



**Politecnico
di Torino**

Politecnico di Torino

Master's Degree in Engineering and Management

A.A. 2025/2026

Graduation Session: March 2026

**Technical and Economic Potential of Organic Rankine Cycle (ORC) Systems
in the Cement and Glass Industry: A Comparative Assessment for Germany and
Italy**

Advisors:
Prof. Alessandro Casasso

Candidate:
Philipp Daniel Engler
(ID 333254)

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ABSTRACT

Energy-intensive industries such as cement and glass production generate significant amounts of recoverable waste heat, much of which remains unused despite rising energy costs and ambitious decarbonization targets in the European Union. This thesis assesses the technical and economic potential of Organic Rankine Cycle (ORC) systems for waste heat recovery in the cement and glass sectors in Germany and Italy. A two-stage approach is applied. At the macro level, data from real-world ORC installations collected in a global database are used to estimate national electricity generation and potential CO₂ emission reductions under different deployment scenarios. At the micro level, representative cement and glass plants are evaluated through thermodynamic modelling and a detailed economic evaluation. The results indicate substantial unused technical potential and strong economic attractiveness, with baseline payback periods of around three years and internal rates of return exceeding 35%. Uncertainty analysis implies that these results remain robust under varying input parameters, with electricity prices, investment costs, and operating hours identified as the most influential drivers. Beyond financial benefits, ORC deployment contributes to job creation and improved grid stability.

Acknowledgments

I would like to thank my supervisor, Prof. Casasso, for his continuous support, guidance, and valuable feedback throughout the course of this thesis. Our regular discussions after the lectures and his willingness to provide feedback and exchange ideas were extremely helpful in shaping the concepts and direction of this thesis.

I am also grateful to the faculty of the master's program in Engineering and Management at Politecnico di Torino for providing a great academic environment over the past two years and for the valuable knowledge and perspectives gained during this time.

Finally, I would like to thank my family and all of my friends for their continuous support and encouragement throughout my time in Torino and during my academic journey which ultimately made this work possible.

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1 Introduction

1.1 Problem Definition and Motivation

The European Union has set ambitious climate targets which include climate neutrality by 2050, that require a significant CO₂ emission reduction across all countries and sectors, including production industries [1]. Efforts to mitigate climate change and reduce greenhouse emissions put increasing pressure onto the energy-intensive industries. At the same time, the geopolitical situation and resulting energy price fluctuations have shown how vulnerable the EU energy markets are and their dependency on imports [2]. Therefore, the improvement of energy efficiency and usage of waste heat are becoming relevant aspects of decarbonization and political strategies.

Energy-intensive industries such as cement or glass production require high temperatures and operate almost continuously, resulting in large amounts of wasted heat energy. As a large share of this waste heat is still technically recoverable but often unexploited, there remains a significant amount which can be recovered [3], [4]. This “low hanging fruit” of decarbonization does not require a fundamental change of the process but instead can be implemented into existing production workflows. Even though the benefits of avoided CO₂ and reduced amounts of primary energy consumption have a significant value, the implementation of large-scale waste heat recovery is low in most European countries [5].

The Organic Rankine Cycle (ORC) is an emerging technology for converting low- to medium temperature waste heat into electricity, operating with organic working fluids which can evaporate at temperatures below 100°C [6]. ORC systems are especially designed for recovering continuous off heat from industrial processes. The advantage of such systems lay in the fact that they can produce electricity directly on-site, leading to reduced amounts of import electricity for the plant operators. Despite these benefits the installations of such devices remain at relatively low levels.

The glass and cement industry are among the most energy and emission intensive industries in the EU [7], [8]. They operate at almost constant-remaining production conditions and serve a consistent waste heat energy output. Germany and Italy are among the countries with the largest production levels for both glass and cement in Europe [9]. At the same time the adoption of ORC systems in the two countries and sectors differ, indicating that a technical and economic ORC potential is still unexploited. Quantifying this ORC potential is important for policy makers, industry representatives, plant operators, and suppliers.

Up to this point many ORC studies focus on individual case studies or on thermodynamic simulations, but do not systematically analyse large numbers of real installations across different countries and sectors. A transparent, sector specific performance evaluation may be a key to wider ORC deployment. For industrial decision makers the uncertainty of electrical power outputs, realistic investment costs, operating expenditures, resulting payback periods, and net present values of ORC projects marks a difficult standpoint when facing investment decisions. Decision makers often lack robust key indicators for ORC plants to decide whether an ORC device at their site is a feasible and attractive choice.

The literature already provides individual building blocks of technical and financial analysis of ORC systems but lacks an approach of combining global data of installed devices to attain national-specific technical potentials and a detailed financial assessment of plant specific financial indicators. For the glass and cement sector in Germany and Italy there exist no integrated study that assesses the technical ORC potential. This makes the judgement of the true role the ORC could potentially play in CO₂ reduction difficult.

To close this gap, the motivation of this thesis is to provide a data driven analysis of the potential of the ORC technology in the cement and glass sector both in Italy and Germany. The analysis aims to assess the potential on two different levels. The first level is the assessment of national technical performance, and the second stage is the one of plant level financial feasibility. By performing so, the thesis wants to help policymakers in quantifying the amount of waste heat that could be converted into electrical energy, assess resulting energy outputs, and identify the emission saving connected to the implementation. Further the thesis wants to guide industrial decision makers by quantifying realistic ORC financial-performance and payback periods. Additionally, the thesis wants to highlight what additional co-benefits the ORC installation holds beyond the given ones, benefitting society.

1.2 ORC Technology Fundamentals and Industrial Context

The energy intensive industries like steel, chemical, glass, or cement release enormous fractions of their inputs energy as waste into the environment. The share of unused thermal wasted energy often lays between 20 and 50% and the EU has identified the secondary usage of waste heat as an important step in decarbonizing industrial processes to improve energy efficiency [1], [4], [10]. Significant amounts of the industrial waste heat lie at a low or medium temperature range between 150 and 400°C. Often in the past these ranges have not been relevant off-heat sources, since they are not recoverable by long-known steam cycle [11]. For continuous, stable off-heat flows,

present in the cement or glass industry with medium temperature, ORC systems are a relevant technology to be implemented [6], [12].

The ORC is a modification of the classic Rankine Cycle that instead of water uses an organic working fluid with a lower boiling point. This allows for electricity generation of low and medium temperatures. A schematic depiction of the basic Organic Rankine Cycle can be found in Figure 1.

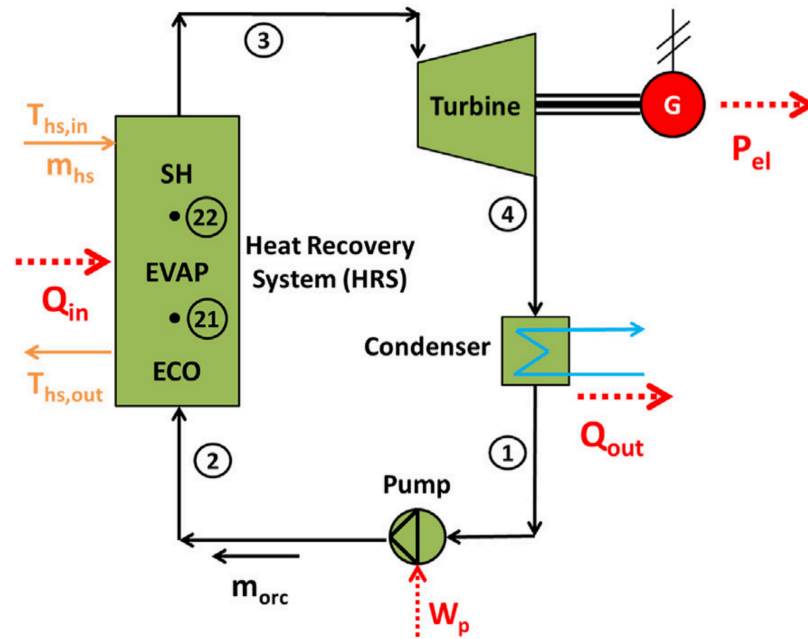


Figure 1. Basic depiction of the Organic Rankine Cycle (figure adapted from Loni et al. [13]).

The key components of the ORC system are the evaporator (Heat Recovery System), turbine, pump, and condenser. The evaporator absorbs the waste heat of the industrial process and vaporizes the working-fluid. The turbine/expander converts the energy of the vapor into electrical energy. The condenser discards the energy from the system by cooling the working fluid down. The pump pressurises the working-fluid and lets it circulate in the system [13].

Typically, the ORC reaches thermal-to-electric efficiency ranges between 8 and 18%, depending mostly on the parameters of waste heat and cooling liquid. Thermodynamically, larger temperature differences in the system lead to larger electricity exploitations [3], [11], [13].

The ORC heat recovery technology is specifically suitable for glass and cement industries. Glass furnaces operate at high temperatures which generate output exhaust temperatures up to 1400°C. This provides a high specific power output [4]. Cement is just like glass produced worldwide

under stable conditions with preheater exhaust gases of 280-350°C and clinker kiln exhaust gasses of 250-300°C [12]. For both cement and glass plants the typical operational time lies above 7000 hours, leading to stable operational conditions to generate electric energy in the ORC.

There exist multiple waste heat technologies which coexist with the ORC. When trying to understand the field of application of the ORC it makes sense to position it along other existing technologies. The Steam Rankine Cycle has high efficiency at high temperatures but requires high-quality steam and is complex to implement. For medium temperature off-heat like in the cement or steel industry it is not a suitable technology [10], [14]. A second alternative, the Kalina Cycle uses ammonia and water in its operation. Currently it is found only in limited numbers as it operates under high pressures and complex operations with corrosion issues commonly occurring [6]. The Trilateral Cycle similarly to the ORC operates at low temperatures but contains a complex expander technology which up to this point only functions under lab conditions. Therefore, this technology is not a mature option on the market [6].

The ORC is a commercially mature technology with thousands of installations worldwide. The field of installations is complex, reaching from geothermal, biomass, solar, waste to energy, to heat recovery from industrial processes. The typical organic working fluids used in the ORC systems are R245fa, R1233zd(E), n-pentane, toluene, or mixtures of such [13], [15].

1.3 Financial Evaluation Methods

The investment decisions for projects typically depend on financial parameters which assess the value and performance of the project before its actual realization. ORC investment decisions depend on parameters like electricity prices, annual operating hours, CAPEX, and OPEX, making an economic assessment essential. As investment decisions inside firms must be compared with alternatives, the projects must be evaluated by financial performance indicators. Typical financial performance evaluation is conducted by using the Simple Payback Period, the Net Present Value (NPV), and the Internal Rate of Return (IRR).

The payback period is one of the most used metrics in assessing an investment due to its simplicity. It measures how long it takes until the initial spendings (CAPEX) are in cumulated form recovered completely by its revenue. The “break-even” point is reached when cumulated spendings and earnings equal another. The payback period does not give information about the long-term profitability of such a project. Typical industrial projects are expected to show payback periods between 3 and 5 years [1], [8].

The Net Present Value is a way of measuring the monetary worth of the project over its full lifetime. It considers the initial investment and all future cashflows until the end of the project. Additionally, it considers the discounted cashflows and can therefore account for the time value of money. A project is attractive, if the Net Present Value exceeds a value zero, meaning the cumulated value of the project over its lifespan is positive [4]. The Internal Rate Return is closely linked to the NPV and represents the discount rate at which the NPV equals 0. It is a useful parameter when comparing alternative investment options [15].

Furthermore, it is important for a project evaluation to consider fluctuating parameters like electricity prices, variability in ORC performance, uncertainty in technical parameters like operating hours, CAPEX ranges, or discount rate assumptions. A Sensitivity analysis is performed to identify the parameters which influence the economic outcomes the most. Tornado diagrams can be used to rank the influence of each individual variation parameter.

With probabilistic methods like the Monte-Carlo simulation it is made possible to simulate large numbers of iterations with changing input parameters to attain a distribution of financial results. This captures the uncertainty in the system and helps assessing its performance in best- and worst-case scenarios and therefore delivers valuable information on the spread and likelihood of possible outcomes.

To sum up, the financial evaluation of investment decisions like the ORC system, requires a combination of economic indicators and probabilistic simulating methods. This mix of financial performance and risk assessment allow for full understanding of ORC project feasibility.

