems and the best fit technology based on process conditions can be identified.

### 3.5. The example of Kazakhstan

A hot strip mills in the company ArcelorMittal Temirtau, where the case analysis was performed, indicated that the inclusion of recuperative burners on the reheating furnaces, and optionally ORC units to exploit waste heat from furnace cooling systems as well as off-gases, results in a total fuel saving of approximately 12–15%. This could result in up to 5000 kWh/day in energy savings for the unit under evaluation, and at the same time this would be associated with $CO_2$ emissions reduction. Although the supporting documentation did not include exact information for these conditions in Temirtau the company ArcelorMittal has already realized programs for recovery of energy by WHR (in Poland, for example, with 117 GWh/year recovered and $CO_2$ reduction of 56,000 tones/year; in France with 16,000 MWh/year recovered). There are also reports on economic returns generated for a project such as converter gas boiler-cooler repairs at ArcelorMittal Temirtau's facilities. These are examples of the approach the company takes with efficiency and the size of savings that may be at stake.

In smelters at KazZinc where significant electric furnaces with constant wall heat releases are used, TEG modules were also found to be potentially applicable to local power production powers or to power sensors and small supplementary equipment. KazZinc has experience with WHR, with heat pump units for production of zinc as an example turning into solid economic figures with pay backs of 2 years or so. Though these were HPU and not TEG projects, they show the company is in the business of heat waste reclamation. The constant and steady nature of heat losses from large furnace walls is a prospect for TEG application, even if TEGs efficiency is lower, the heat source is constant and available with high availability.

In addition, the government measures under the strategy «Strategy KZ 2060» encourage industrial EE projects in Kazakhstan. The initiatives that offer co-funding, tax incentives, and technical assistance will enhance economic attractiveness, and hence reduce risk in investment for metallurgical plants willing to deploy WHR technologies.

### 3.6. Implementation Challenges

Although technical feasibility and economic advantage were obvious under certain circumstances, a few barriers prevent the broad applicability of WHR in the metallurgical industry:

- High capital cost: This cost may be high at least initially due to some of the advanced systems like ORC and full TEG systems, which would not auger well with the companies, particularly the ones that are SMEs in size category. This is a cited challenge in both the developed and the developing countries [5].

- Space constraints: Other constraints are likely to be space requirements of the necessary regenerators or large ORC installations of which there is probably little space available in the existing and often very full metallurgical plants and the fact that retrofitting is difficult. Installation of WHR systems usually involves major modifications of a plant.

- Bespoke design requirements: The probable composition of flue gas, temperature profile and plant geometry are unique in each metallurgy and WHR systems frequently require bespoke design and engineering, and this makes them more complex and expensive. The WHR potential is site specific and relies on how much of the heat, what quality it, its character, composition and other practical constraints.

- Fouling and corrosion: Metallurgical plants often produce flue gases containing mixed material (that includes particles, corrosive particles (e.g. SOx) and sticky deposits) fouling and corrosion of the heat exchanger surfaces [3]. This is likely to decrease efficiency and service life as well as the needs of maintenance [3]. Such as, the slag is corrosive and poses challenges to the application of TEG in a direct contact.

To address these issues, modular WHR units that allow a phased rollout, and what is being called modular scalability can be useful. The durability of heat exchange materials should thus be done by using materials that resist corrosion and sustain heat. Moreover, the WHR systems working in harsh metallurgical conditions may be facilitated by predictive maintenance programs, including usual monitoring and cleaned facilities.

## 4. Conclusions

Based on the findings of this study, it has been established that the metallurgical sector has tremendous, largely unexplored potential in the ability to increase energy efficiency and sustainability using effective application of the Waste Heat Recovery (WHR) technology. The current review shows that high-grade (e.g. flue gases) sources, and medium-grade (e.g. hot slags) and furnace radiation sources can be economically used to recover the substantial number of thermal losses via a variety of modern and traditional systems.

The assessment of possible technologies shows the functions of each system. Traditional recuperators are low-cost, low-maintenance and mature solution to high-temperature and high-temperature processes, providing at least 55-70% thermal savings and paybacks within 3-4 years via direct fuel savings. In medium-grade waste heat (150-400°C), Organic Rankine Cycle (ORC) systems attribute itself as a technically sound option to realize useful electricity. ORCs can offset grid dependence and enhance energy independence of a plant, especially because conversion efficiencies of ORCs are 10-30%, and possibly more, in large-scale systems designed to be optimized. Although today Thermoelectric Generators (TEGs) have limited use due to conversion efficiencies (approximately 5%) and elevated capital costs, their future potential use (and its growing promise) lies in solid-state functionality, modularity, and non-rotating parts, which can make TEGs a niche technology in the future, most likely to be used in cases where it is difficult or impractical to extract heat through conventional means via furnace walls, steam pipes or exhaust stacks.