1.4 Objectives of the Thesis and Research Questions

As identified there exists a research gap in combining global ORC data to attain national potentials and detailed financial plant parameters. This thesis wants to close the identified research gap by providing a data-driven analysis consisting of two stages. In these two stages the aim is to identify the potential of Organic Rankine Cycle systems in the glass and cement sectors of Germany and Italy. It is necessary to combine a technical, economic and contextual perspective to fully understand the role ORCs can play in increasing energy efficiency and reducing carbon emissions. The thesis aims to derive sector-specific electric performance indicators from all currently present real-world ORC applications. In the second step the thesis wants to evaluate financial decisions for individual industrial plant owners, including their uncertainty. In a last step the aim of the thesis is to evaluate, resulting co-benefits which come with ORC installation for plant owners, policy makers, and society.

The aims and scopes of the thesis can be translated into four specific objectives. The first objective is to quantify the national technical ORC potential for electricity generation in the cement and glass industry for Germany and Italy. This objective can be achieved by developing sector-specific ORC performance indicators by analysing a global database of related ORC installations and finding specific power outputs and electrical yield for the cement and glass industry.

The second objective contains the evaluation of plant-level feasibility of ORC systems using financial key performance indicators like Payback Period, NPV and Internal Rate of Return. The objective is to give performable insights for industrial decision makers and technology suppliers, regarding the profitability of this rising technology. The third objective is the one of analysing the sensitivity of financial outcomes by identifying key variables which influence ORC profitability.

The fourth and last objective of this thesis is to assess the environmental, social and economic co-benefits which result from the ORC deployment, including electricity grid benefits, carbon reduction, and job creation.

The defined objectives lead to the following 5 research questions for this thesis:

- 1. How large is the recovered ORC electricity potential in the cement and glass sector in Germany and Italy, derived from sector specific performance indicators and the electric yield, derived from real-world installations?**
- 2. How do ORC potentials for the cement and glass sector differ structurally from another?**
- 3. Under which technical and economic conditions is the installation of an ORC turbine financially feasible for a typical cement and glass plant?**
- 4. Which technical, financial, and market parameters have the strongest influence on ORC profitability in the cement and glass industry and how fluctuating are payback periods when including realistic uncertainty?**
- 5. To what extent can ORC installations contribute to electricity grid stability and labour opportunities?**

1.5 Structure of the Thesis

To answer the given research questions a set of steps must be performed. The outline of this thesis is structured as follows. The thesis is organised into five main chapters of which each chapter focusses on one component of the defined objectives.

The first stage (macro-level) introduces the global ORC installation database and derives sector-specific performance indicators. With the derived indicators like the specific electric yield and sector specific indicators, the national technical ORC potential for the glass and cement industry can be derived for Germany and Italy. Additionally, a comparison between specific cement and glass parameters can be derived highlighting the fundamental differences between the two industries.

Stage 2 (micro-level) operates completely independent of stage 1 and firstly introduces the thermodynamic modelling of the representative example cement and glass plants. In the next step the operational and financial parameters are defined. They are needed to perform the economic performance calculations. The cashflow model and derived financial economic indicators are presented for both the glass and cement plant. The evaluation of economic feasibility is performed using the payback period, NPV, and IRR. The important variables are in a next step evaluated using sensitivity and uncertainty analysis, to determine the most realistic outcome for decision makers and enable rational decision making. This step is followed by the presentation of the CO₂ reduction values for both plants.

The last set of analysis in this thesis regards the co-benefits that go along with the ORC deployment. These co-benefits reach beyond the electricity generation and resulting financial benefits but aim at finding value of these projects favouring society. Firstly, an analysis of contribution to the baseload and grid stability is performed using electric system data. Secondly, the relevance of carbon-credits is evaluated, which results from the CO₂ reduction. Lastly the resulting labour opportunities associated to ORC deployment on a macro scale are discussed.

2 Stage 1: Potential of ORC Technology in the Glass and Cement Sector in Italy and Germany (Macro Level)

2.1 Methodical Approach for Sector-Level Screening

The core idea of stage 1 is to assess the potential of the ORC technology in both the glass and cement sector for Germany and Italy. The data on which this analysis is based on, originates from a comprehensive ORC database provided by Politecnico di Milano, containing all known ORC installations worldwide across all industrial applications to this current day. The database includes information on electric capacity, manufacturer, location, year of construction, working fluid, and type of application. For this thesis, the database was filtered for ORC installations in the cement and glass sector, resulting in 22 and 18 installations respectively. The production capacity of all plants is manually researched to be linked with each plant.

The data of these worldwide installations is used to derive specific electric yields for each sector. This is followed by scaling the specific electric yields up using national production volumes and operational time. This leads to conservative, realistic and optimistic scenarios for national ORC potential in these two fields for Germany and Italy. With the help of current coverage ratios for the ORC technology in both countries and industries an estimation of waste heat recovery potential can be performed. This approach creates a robust, evidence-based macro level assessment.

2.2 Derivation of Specific ORC Performance Indicators

2.2.1 Data Collection and Filtering

The dataset owned by Politecnico di Milano professor Marco Astolfi contains an up-to-date collection of all ORC installations worldwide and includes all known up-to-date industrial applications. Overall, the dataset contains more than 1700 entries, which are gathered by the research group in Milano. The dataset also contains plants still in construction. The current version was last updated in September 2025. It contains information on the installed electric power, manufacturer of the ORC device, ORC-model, customer, location, year of construction, application/sub-application, working fluid used, number of parallel units, coordinates of the plant, and a description.

The ORC applications in the dataset reach from biomass, geothermal, solar, waste-to-energy, heat-pump, and waste heat recovery. This thesis focusses solely on waste heat recovery and targets even more precisely the cement and glass applications.

Within this database cement and glass plants were identified using the field “Application” and “Sub-application”. For each plant, the total electric capacity (kWel) is extracted from the database, considering that possibly multiple ORC applications are installed within one site. The database does not provide production volumes. Therefore, these values are researched manually from public sources for every individual plant.

The outputs in the ORC dataset (MW) are linked to its production capacity (t/day) for each of the cement and glass plants. The full lists of plants and all production capacity data for cement and glass are provided in Appendix A.

2.2.2 Cement Sector: ORC Performance vs Production Capacity

The attained data tables (Appendix A) are used to construct a scatter plot (Figure 2) for the 22 ORC cement applications to highlight the correlation between production capacity and ORC power.

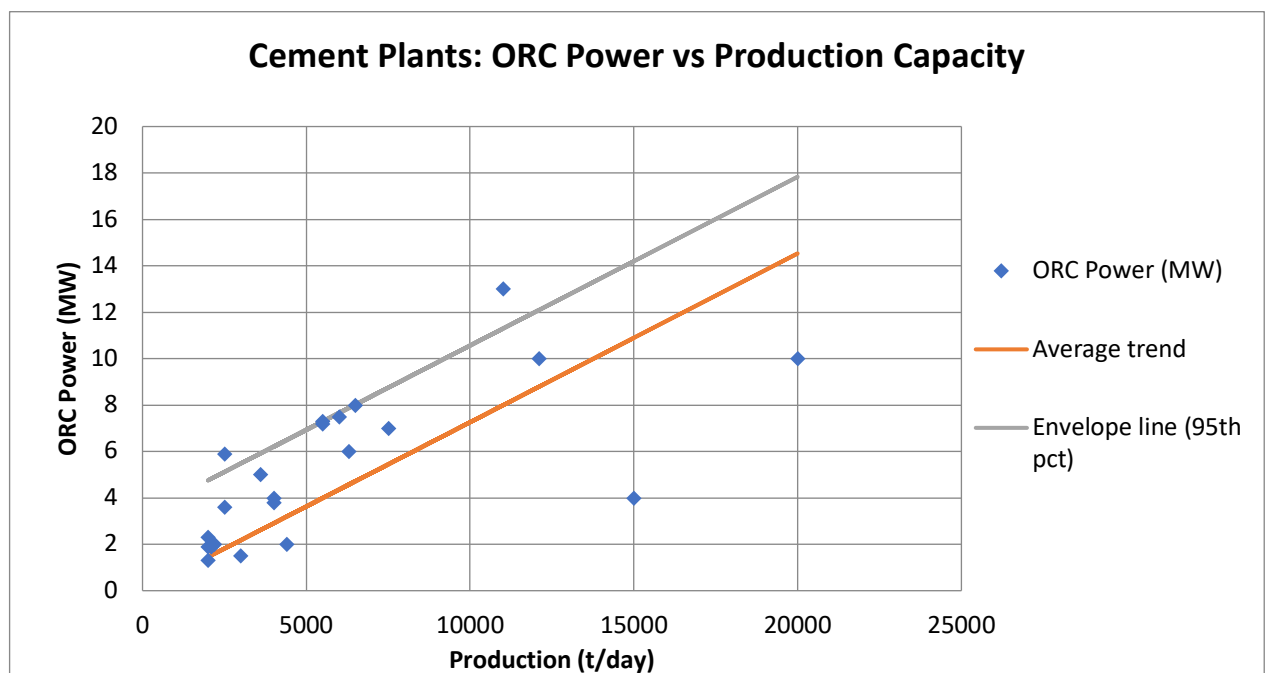


Figure 2. Cement Plants: ORC-power output dependent on the production capacity.

The production capacities for cement, in which ORC turbines are installed reach from 2,000 to 20,000 t/day and ORC output lays between 1.5 and 14 MW. The depicted scatter plot indicates a clear positive correlation between production capacity and ORC power.

Inserted is an average trend line (orange) which is derived by performing a linear regression. The linear regression is described by Equation 2.1.

$$P_{ORC} = 0.000726553 \cdot \text{Production capacity} \quad (2.1)$$

The slope of 0.000726553 MW per t/day describes that by an increase of 1000 tons per day an ORC output increase of 0.726 MW is achieved. The linear regression is performed in a way that at 0 production, no ORC power is recorded. The coefficient of determination $R^2 = 0.792$ indicates a high correlation for this industrial analysis.

For further ORC potential analysis, it is helpful to construct the upper envelope line (grey), which represents the high-performance boundary of ORC turbines in cement plants. It is also depicted in Figure 2 and is constructed by using the 95th percentile residual. This envelope captures the best-performing worldwide installations which represent most advanced technologies with optimized heat exchange and higher mass flow and/or modern ORC designs. While the regression is constrained through the origin for physical consistency, the upper envelope reflects variability and is therefore not forced through the zero point.

The goal at this stage is to derive specific ORC power values for the cement industry. To archive this, the Specific Power (MW/1000 t/day) for each plant can be calculated with Equation 2.2.

$$P_{Specific}(MW/1000 t/day) = \frac{\text{ORC Power}}{\text{Production Capacity}} \cdot 1000 \quad (2.2)$$

The specific power of the cement plant describes how much ORC output can be archived by each ton of production output at the individual plant. Applying this to each power output for the individual cement plant allows for deriving the values of specific power which can be found in Appendix A.

Using this derived data, it is now possible to attain a mean specific power value for all cement plants, which lays at 1.019 (MW/1000 t/day).

Equally, reasonable upper and lower limits can be derived with the goal to attain a realistic, conservative, and optimistic specific ORC-Power potential. The upper limit (optimistic) is taken from the 95th percentile, derived earlier. The lower limit (pessimistic) is taken from the 10th percentile value. The values of realistic and optimistic specific power are 0.80. and 2.36 MW/1000 t/day respectively. These values found in Table 1.

It is valuable for further calculations to transform this specific power into a specific electric yield (kWh/t) which is attained using the following Equation 2.3.

$$\text{Specific Electric Yield (kWh/t)} = \frac{P_{\text{Specific}} \cdot h_{\text{year}} \cdot 1000}{d_{\text{year}} \cdot 1000} \quad (2.3)$$

The value of h_{year} is defined by industry standards to be **7500h** as a base value. While d_{year} is also equally defined in the literature to be **350 days** [4], [16].

The previously attained values of Specific Power for the realistic, optimistic and pessimistic case can be transformed into Specific Electric Yields. These values are additionally found in Table 1.

Table 1. Specific Power and Specific Electric Yield derived for cement plants.

	Pessimistic	Realistic	Optimistic
Specific Power (P_{Specific}) (MW/1000 t/day)	0.80	1.02	2.36
Specific Electric Yield (Y) (kWh/t)	17.14	21.86	50.57

Values in the literature are found to be very similar to the ones attained here. The International Finance Corporation [8] estimates a specific electric yield from 25 to 45 kWh/t. With this validation it is reasonable to use the attained values for further calculations.

2.2.3 Glass Sector: ORC Performance vs Production Capacity

Analogously to cement applications, the same analysis is performed regarding glass plants. The 18 worldwide applications of ORC turbines are plotted with their according production capacity Figure 3.

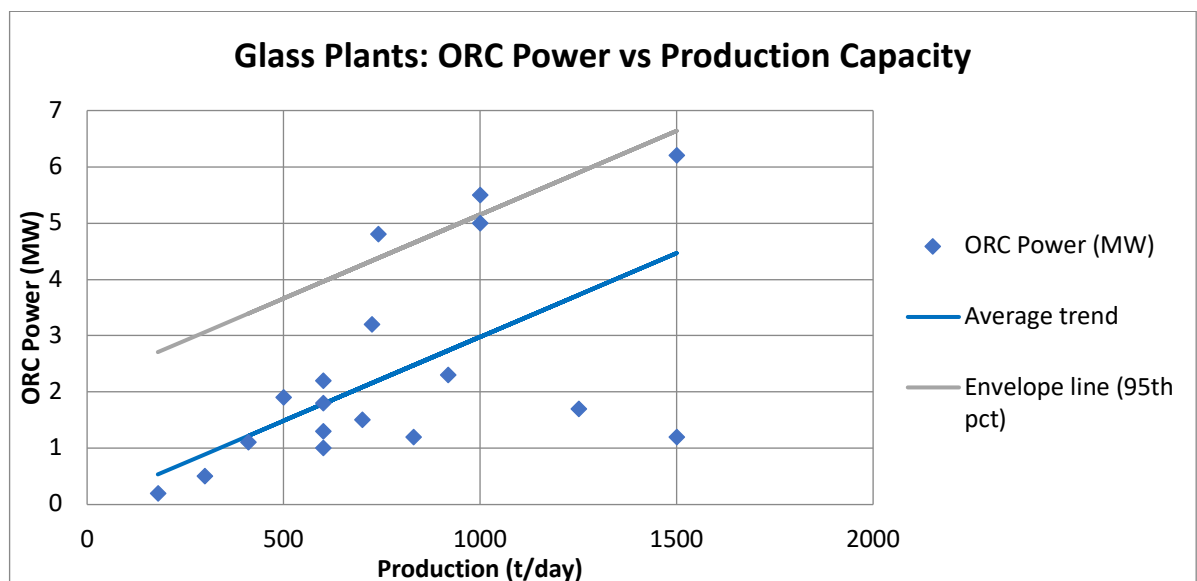


Figure 3: Glass Plants: ORC-power output dependent on the production capacity.

The glass production capacities are evidently smaller than the ones in the cement sector. They range between 180 and 1,500 t/day. The ORC output varies between 0.2 and 6.2 MW. When observing the plotted datapoints it becomes visible that they are more scattered compared to the cement sector, hinting that there is larger variability on waste heat quality in the glass sector. This is supported by the R^2 value of the linear regression which lays at 0.254. This can be explained by more variations in the glass production for different products. Furnace types vary depending on the glass types (float, container, fiberglass) [17]. Also, the temperatures are alternating between different glass-type productions.

The linear regression is defined by Equation 2.4.

$$P_{ORC} = 0.002978 \cdot \text{Production} \quad (2.4)$$

Once again, a clear positive correlation between production capacity and ORC power can be seen. The slope reveals that with the increase of production capacity by 1000 t/day an extra 2.98 MW ORC output is attained. The 95th percentile residual marks the upper performance of the waste heat recovery for large float glass furnaces. This represents the optimistic scenario, just like in the cement case. Also, here it is not forced through the zero point, since it marks the upper envelope. With the help of Equation 2.2 the specific power (MW/1000 t/day) for each plant can be obtained, with values to be found in Appendix A. The mean of the specific power for glass plants lays at 2.97 (MW/1000 t/day). This value is significantly larger compared to the cement industry. As done for cement, it is possible to obtain pessimistic and optimist values and with Formula 2.3. transform them into electric specific yields for which the results can be found in Table 2.

Table 2. Specific Power and Specific Electric Yield derived for glass plants.

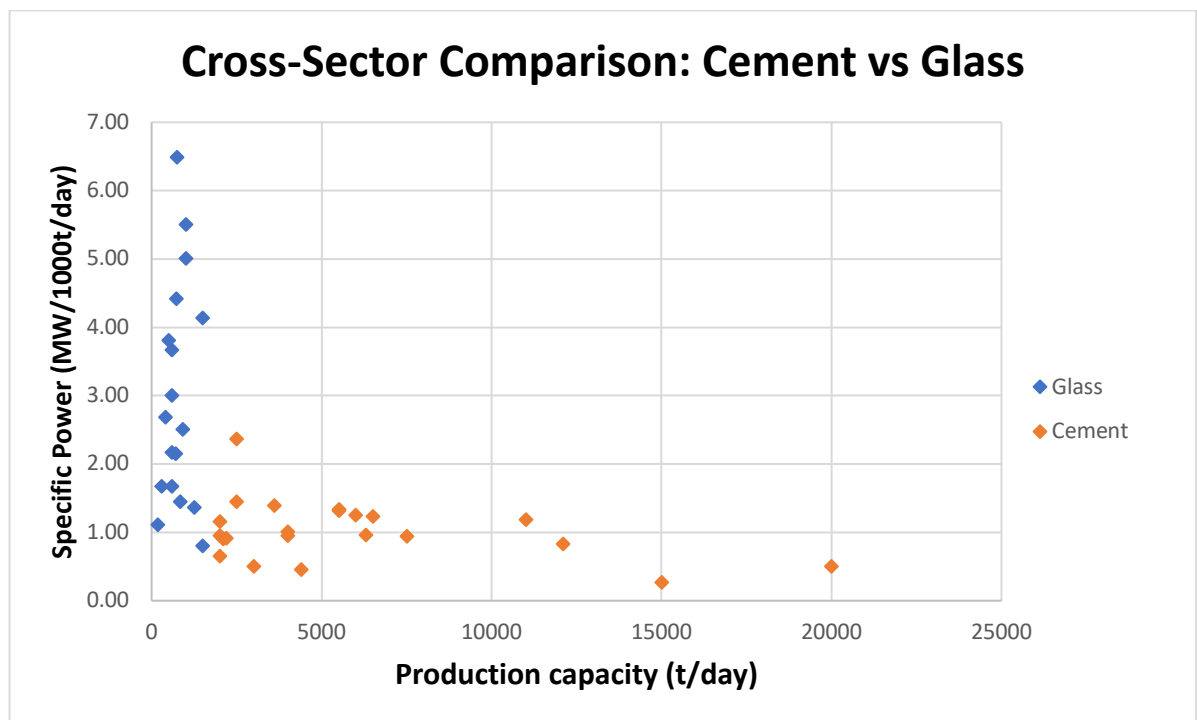
	Pessimistic	Realistic	Optimistic
Specific Power (P_{specific}) <i>(MW/1000 t/day)</i>	1.41	2.97	5.64
Specific Electric Yield (Y) <i>(kWh/t)</i>	30.21	63.64	120.80

Values in the literature are found to similar in magnitude to the ones attained here. For the cement sector, Campana et al. [4] estimates a value of 2.7kW ORC power per metric ton of daily capacity which is very close to the 2.97 (MW/1000 t/day) mean value attained by analysing the worldwide data.

2.2.4 Cross-Sector Comparison: Cement vs Glass

It is valuable to understand how fundamentally different the exploration of waste heat energy is between the glass and cement sector. Using the above attained data, the specific power values over the production capacity can be plotted in a scatter plot (Figure 4). The data that goes along with the scatter plot derived earlier can be found in Appendix A.

The cross-sector graph shows two clearly separate clusters, blue representing the glass plants which indicate high specific power reaching up to 6.5 (MW/1000 t/day), at low to medium production scale (maximum 1500 t/day). Cement plants depicted in orange reach much lower specific power values with a median value of 1.02 (MW/1000 t/day) and maximum of 2.36 (MW/1000 t/day). There is only minimal overlap, highlighting the structural differences of the two industries.



is much larger than in cement production. Typically, the glass production capacities are marginal at the individual plants as seen in the data. The combination of high exhaust temperatures and low production levels, results in high specific power values and equally high specific electric yields.

Cement kilns operate at much lower exhaust temperatures (300-400°C) [8], leading to significantly lower specific power values, which typically lay between 0.5 and 2.4 (MW/1000 t/day). From a thermodynamic point of view these results are logical as the Carnot efficiency increases strongly with higher temperature source and the temperature level is a dominant driver of electricity conversion efficiency.

But despite lower specific power, cement plants operate at massive production scales which outrun the glass industry up to factors of 10. This benefits the cement industry with economies of scale in the ORC heat recovery. Equally beneficial are the steady operation parameters (significantly larger R^2 value compared to glass) and large absolute heat flows make the ORC a relevant choice in heat recovery.

Since the electric specific yields differ structurally between sectors, it is important to calculate national potentials for glass and cement separately from another. The three scenario values for each industry (realistic, optimistic, pessimistic) which can again be validated with the scatter plot, will be crucial for further analysis. The differences in the two sectors will shape aspects of national ORC potential like annual generation (GWh/year), ORC-MW potential, and CO₂ savings.

At this point of the analysis, it is important to gain an overview of currently used ORC potential in both industries and countries, in form of installed ORC-plants. The dataset of installed ORC plants allows for a precise analyse of the current situation in Italy and Germany. Each countries production level, for which the ORC technology is used, can be summed up to attain the market overview to the current day. As the production levels are given in tons per day, they must be converted into tons per year. For this conversion a factor of 350 days per year is used to stay aligned with previous estimations. The according production levels for both industries are shown in Table 3.

Table 3. Installed ORC capacity in the glass and cement industry for Germany and Italy

	Production Levels – used by ORC technology	
	Cement (<i>Mt/year</i>)	Glass (<i>Mt/year</i>)
Germany	1.05	0
Italy	1.65	1.34

From these numbers it becomes evident that Italy is using waste heat recovery via ORC much more frequent than Germany. For both sectors Italy has a higher usage rate, and the difference is particularly visible in the glass industry. While Germany has zero installations recorded, Italy counts seven different installations. Relative to the rest of the world Italy is by far the country with the most installations and makes up almost 40% of all ORC turbines in the glass industry. In the cement sector Italy counts two installations and Germany only one.

2.3 National Production Data

The cement and glass production volumes within countries determine the scale of off-heat potential for ORC technologies. To arrive at reasonable potential estimations, it is therefore essential to precisely analyse the current production levels for both Italy and Germany.

The cement sector is deeply intertwined with macroeconomic cycles, construction trends and demographic trends, all influencing the local production amounts. The European construction sector had experienced moderate growth in 2022 by 3%, being followed by a decline in 2023 and 2024 due to inflation and declining investment [19]. The two countries Germany and Italy were among the countries with the largest decline in housing construction with a fall of -8.1% (Germany) and -18.6% (Italy) in recent years [19]. But despite this downturn, both countries continue to perform large scale cement productions which are required for infrastructure, renovation and other applications.

To this current time Germany operates around 54 cement plants with a combined annual production of **35 Mt/year** [9], [20], [21]. Italy remains the second-largest producer in the EU after Germany, consistently producing around **19 Mt/year** [9], [20]. Today, Germany and Italy together still make up 20-25% of all EU cement production, making them extremely relevant countries, equally so for ORC heat recovery installations.

Germany and Italy both hold large glass production industries, covering flat glass, container glass, and specialty segments such as technical glass for industry applications. For the recent years, Italy experienced strong growth in the glass production sector reaching up to an increase of 23% for flat glass [22]. To this current time Italy produces circa **6 Mt/year** [7], [22], [23], [24]. Germany shows similar and equally diversified glass production. Recent data suggests a split in production as follows: 3.8 Mt container glass, 1.8 Mt flat glass, 0.3 Mt special glass, and 0.8 Mt of additional glass products making a total production volume of **6.7Mt/year** [17], [25]. The production values for both countries and industries are gathered in Table 4.

Table 4. Annual glass and cement production levels in Italy and Germany

	Annual Production (P)	
	Cement (Mt/year)	Glass (Mt/year)
Germany	35	6.7
Italy	19	6.0

2.4 Results of Stage 1: National Technical Potential of ORC Technology

2.4.1 Baseline: Existing ORC Sector Coverage

With the estimated annual production levels of cement and glass and the production levels for active ORC devices, it is now possible to derive usage ratios for each country and industry. These represent the percentage of ORC usage in the given country and industry and help to understand the level of technological advancement regarding the ORCs. Results are found in Table 5.