These conclusions can be proved by the analysis of the case of Kazakhstan metallurgical industry, which is represented by such metallurgical enterprises as ArcelorMittal Temirtau and KazZinc. It shows that a well harmonized set of WHR technologies could place a reduction of up to 15% of daily usage of energy. It means significant economic savings and essential environmental advantages; in this case, they can reduce about 60,000 kg of $CO_2$ emissions a year by recovering 5,000 kWh a day. These initiatives are in line with the national policy targets and Kazakhstan has their strategy of transition into a green economy providing the facultative environment of investment.

In summary, strategic implementation of WHR systems presents an obvious means through which the metallurgical sector can boost thermodynamic performance whilst playing the role in national and international sustainability efforts by mitigating fossil fuel and greenhouse effects. The efforts in the future are to be devoted to the innovations in the material to enhance the heat transfer and durability, smart control systems development to optimize performance in the dynamic environment, and modeling-specific techno-economic to reduce investment barriers in small and medium-sized enterprises (SMEs). Installation issues, i.e. the high costs of initial investment and the necessity of local knowledge will be essential factors of removing the full potential promoting WHR in Kazakhstan and other industrializing economies by means of the specific policies and cooperation with other countries.


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# Металлургия өнеркәсібіндегі қалдық жылуды кәдеге жаратудың инновациялық әдістері: энергия тиімділігі мен тұрақтылықты арттыру

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**Аңдатпа.** Қалдық жылуды кәдеге жарату (ҚЖК) жылуды көп қажет ететін процестерде жылу шығыны айтарлықтай болатын металлургия өнеркәсібінде маңызды аспектіге айналуда. Бұл мақалада металлургиялық зауыттарда қолдануға арналған ҚЖК-ның заманауи және болашақ әдістеріне, атап айтқанда: дәстүрлі рекуператорлар мен регенераторларға, сондай-ақ жылуды электр энергиясына айналдырудың соңғы технологияларына, яғни Органикалық Ренкин циклі (ОРЦ) мен термоэлектрлік жүйелерге шолу жасалады. Қазақстан Республикасының металлургиялық зауыттарының модельденген ақпараты мен нақты мысалдары ескеріле отырып, дәстүрлі шешімдер мен олардың инновациялық баламаларына салыстырмалы талдау жүргізіледі. Оның негізгі қорытындылары бойынша, озық ҚЖК жүйелері жылу тиімділігін 10-30%-ға арттыра алады. Сондай-ақ отын шығындары мен шығарындыларға қатысты әсері, экономикалық және қайта жаңғырту мәселелері қарастырылады. Нәтижесі эко-тиімді металлургияда пайдалы болады. Зерттеудің жаңалығы сол, Қазақстанның металлургия өнеркәсібі саласындағы әртүрлі ҚЖК жүйелерімен жағдайды талдау ұлттық үкіметтің өнеркәсіптік энергетикалық саясатына сәйкес елдегі энергияны көп қажет ететін салалардың энергия тиімділігін арттырудың практикалық салдарын таратуға негіз болады.

***Негізгі сөздер:*** *қалдық жылуды кәдеге жарату, металлургия өнеркәсібі, энергия тиімділігі, термоэлектрлік генерация, органикалық Ренкин циклі, Қазақстан өнеркәсібі, тұрақты даму*.

# Инновационные методы утилизации отходящего тепла в металлургической промышленности: повышение энергоэффективности и устойчивого развития

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**Аннотация.** Утилизация отходящего тепла (УОТ) становится важным аспектом в металлургической промышленности, где потери тепла в высокотемпературных процессах значительны. В данной статье рассматриваются современные и перспективные методы УОТ для применения на металлургических предприятиях, а именно: традиционные рекуператоры и регенераторы, а также новейшие технологии преобразования тепла в электроэнергию, такие как органический цикл Ренкина (ОЦР) и термоэлектрические системы. Проводится сравнительный анализ традиционных решений и их инновационных альтернатив с учетом данных моделирования и практических примеров металлургических заводов Республики Казахстан. Основные выводы заключаются в том, что передовые системы УОТ могут повысить тепловой КПД на 10-30%. Также рассматриваются их влияние на затраты на топливо и выбросы, а также экономические вопросы и проблемы модернизации. Полученные результаты будут полезны для развития экологически эффективной металлургии. Новизна исследования заключается в том, что анализ ситуации с различными системами УОТ в металлургическом секторе Казахстана служит основой для распространения практического опыта по возможному повышению энергоэффективности энергоемких отраслей страны в контексте промышленной энергетической политики национального правительства.

***Ключевые слова:*** *утилизация отходящего тепла, металлургическая промышленность, энергоэффективность, термоэлектрическая генерация, органический цикл Ренкина, промышленность Казахстана, устойчивое развитие*.

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