Table 5. Ratio of ORC technology usage in the cement and glass industry for Italy and Germany

	Usage Ratio of ORC technology	
	Cement	Glass
Germany	3.0%	0.0%
Italy	8.7%	22.3%

From these relative values it becomes even more evident that Italy's usage of ORC heat recovery is higher in both industries compared to Germany. Giving this perspective, Germany still holds a larger ORC potential for waste heat recovery. But also, in Italy there still lies significant amounts of unused potential to be exploited.

2.4.2 Methodology for Potential Calculation

To calculate the national cement and glass potential for Germany and Italy a set of parameters, assumptions and formulas must be introduced, that allow to precisely derive plausible values in this last step. The logic behind these calculations is to use the attained specific power parameters and to scale them up by the national production values to derive plausible electricity production levels. This is followed by estimating the CO₂ savings that result from this regenerative electricity production.

The previously derived specific power values are the base of these calculations. The conservative realistic, and optimistic specific electric yields (kWh/t) are each used to create the three different

scenarios and depict a range of plausible outcomes. This is performed separately for the cement and for the glass industry.

A first assumption to be made regards the penetration rate. This parameter describes the percentage of plants with remaining waste-heat potential, where an installation of ORC turbines is realistic within the next years. Meaning that the installation of a new ORC turbine is both economically and physically feasible within the next time period. This percentage value should give an indication on how much of the potential is realistically exploitable in the near future. If the penetration rate is not defined and implemented, we would wrongly assume all plants are technically feasible for the ORC implementation.

This is a crucial value in the calculations and has a large influence in final estimations but must not be chosen to be overestimated.

Previous research shows that the current waste heat recovery ratio for cement lays around 10% [4], while the waste heat recovery in the glass sector is not much higher, laying at around 10-15% [10], [26]. This goes along with the ORC usage ratio discussed in the previous Section (2.4.1). Demonstrating only small fractions of production levels are using ORC waste heat recovery in Germany and Italy. This leads to an unused potential between 80 and 90%. The immediate adoption of all these plants is unrealistic within a short time period, as not only the willingness of installation but also the supply chain is not equipped for this large demand.

To remain conservative and avoid overestimations this research adopts a **penetration rate of 35%** for the cement industry in both Italy and Germany and the glass industry in Germany.

As the ORC usage ratio in Italy in the glass sector already lays at 22,3% the number for this specific case is decreased to **20%**, representing the share of plants where to this current day ORC implementation is technically and operationally feasible within the next years.

The next parameters needed to be defined are uptime numbers per year and auxiliary consumption. Uptime hours per year describes the hours in which the plant operates each year. This is equally the time in which the ORC can transform heat energy into electrical. To stay conservative and be aligned with previous calculations this number is set to be at **7500 h/year**. The auxiliary consumption describes the own consumption of the ORC to enable the transformation of heat into electricity. This value gains special attention when deriving the CO₂ value saved by implementing the ORC technology. The extra consumption that pumps, system monitoring and ORC-control are creating must be subtracted from production values. The literature shows auxiliary values varying between 10% and 20% of its own production [27]. For this research a base auxiliary value of **12%** is chosen.

The grid emission factor is used to determine CO₂ savings for respective countries. It is given as a ratio of how much grams of CO₂ on average are emitted for every kilowatt-hour (kWh) consumed. This value heavily depends on the mix of carbon intensive electricity means and electricity originated from carbon neutral energy sources. Since every country uses different resources and approaches, this value heavily depends on each country individually.

The approach is as follows: With every kWh that is generated with the ORC turbine, it is saved by carbon intensive energy source and it does not need to be bought from the local electricity grid, therefore saving this amount of CO₂. In recent years grid emission values have typically dropped in the EU, since more carbon neutral energy sources, like solar and wind are implemented. For Germany this value has dropped from 0.41 in 2021 to a current value of 0.36 (tCO₂/MWh) [2], [28]. The values for Italy lay slightly below, with an electric mix that is already more sustainable than the German ones at current levels estimated to be 0.3 (tCO₂/MWh) [29].

Table 6. Collection of industry and technical parameters used to derive the ORC national potential.

Variable	Penetration Rate (β)	Penetration Rate (β) (Glass – Italy)	Operating hours (t)	Auxiliary consumption (α)	Grid emission factor Germany (EF)	Grid emission factor Italy (EF)
Value	0.35	0.20	7500 (<i>b/a</i>)	0.12	0.36 (<i>tCO₂/MWh</i>)	0.30 (<i>tCO₂/MWh</i>)

To be able to calculate the desired values three formulas must be introduced. Firstly, the annual electric ORC potential, which represents the potential within one country, can be derived by using Equation 2.5.

$$E_{ORC} (MWh/a) = \frac{Y \cdot P \cdot \beta \cdot (1 - \alpha)}{1000} \quad (2.5)$$

Where:

Y = specific electric yield (*kWh/t*)

P = annual production (*t/a*)

β = Penetration rate

α = auxiliary consumption

The ORC electric capacity equivalent is the indicator of how much capacity the ORC installations in the given country holds. This is the second relevant calculation to be performed and can be derived with Equation 2.6.

$$C_{ORC} (MW) = \frac{E_{ORC}}{t} \quad (2.6)$$

Where:

E_{ORC} = anual electric ORC potential (MWh/a)

t = operating hours per year (h/a)

The net CO₂ saved is the third of the three relevant parameters and can be derived by using Equation 2.7.

$$CO_2(tCO_2/a) = E_{ORC} \cdot EF \quad (2.7)$$

Where:

E_{ORC} = anual electric ORC potential (MWh/a)

EF = grid emission factor (tCO₂/MWh)

2.4.3 Results: National Potential Cement Sector (Italy and Germany)

Using the specific electric yields derived in 2.2, the national production volumes presented in Section 2.3, and the methodology including the formulars and variables of 2.4.2, the technical ORC potential for the cement sector in Italy and Germany can be quantified. Each of the three scenarios is depicted individually and the parameters Electricity Potential, ORC Capacity and CO₂ Savings are derived. The results are presented in Table 7.

Table 7. Results: National ORC Potential in the cement sector for Italy and Germany with conservative, realistic and optimistic scenarios.

County	Scenario	Electricity Potential (GWh/a)	ORC Capacity (MW)	CO ₂ Savings (ktCO ₂ /a)
Germany	Conservative	184.88	24.65	58.57
Germany	Realistic	235.65	31.42	74.65
Germany	Optimistic	545.14	72.69	172.70
Italy	Conservative	100.36	13.38	26.50
Italy	Realistic	127.92	17.06	33.77
Italy	Optimistic	295.94	39.46	78.13

Germany shows higher absolute electricity potential across all scenarios, led by previous findings and parameter settings. In the optimistic scenario in Germany the ORC technology would create up to 545 GWh of electricity every year. This value lies at 296 GWh/a in Italy. In the realistic scenario over 74 thousand tons of CO₂ could be saved annually in Germany by implementing the ORC technology. This value is derived to be 34 thousand tons CO₂ in Italy. Both countries exhibit

a parallel scenario behaviour, meaning that the steps between scenarios occur at the same relative order and magnitude across all values.

2.4.4 Results: National Potential – Glass Sector (Italy and Germany)

The national ORC potential for the glass sector is quantified in the same way as the one for cement. The values of electric potential are derived by using the specific electric yields and production data. Form Section 2.3. Just like the other parameters, it is derived using the methodology described in Section 2.4.2. The results are presented for the three scenario levels (Table 8).

Table 8. Results: National ORC Potential in the glass sector for Italy and Germany with conservative, realistic and optimistic scenarios.

County	Scenario	Electricity Potential (GWh/a)	ORC Capacity (MW)	CO ₂ Savings (ktCO ₂ /a)
Germany	Conservative	62.34	8.31	22.44
Germany	Realistic	130.71	17.43	47.06
Germany	Optimistic	249.28	33.24	89.74
Italy	Conservative	23.93	3.19	7.18
Italy	Realistic	50.17	6.69	15.05
Italy	Optimistic	95.67	12.76	28.70

For glass, the calculated electricity potentials range in Germany from 62 to 249 GWh/a, while these values for Italy span between 24 and 96 GWh/a, reflecting the difference in penetration rate and annual production. The remaining potential for both countries is high with optimistic values leading to a CO₂-saving-potential of around 29-thousand tons in Italy and a value of almost 90-thousand tons in Germany. Comparing the two industries it can be noted that the overall potential in the cement industry is higher in terms of all three parameters compared to glass.

2.5 Interpretation of Stage 1 Findings

Overall, this analysis depicts that ORC systems can be considered a substantial national-scale waste-heat electricity source in both the glass and the cement industry. There are some country differences which mostly arise because of the production volumes and country specific parameters. Equally there exist substantial differences between the waste heat recovery for cement and glass.

The results found in Section 2.4 reflect the fundamental thermodynamic contrast outlined in Section 2.2.4. Glass furnaces provide high-temperature exhaust gases, resulting in higher specific yields, while cement kilns provide lower temperature but higher mass flow exhaust gases, leading to lower specific energy values but to higher absolute potential volumes. This effect is enlarged by the absolute production numbers for cement which outweigh glass production, making economies of scale equally a relevant factor. This results in overall higher total electricity potential and CO₂ avoidance in both countries for cement.

Across both sectors and all scenarios, Germany consistently shows higher absolute national ORC potential than Italy, indirectly reflecting the difference in production volumes. This trend continues for CO₂ avoidance levels which remain above the Italian ones.

The important factor not to neglect is the existing coverage difference between the two countries. Italy is comparably advanced when it comes to ORC installations. For cement the coverage is at almost 9% and for glass even 22.3%. In Germany these values are 3% and 0% respectively. This partly also explains the lower remaining potential in Italy.

These usage ratio difference in the glass industry suggests that the markets are not heterogeneously developed. Of all worldwide ORC installations, Italy holds a 40% market share, showing the early industrial adoption for this technology. One way of explaining these market dynamics is the presence of major ORC companies located in Italy. Turboden, is one of the largest ORC manufacturers worldwide acting heavily in the glass and cement sectors. Exergy, with its headquarters in Milan is equally a large player in Italy with focus on geothermal and waste heat recovery energy.

When it comes to CO₂ savings the importance of the electricity mix (EF-factor) must be considered. The higher this value lies, the larger the potential CO₂ saving, keeping in mind that an increase of ORC usage automatically leads to a drop in the grid emission factor.

The combined findings of this chapter provide the basis for the microeconomic assessment in Stage 2, where plant-level feasibility will determine how the calculated national potential is economically feasible to be implemented for individual firms.

3 Stage 2: Economic Feasibility of ORC Technology (Micro Level)

3.1 Methodological Approach for Plant-Level Economics

The results of stage one give insights into national ORC potentials and find that there is a large potential for the ORC technology in the glass and cement sector remaining to be exploited. Stage 2 zooms in on one representative glass plant and one representative cement plant to assess the economic attractiveness of installing an ORC turbine for individual firms.

The glass sector reference case is based on a representative float-glass furnace with an approximate 600 to 800 t/day in production, which corresponds to a mid-range facility identified in stage 1 which could be located in Germany or in Italy. The waste heat is directly recovered from the regenerator exhaust, where typical temperatures range at around 400°C. The flue gas is not directly channelled into the ORC but is instead transferred into a secondary thermal-oil loop via a high-temperature heat exchanger. This is consistent with waste heat recovery setups in the glass sector described in the literature [5], [10], [30], [31].

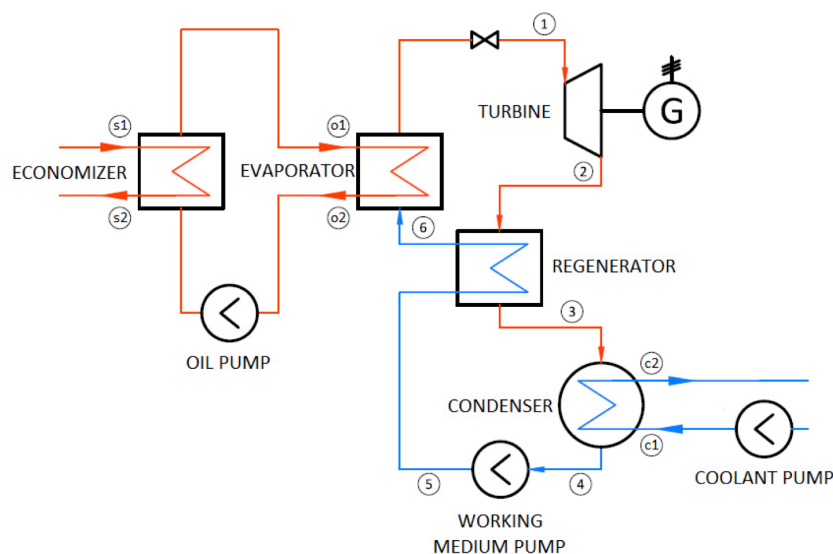


Figure 5. Schematic layout of the ORC system including an intermediate thermal-oil loop for waste heat recovery, used for the glass sector reference case (Figure adapted from Musial et al. [30]).

The basic ORC configuration was introduced by Figure 1 in Section 1.2. The setup here (Figure 5) shows a specific configuration used in the glass reference case. The figure shows the additional thermal oil loop which is used to transfer the off heat via the economizer to the evaporator. The working fluid is evaporated and expanded in the turbine, where the electricity generation takes

place. Such indirect heat transfer is chosen to protect the working fluid and guarantee for thermal stability. Therefore, this is a common setup in industrial applications.

The cement sector reference case is based on a representative clinker production, where approximately 4000 to 5000 tons are produced every day, also this plant could be in Germany or Italy, and aligns with stage 1 findings, representing a mid-sized facility. In the cement plant waste heat is recovered from two primary sources. The preheater exhaust gas and the air quenching cooler exhaust. In combination a total of 330°C can be recovered. Just as in the glass sector, the heat is transferred into a liquid secondary thermal loop. This setup is consistent with cement plant ORC installations described in the literature [4], [26], [26], [32].

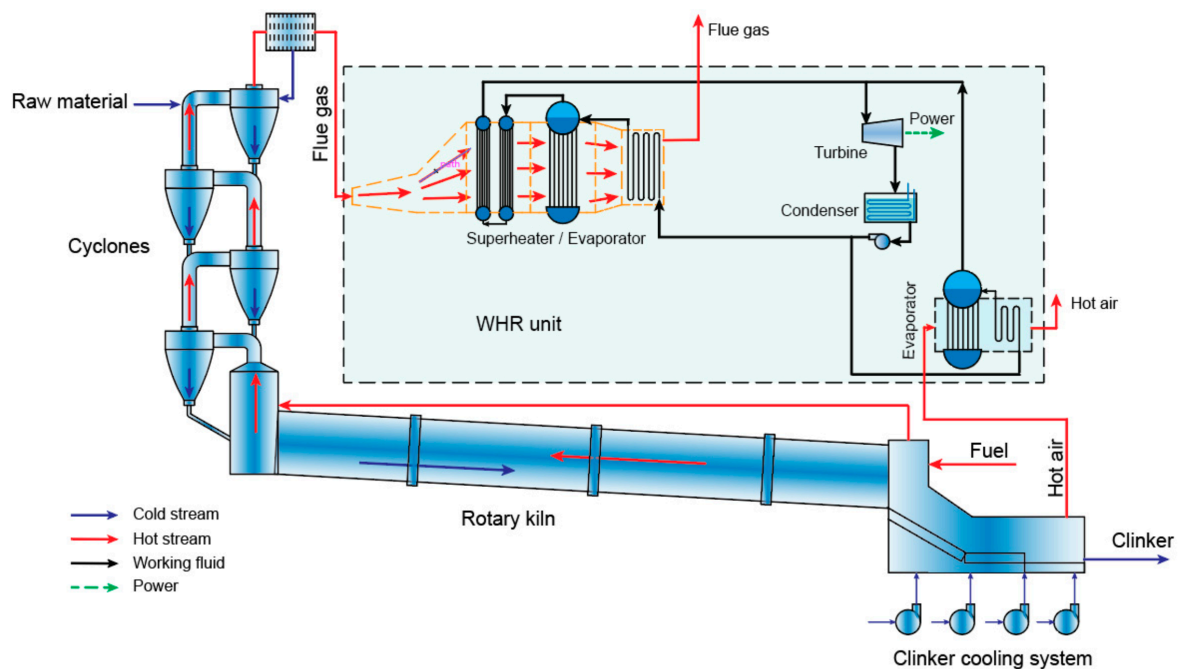


Figure 6. Schematic layout of the waste heat recovery (WHR) system integrated in a cement clinker production line which uses the exhaust heat from the preheater just as clinker cooler off heat to supply an ORC for electricity generation (Figure adapted from Turakulov et al. [32]).

Figure 6 shows a schematic layout of waste heat recovery systems such as the ORC for a cement plant. The figure shows how the ORC is integrated into the active clinker production line. As pointed, waste heat is recovered from two major waste heat sources. The first source of heat is represented by the preheating of the exhaust gas seen on the left of the diagram. The second source of waste heat is taken from the clinker cooling system, just after the rotary kiln. Just like in the case of glass production, the exhaust heat can be transferred to the heat exchangers by a secondary thermal loop. The combined heat sources increase overall recovery potential.

To analyse the economic feasibility of the two plants, a set of steps need to be performed:

In a first step a thermodynamic parameter analysis of the exemplary plants is performed with the goal of determining the net electrical capacity. In a next step a cash-flow model is set up, by determining relevant operational and financial parameters. This is followed by applying the financial and market parameters like CAPEX, O&M, discount rate, and electricity prices on the electrical input, leading to economic performance metrics. These economic metrics like payback period, NPV, or IRR can be determined for each of the plants separately.

The next step contains a sensitivity study in form of a Tornado-analyse and a Monte-Carlo simulation performed on the payback period and the NPV. In a last step of the individual firm analysis, the CO₂ savings for the installation can be quantified.

To give a simplified overview of this complex undertaking in the following chapters, the steps are recoded in Figure 7.

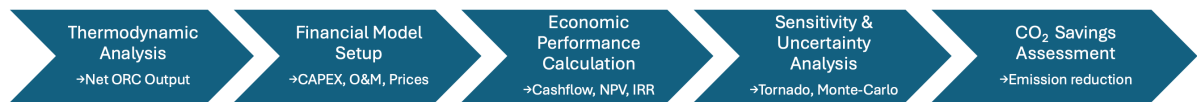


Figure 7. Overview of the steps to perform to archive a micro analysis of an ORC-plant in the cement and glass industry.

3.2 Thermal-to-Electric Conversion Modelling

3.2.1 Modelling Framework

The purpose of this thermodynamic modelling step is to determine the net electric output of the ORC system for both the glass and cement plant. For this thesis the net electric output represents one of the most important parameters since the whole economic evaluation is based on it. Equally, the determination of electric potential with given heat parameters will decide over the installed ORC capacity for a firm and therefore the financial investment. Choosing an ORC turbine larger than the heat potential would mean inefficiency, just as a device chosen too small would mean that the full potential is not used.

The conversion from thermal energy to electrical power is modelled using GeoSimple, which is used to simulate the ORC turbine in form of the secondary heat-transfer loop. This tool was originally built to model geothermal ORC applications but can equally be used for waste-heat recovery applications, by changing the input parameters. As the focus of this thesis lies on the financial aspects, the thermodynamic conditions and parameters are described in simpler terms.

GeoSimple can model the temperature drop across the ORC evaporator and calculates the thermal power by considering the mass flow of the heat-transferring fluid, just as its specific heat capacity. Equation 3.1 represents this calculation.

$$P_{th} (kW) = \dot{m} \cdot c_p \cdot (T_{hot,in} - T_{hot,out}) \quad (3.1)$$

Where:

\dot{m} = Mass flow of rate of fluid (kg/s)

c_p = Specific heat capacity (KJ/kg · K)

$T_{hot,in}$ = Inlet temperature at ORC evaporator (°C)

$T_{hot,out}$ = Outlet temperature at ORC evaporator(°C)

The attained thermal input is converted into gross electrical output by multiplying an efficiency factor in the transformation of heat to electrical energy. The net electrical output can be determined by subtracting auxiliary loads as done in Equation 3.2.

$$P_{net} = P_{gross} - P_{aux} \quad (3.2)$$

Auxiliary loads entail all internal electrical process consumption like pumps, fans and system monitoring. Typical values for P_{aux} lay between 10 and 15% [5], [5], [31].

3.2.2 Input Parameters and Results

The two reference cases were described in detail in the Section 3.1 and were chosen to represent typical mid-scale installations in the glass and cement sectors. Their thermodynamic characteristics were derived from findings in Stage 1 and sector specific waste heat recovery industry studies.

In the glass plant the waste heat is recovered from the float-glass furnace, where the off-heat lays at around 400°C. In waste heat recovery systems this heat is transferred into a secondary thermal loop, which supplies the ORC directly with the heat energy. The temperature at the inlet of the ORC is estimated to be at 350°C and at the outlet the temperature is assumed to be 165°C. The cooling-water temperatures enter the system at an estimated temperature of 15°C and leave with a temperature of 30°C. The mass flow of the heat transfer fluid is chosen to be 10 kg/s. The given input parameters result in a net a net system size of around **2000kW**. According to literature this lies within the typical range of waste heat recovery installations in the glass industry [5].

In the cement plant the heat is recovered from two different sources. The preheater and the air quenching cooler exhaust make up exhaust streams of approximately 330°C. Just as in the glass plant the waste heat is firstly transferred into a secondary thermal loop, which leads the energy into the ORC. The temperature in the moment of entry is at 300°C and leaves the system with a temperature of 160°C. The cooling water cycle enters the system with a temperature of 15°C and leaves at a temperature of 30°C. The mass flow of the hot fluid entering the cycle lays at 15 kg/s. The GeoSimple tool calculates a net output of this ORC configuration to again be at approximately **2000kW**. The result of the cement plant represents typical values also to be found in previous literature research [26].

For further research it is convenient that the output values of the cement and glass plant lay closely to another with the given representative input parameters. This condition is valuable for the following research as it makes financial analysis comparable between the two cases, making it easier to highlight structural differences on a financial level.

3.3 Operational and Financial Parameters

To create a stable financial model, it is important to base calculations on a solid foundation. Therefore, the parameters and assumptions made for this study are introduced in the following chapters. The introduced parameters are sorted by technical, financial and energy related parameters. Some of the values differ for the two industries and if needed will be assessed separately. It is to be mentioned that some of the parameters entail uncertainty, which are relevant for the following sensitivity analysis (Section 3.5).

3.3.1 Technical and Operational Parameters

The first set of parameters to be defined deal with the technical and operational aspects of the ORC. This surrounds the operation of the turbine itself and should give information about the behaviour of the ORC on a long term.

The net capacity is the first and most important parameter. It describes the nominal power output of the system and has been estimated in Section 3.2 to be **2000kW** for both installations. It is important to highlight that this net output already covers the own consumption and can purely be used for financial purposes.

The second parameter to be determined is the operating hours per year. Both reference plants operate in continuous high- temperature industrial processes, where waste heat is available almost all year long. Considering maintenance and operational stops throughout the year, the literature suggest realistic values of operation ranging between 7500 and 8500 h/year out of the 8760 hours

available. Cement is typically assumed at around 8000 h/a [4], [18], [26]. Flat-glass furnaces can operate even more continuous with little downtimes. The literature suggests optimistic values that can even reach up to 8500h/year [16]. For this thesis a conservative approach is chosen for both plants, but with slightly different values. For the cement plant a value of **7500 h/a** is adopted as a base value. The optimistic one lays at 8000 h/a, while the pessimistic one is set to 7000 h/a. For the glass plant a slightly higher value can be assumed. The base value of **7700 h/a** is adopted, and the optimistic case sits at 8200 h/year and the pessimistic one at 7200 h/a. This parameter already includes planned downtime, maintenance and unavoidable outages. Therefore, no separate parameter like an “availability factor” is applied at later stages.

The project lifetime is one of the most known project related parameters. It determines the time for which the project is estimated to last. This also includes an estimation of the functionality of the ORC. A standard value for the ORC lifetime, in which the net present value of the project is determined, is set to 20 years. Multiple previously performed studies also use 20 years as their expected horizon, because of this also this thesis adopts a **20-year project lifetime** [15], [18], [31], [33].

The final technical parameter to define is the degradation rate. This rate describes the annual degradation that the ORC turbine undergoes in its 20-year lifetime, resulting in decreased performance year by year. According to literature the annual degradation for the ORC turbine is low, since no own combustion chamber is present, resulting in low overall mechanical stress. The literature suggests annual degradation that reduces the performance by **2% each year** and this value is adapted by this thesis [31], [34].

3.3.2 Financial and Investment Parameters

There are three financial parameters needed to be defined to enable a cashflow analysis. The Specific CAPEX, the O&M costs and the discount rate.

The Specific CAPEX is the total investment cost of the ORC plant divided by its net electrical capacity (€/kW_{net}). It includes everything that is needed to properly install the ORC module. Besides the device itself also the installation, engineering and contingencies, and any supplementary items are included. The Specific CAPEX is a way of estimating the total costs, without requesting an offer by the suppliers. But the Specific CAPEX is made up of actual installations recorded. Economies of scale can be found in the estimations of the specific CAPEX as it typically increases with decreasing electrical capacity [34], [35].

For this thesis, values for the Specific CAPEX are adapted directly from the literature. The literature suggests that on average, glass ORC installations are more capital expensive than the ones for cement. This has to do with the temperature difference in the two sectors. The lower temperatures in the cement industry can be recovered in easier ways with simpler heat-recovery boilers, while the warmer heat source of the glass furnaces require more corrosion resistant heat exchangers and more complex integration with the furnace, which increases the costs.

For the cement plant the values adapted from the literature for this thesis are quantified to be **2400 (€/kW_{net})** as the base value. In the optimist case this value is at 2000 (€/kW_{net}) and for the pessimistic one it is at 3000 (€/kW_{net}). The higher equipment and integration cost in the glass industry justify slightly higher Specific CAPEX of **2800 (€/kW_{net})** as a base value. The optimistic case is quantified to be 2200 (€/kW_{net}) and the pessimistic one is 3300 (€/kW_{net}) [18], [35].

The fixed Operations and Maintenance costs, short O&M costs, cover all ORC setup related costs which occur each year. They include routine maintenance, spare parts, inspections, just as consumables like working fluids and administrative and insurance costs. The O&M costs are taken every year as a percentage of the CAPEX. The literature suggests that these costs are at **3% of the CAPEX expenses each year** [35]. This is the base value for our calculation in both the cement and the glass plant. Typically, this value is composed by 2% maintenance, 0.3% consumables, and 0.7% in management and insurance. To be aligned with literature implications, a range with an optimist value of 2% and a pessimist value of 4% of the CAPEX each year is defined for this thesis [18], [35].

The discount rate is the final financial parameter to be introduced. It reflects the required rate of return or weighted average cost of capital of the investing company. The discount rate is used to convert future cashflows of the projects into their present economic value. It represents the return the company could earn by investing its money in alternative projects and can therefore be called opportunity cost. The discount rate additionally accounts for the remaining risk of the project. Typically projects with higher risk of success are discounted with a higher discount factor. For this thesis the discount value is adapted from the literature, where it typically ranges for ORC projects between 6% and 12% [36]. These values make up the upper and lower bound of the uncertainty. The base value for this thesis is chosen as in CE Delft [18] to be at **8%**.

3.3.3 Energy Market and Policy Parameters

The last set of parameters needed to be introduced are the ones surrounding the energy market. These include the import and export price, the price escalation factors, just as the share of self-consumption.

The import electricity price is the one that electricity is bought for from the grid. It varies between countries and in Europe usually ranges between 0.10 and 0.18 €/kWh [4], [37]. This thesis adapts an electricity impact price of **0.14 €/kWh** as the base value, as done in other ORC studies [18]. The tolerance range is chosen to be 0.18 €/kWh in the best-case scenario and 0.10 €/kWh in the worst case. In this situation, a higher import price can be directly related to a higher potential of saving money, therefore a higher price is given a positive conjugation.

The export price is the value for which the ORC-produced energy can be sold to the market. This value is typically smaller than the import price. From the literature it can be analysed that this parameter usually sits in the range between 0.06 and 0.10 €/kWh [37]. This is exactly the range chosen in this study for future calculations. The base value is at **0.08 €/kWh**. Here, a higher value is given a positive conjugation.

The next value to be defined is the price escalation for imports. This value is the percentage increase that the electricity price will change year by year. It is important to consider this value, as the project lifetime spans over 20 years. It would not be realistic to assume constant staying electricity prices. The past has demonstrated that the imported electricity prices are rising. Literature suggests that a long-term increase of 2 to 4% per year for the European market is a realistic value [38]. The conservative and optimist values are chosen accordingly, and the base value is set at a growth of **3 %/year**, over the project timeframe of 20 years.

The sold electricity prices have historically risen slower than the imported ones. The literature suggests an increase of **1.5 %/year** [37], [38]. This value is adopted for this study, with optimistic values at 3% and pessimistic at 1%.

The last parameter to be defined is the share of self-consumption. This parameter determines how much generated ORC electricity is used internally and how much is sold to the grid. As the self-consumed electricity saves the full import price this has the highest economic value. Exported electricity to the grid only earns the export price, leading to lower economic value. In both the glass and cement sector electricity is consumed in large quantities. For example, in processes like melting, grinding, and kiln operation. This makes an elevated self-consumption share realistic. Also, the literature suggests a significant self-consumption share in energy-

intensive industries dominates the ORC business case [18]. For this thesis a base value of **95%** is assumed with uncertainty between 85 and 100%.

3.3.4 Summary Table for Both Plants

The adopted variables for this thesis are provided in Table 9. As the only differences between cement and glass lie in the values of the Specific CAPEX and Operating Hours, the values are found to be in the same table.

Table 9. Summary of operational and financial parameters used to determine the potential for the installation of an ORC-turbine in the cement and glass industry.

Variable	Unit	Base	Best Case	Worst Case
Net System Size	kW	2000		
Operating Hours - Cement	h/a	7500	8000	7000
Operating Hours - Glas	h/a	7700	8200	7200
Project Lifetime	a	20		
Degradation Rate	%/a	2		
Specific CAPEX - Cement	€/ kW _{net}	2400	2000	3000
Specific CAPEX - Glas	€/ kW _{net}	2800	2200	3300
O&M	%/a	3	2	4
Discount Rate	%	8	6	12
Import Electricity price	€/kWh	0.14	0.18	0.10
Export Electricity price	€/kWh	0.08	0.10	0,06
Price Escalation import	%/a	3.00	4%	2%
Price Escalation export	%/a	1.50	3%	0.5%
Self- Consumption	%	95	100	85
Grid emission factor (EF)	tCO2/MWh	0.3		

3.4 Economic Performance Calculation and Results

This chapter explains how the given input parameters from Section 3.3 are turned into an economic performance calculation. First the cashflow structure is introduced and key performance economic indicators are presented. In the second step the goal is to arrive at an estimation of the Payback Period, Net Present Value, and Internal Rate of Return of the project. These values give information on the performance of the project and are essential to evaluate its success prior to the initial investment.

3.4.1 Cashflow model Structure and Economic Indicators

This sub-chapter gives a conceptual overview of the cashflow model structure. It explains what the cashflow model contains, how revenues and costs are computed and how discounting is

performed. This does not include any results or numbers but focusses on the architecture of the cashflow analysis.

The goal of the cashflow model is to quantify the economic performance of the two reference ORC installations on a yearly basis. The model follows a standard project-finance structure in which Year 0 entails the initial investment of the ORC turbine. Year 1 to 20 contain all the operational and economic cash flows. These contain the projected performance of each year and calculate the difference of earnings and spendings for each year individually, resulting in a cashflow value annually. For both reference plants, the same modelling logic is applied, only the differentiating technical parameters are altered accordingly.

Figure 8 represents the basic logic of the cashflow model and is explained in the following.

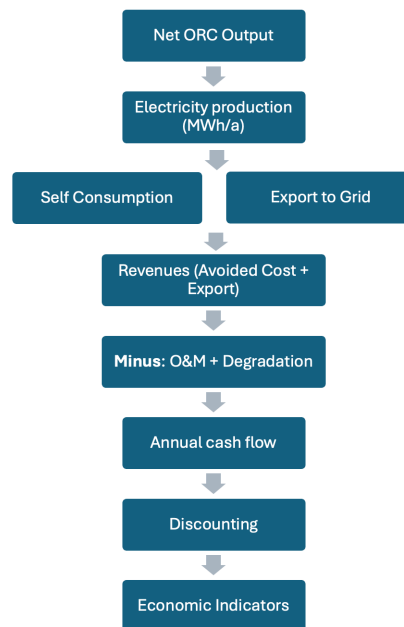


Figure 8. The logic of the cashflow model used to derive the economic indicators.

With the input parameters of the net ORC output and operating hours, the electricity production can be derived. In the next step the yearly revenues are calculated. They are derived individually for self-consumption and exported electricity. The revenue of self-consumption is made up by the avoided electricity purchase. The revenue from exported electricity is made up by the sale into the grid (Equation 3.3 and 3.4).

$$Rev_{self} = E_{ORC,self} - p_{import} \quad (3.3)$$

$$Rev_{export} = E_{ORC,export} - p_{export} \quad (3.4)$$

The annual cash flow can be derived by subtracting the Fixed O&M costs, which are calculated as a percentage of CAPEX, and subtracting the performance degradation, which reduces the annual electricity output by the degradation rate. This is done as in Equation 3.5.

$$CF_t = Rev_{self} + Rev_{self} - O\&M \quad (3.5)$$

The final step to perform is combining the individual cashflows and discount rate, defined in Section 3.3.2, to discount the cashflows of each year.

In the following, the economic key performance indicators of the investment can be derived. Starting with the Net Present Value (NPV) which is calculated as the sum of all discounted cashflows, minus the initial investment (CAPEX). In the case of the cement and glass reference plants the NPV is calculated for a 20-year reference frame, A positive NPV indicates that the discounted revenues exceed the discounted costs, leading to a created economic value over the project lifetime. The NPV is an important metric when estimating the long-term profitability of the project.

The simple payback period is determined by estimating the first year in which the cumulated cashflow, including the CAPEX, becomes a positive value. It ignores all cashflows after the break-even year and is therefore best interpreted as a risk indicator.

The Internal Rate of Return (IRR) is the third financial indicator used to evaluate the project. It is the discount rate for which the NPV equals zero. It can be seen as the evaluation of attractiveness of the project. If the IRR exceeds the discount rate, the project is economically valuable.

This workflow provides a basis for estimating the financial performance of the project, even before the investment is made. Deriving these indicators also allows for comparison between the cement and the glass plant at a later stage of this thesis (Section 3.6).

3.4.2 Results – Cement

This section presents the economic results for the reference cement plant using all base parameters previously defined in Section 3.3. The computations of payback period, NPV, IRR is performed with the methods explained in Section 3.4.1. The results are gathered in Table 10. Additionally, the initial total investment of the turbine (CAPEX) is presented. The full results of the full cashflow-analysis including all yearly revenue, cashflow and discounting operations is

found in Appendix B. It is to be noted that the value of payback period (years) is given as a decimal.

Table 10. Economic metrics describing the cement ORC-installation.

Indicator	Value (base)	Unit
Payback period	2.958	years
NPV	14,871,177	€
IRR	39.86	%
Total CAPEX	4,800,000	€

Table 10 summarizes the main economic indicators for the cement plant, in the base-case condition. The payback period is 2.96 years, and the Net Present Value of the 20-year project lies at 14.87 million euro, considering the 8% discount rate. The internal rate of return of the project is 39.86%, and the initial total investment is at 4.8 million euros.

Figure 9 illustrates the cumulative cashflow trend for the cement plant. The curve crosses the zero line shortly before year 3, consistent with the calculated payback period. After reaching the break-even point, the cumulative cashflow increases steadily over the project lifetime as annual net cash inflows accumulate. The graph follows an asymptotical trendline and reaches a maximum value of almost 15 million euro in year 20, representing the previously calculated NPV value.

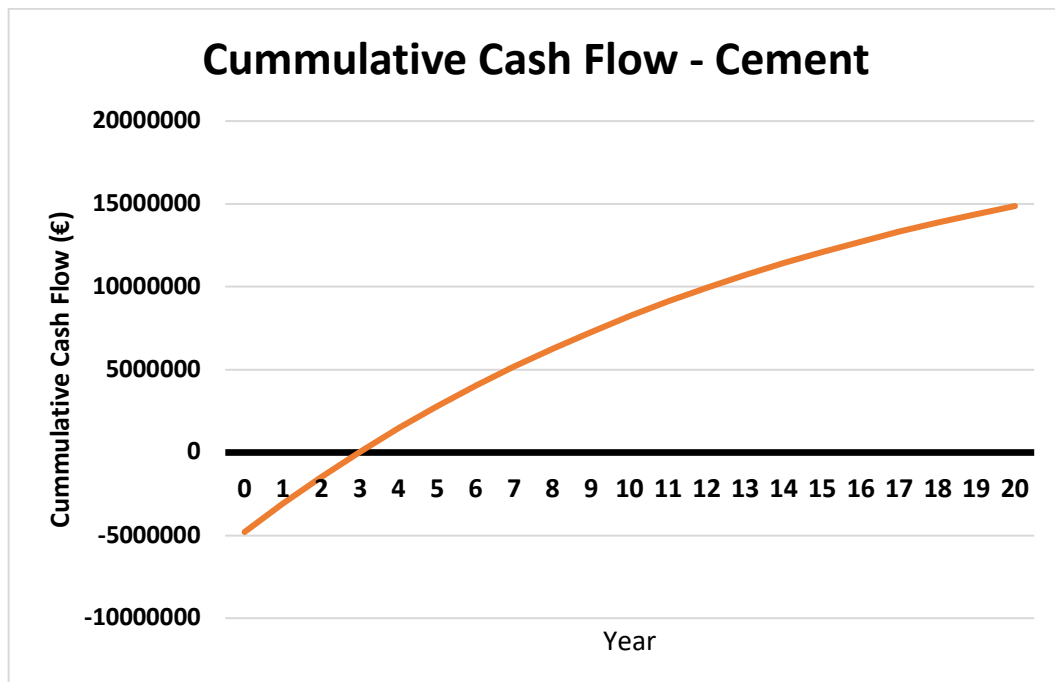


Figure 9. Cumulated cash flow over years of the cement installation, showing the break-even point.

3.4.3 Results – Glass

This section presents the economic results for the reference glass plant using all base parameters previously defined in Section 3.3. The computations of payback period, NPV, IRR is performed with the methods explained in Section 3.4.1. All the results are gathered in Table 11. Additionally, the initial total investment of the turbine (CAPEX) is presented. The full results of the full cashflow-analysis including all yearly revenue, cashflow and discounting operations is found in Appendix B. It is to be noted that the value of payback period (years) is given as a decimal.

Table 11. Economic metrics describing the glass ORC-installation.

Indicator	Value (base)	Unit
Payback period	3.458	years
NPV	14,397,807	€
IRR	34.79	%
Total CAPEX	5,600,000	€

The key economic indicators for the glass plants are reported in Table 11. The base-case payback period is at 3.458 years and the discounted cashflow over the full time of 20 years adds up to a NPV of 14.40 million €. The internal rate of return is 34.8%, and the required investment cost (CAPEX) is at 5.6 million euro.

The cumulated cash flow of all 20 years, including the initial investment, can be used to visually represent the payback of the project.

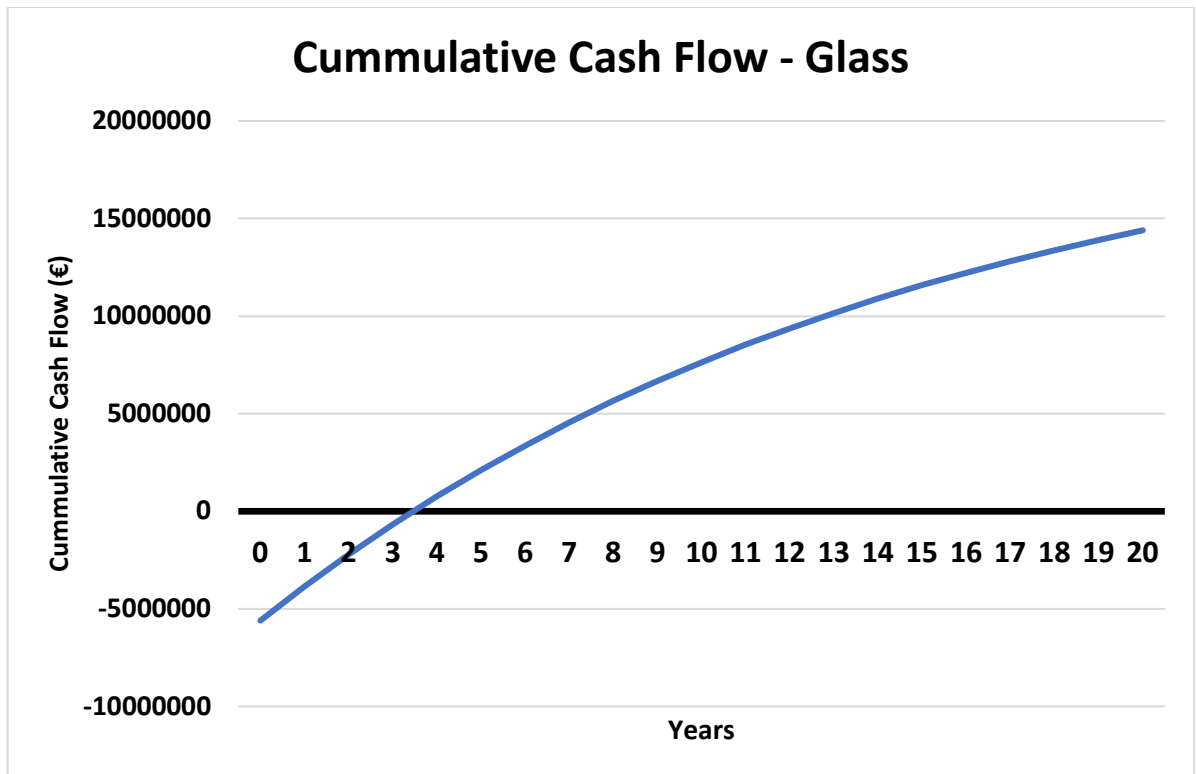


Figure 10. Cumulated cash flow over years of the glass installation, revealing the break-even point.

Figure 10 provides the cumulative cashflow progression for the base case in the 20-year lifetime of the project. It becomes visible, that the cumulative cashflow curve turns positive in the middle of year 3 and year 4. This corresponds to the previously calculated payback period. After this break-even point, the cumulated cashflow keeps steadily increasing. The graph follows a slightly asymptotic trend, with a continuous positive, but decreasing slope. At year 20 the cumulated cashflow sits at approximate 14.5 million euro, corresponding to the net present value of this project.

3.4.4 Results - CO₂ Reduction Cement and Glass Plant

This section quantifies the plant-level CO₂ savings connected to the ORC electricity generation for both the cement and the glass industry. The calculation approach is the same as defined in Section 2.4, where national emission factors were calculated. Formula 2.7 which is used to derive the net CO₂ savings was also defined in this chapter and is the basis for the calculation of avoided emissions here. Considered is the amount of CO₂ that can be avoided because of fossil fuel intensive electricity production. Not considered is the CO₂ emissions emitted by the production of the ORC device or the installation. The grid emission factor (tCO₂/MWh) is chosen

conservatively and therefore is set to the one of Italy for both plants 0.30 (tCO₂/MWh), since this value is lower than the one of Germany. The value is taken from Table 9.

The emission reduction tCO₂ of each year varies with the net electricity production. Because of the previously defined degradation rate which the ORC device undergoes each year. This is due to corrosion and degradation effects (2%/a). A change in the EF value because of reduced CO₂ levels in the electricity mix is not considered in this process. The values of the annual emission reduction for the cement plant are depicted in Figure 11.

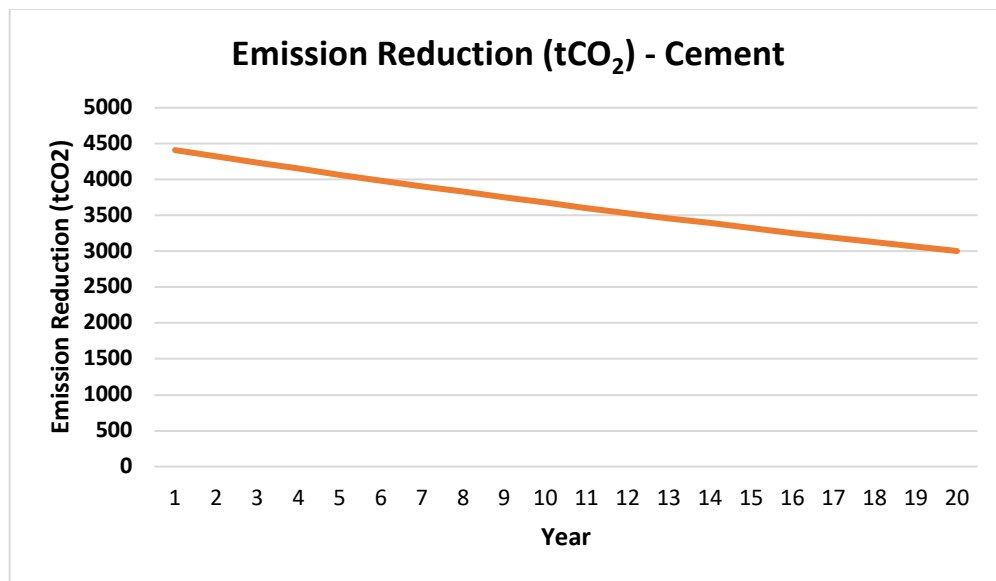


Figure 11. Emission reduction each year by the ORC installation in a cement plant.

The yearly CO₂ savings for the cement plant reveal a slight decline year by year, explained mostly by the degradation rate of the ORC device (2%/a). It should be considered that the implementation of a degradation rate of 2%/a is a conservative approach. The effect is strongest in the early years, decreasing in the following ones. Despite the decline, the yearly CO₂ savings remain significant throughout the whole project scope. In the beginning of the project the savings are at almost 4500 tCO₂ and at the end at around 3000 tCO₂. Throughout the 20-year project-lifetime, the installation of the ORC plant can save a total of 73,292 tCO₂. The full data can be found in Appendix B.

In the following the emission reduction graph for the glass plant is presented (Figure 12).

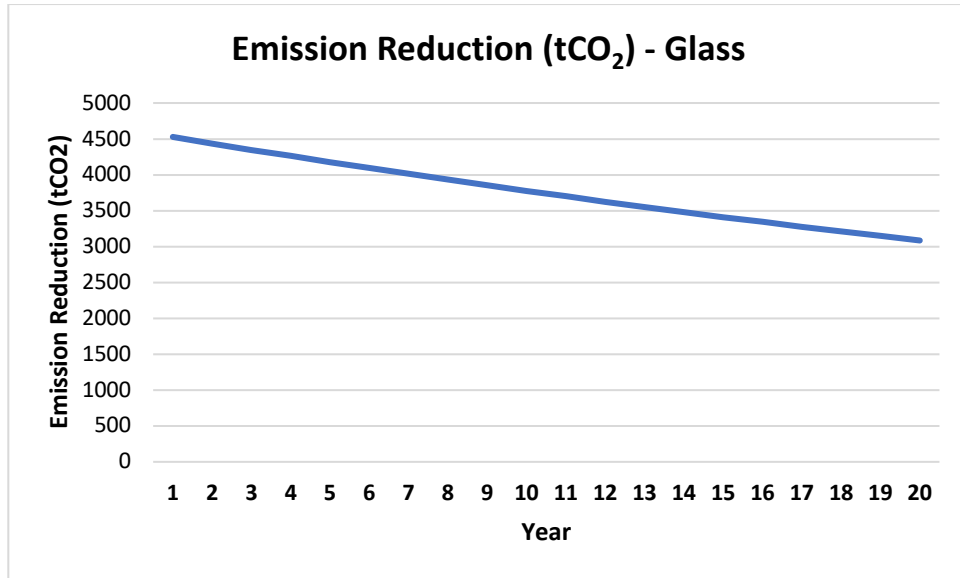


Figure 12. Emission reduction each year by the ORC installation in a glass plant.

For the glass reference plant, the annual CO₂ reduction follows a similar pattern. Starting off with the highest savings in the first year and then a gradual decrease over the following years, yet with a significant carbon-saving value in each year. Comparing to cement, the annual carbon savings are slightly higher year by year. Starting at an initial value of above 4500 tCO₂ and finishing in year 20 at a value that stays above 3000 tCO₂. Cumulated a total of 75,247 tons of carbon-dioxide can be saved by implementing the ORC, which is 2000 tons more than in the cement plant. The full data also for the glass plant can be found in Appendix B.

3.5 Sensitivity and Uncertainty Analysis

This section evaluates how the previously defined uncertainties in the key technical, financial, and market parameters influence the economic performance of the two representative plants. A Tornado Analysis and a Monte-Carlo simulation are each performed to quantify the reliability of the previously derived base values of payback period and NPV.

3.5.1 Tornado Analysis - Methods and Results

The Tornado Analysis evaluates how variations in individual parameters affect the combined outcome. In the case of the cement and glass plant it is analysed how the previously defined sensitivity parameters (Table 9) alter the economic parameters payback period and NPV. This method is also referred to as one-at-a-time sensitivity, since each parameter from Section 3.3 is verified independently between its best-case and worst-case values, while the other values remain fixed at their base. The relative change of the observed financial metric to its base value for each

parameter change (to worst or best case) is recorded in a bar diagram. The goal of this analysis is to attain information on the magnitude of influence each parameter has on the metric. This allows for a comparison between individual parameters. Largest changes from the base value identify the most influential parameters, while ones with marginal change represent limited influence.

The analysis is performed for two different output metrics, the payback period and the NPV. These two parameters are analysed since they represent two different time scopes. The payback period focuses on parameters which effect the cost calculations on the short term (3 to 5 years), while the NPV analysis focuses the long-term influence (20 years) of the parameters. The parameters tested include CAPEX, electricity import price, electricity export price, O&M, discount rate, annual operating hours, self-consumption share, and the price escalation rates. For each plant a different tornado diagram is generated. The values used in the sensitivity analysis are found in Section 3.3.4.

In the case of the cement ORC-installation payback period (Figure 13), which is the first to be performed it can be observed that the largest variation exists for the import electricity price. Highest import prices increase the payback period by approximately 1.47 years, and lower import prices reduce it by -0.73 years. This means directly, that setting the import price parameters to the minimum and maximum values, leads to the largest change of all parameters analysed. The second largest influential parameter is the CAPEX which could potentially shift back the payback period by 0.93 years. Operating Hours, Discount Rate and Self Consumption indicate moderate effects which lie between +0.26 and +0.17 in the worst case and between -0.21 and -0.07 the best case. Parameters O&M, Export price, and both price escalation parameters reveal only minor changes (< 0.1) in the payback period.

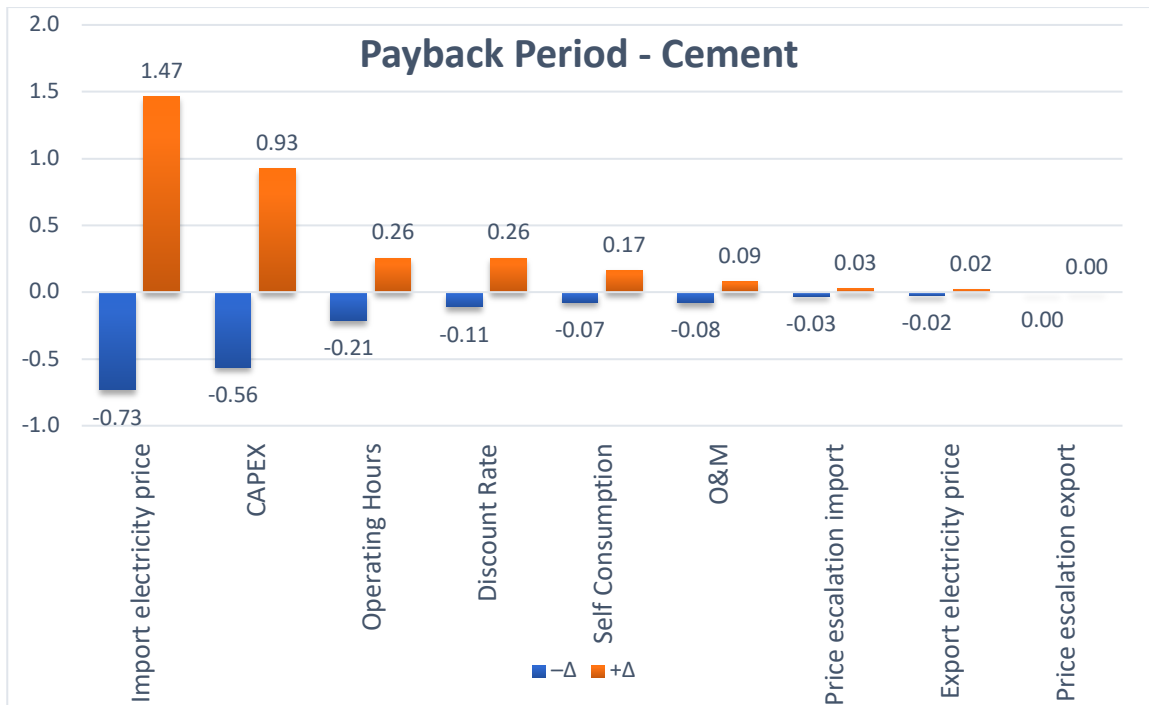


Figure 13. Tornado analysis for the payback period in the cement plant highlighting the most influential factors.

For the NPV-tornado chart in cement reference plant (Figure 14), which is the second analysis to perform, the largest relative change can be observed for the import price. Adapting the best or worst case causes a symmetrical change (± 6.31 million €). The discount rate is the second most influential parameter of the 20-year long lasting project, shifting the NPV by 3.75 and -5.28 M€. The parameters Price Escalation Import, Operating Hours and CAPEX have a mid-range influence on the projects NPV, which cause changes between approximately 2.9 and 1 million €. Self-Consumption and O&M cause smaller but still visible variations between 1 million and 200 thousand €. Almost no impact on the 20-year-project NPV has the Export Price and the Price Escalation of exports.

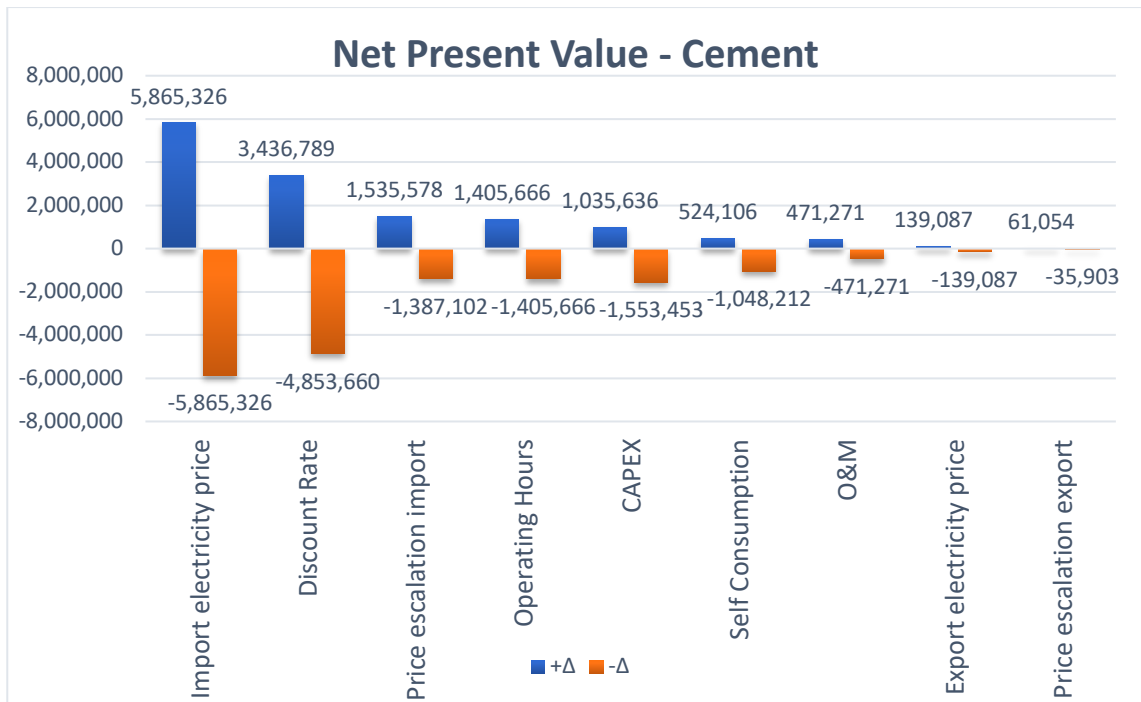


Figure 14. Tornado analysis for net present value in the cement reference plant revealing the most influential factors.

For the glass payback period sensitivity-analysis, similar results as the ones of the cement plant can be seen (Figure 15). The import price is once again the dominant driver of payback variation. Leading to even larger changes than in this parameter. The value here lies at -0.87 and + 1.78 years. As the base value of payback period is at 3.46 years, this could in situation of worst case, lead to a 51% increase of payback period and is therefore the most critical parameter. The variation of the CAPEX (initial investment) has the second most influence on the payback period leading to a change of +0,78 and -0.87 years respectively. The Discount Rate and Operating Hours suggest moderate changes in the order of magnitude of ± 0.3 years. The Self-Consumption, O&M, and price escalation of the import price cause rather small shifts (<0.2 years). The Export price and export price escalation factors have negligible impact on the payback period.

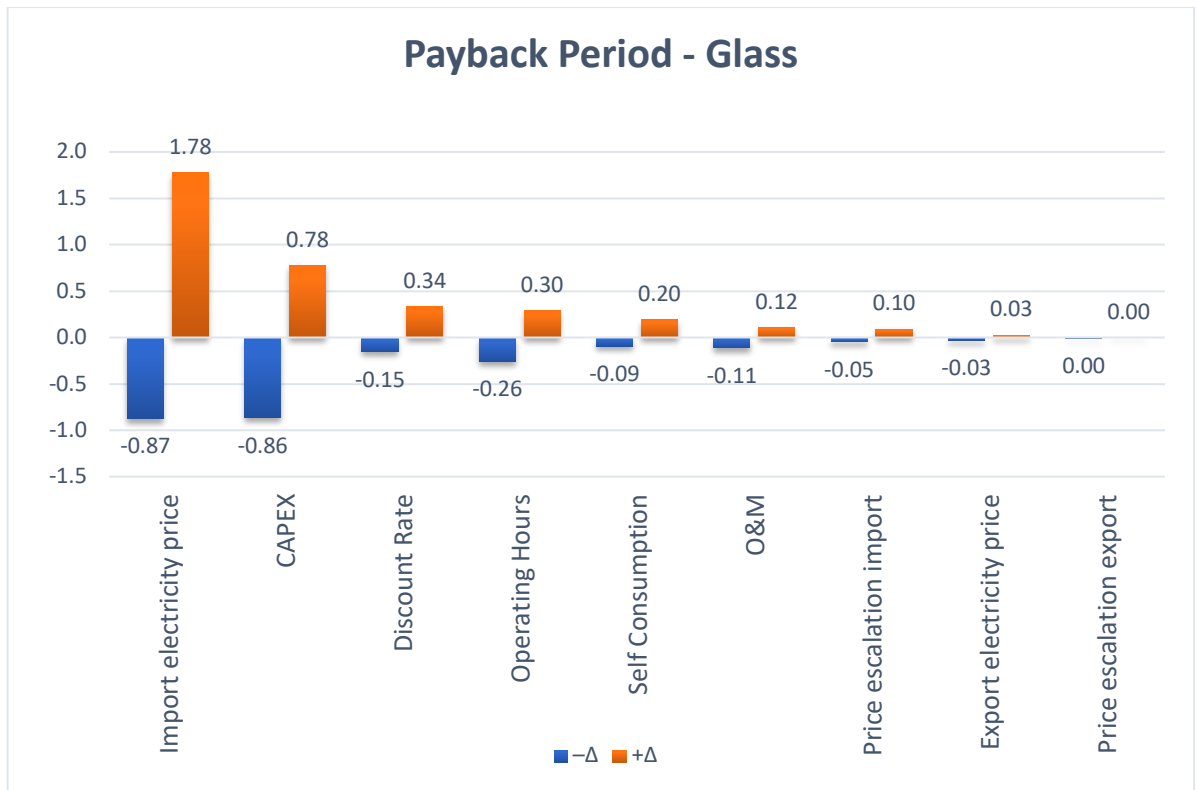


Figure 15. Tornado analysis for the payback period in the glass reference plant highlighting the most influential factors.

The final tornado one-at-a-time analysis regards the NPV of glass plants (Figure 16). Here also a strongly similar trend as in the case of the cement plants can be seen with the import price being the most influential parameter, leading to a symmetrical increase and decrease of around ± 6 million €. With a baseline NPV of 14.4 million € this is parameter alone can change the 20-year project value by 41%. The second largest parameter influencing the NPV is in orders of magnitude of the discount rate. The influence here is at +3.5M and – 4.9M€ respectively. Price escalation of import price, Operating Hours, and CAPEX generate mid-range changes (approximately 1.3 and 2.7 million €). The parameters Self-Consumption and O&M cause smaller but still noticeable effects of the NPV value. The range for these parameters goes from 1 million to 0.5 million euros. The Export Price and Export Price Escalation have the smallest influence (<0.15 million €).

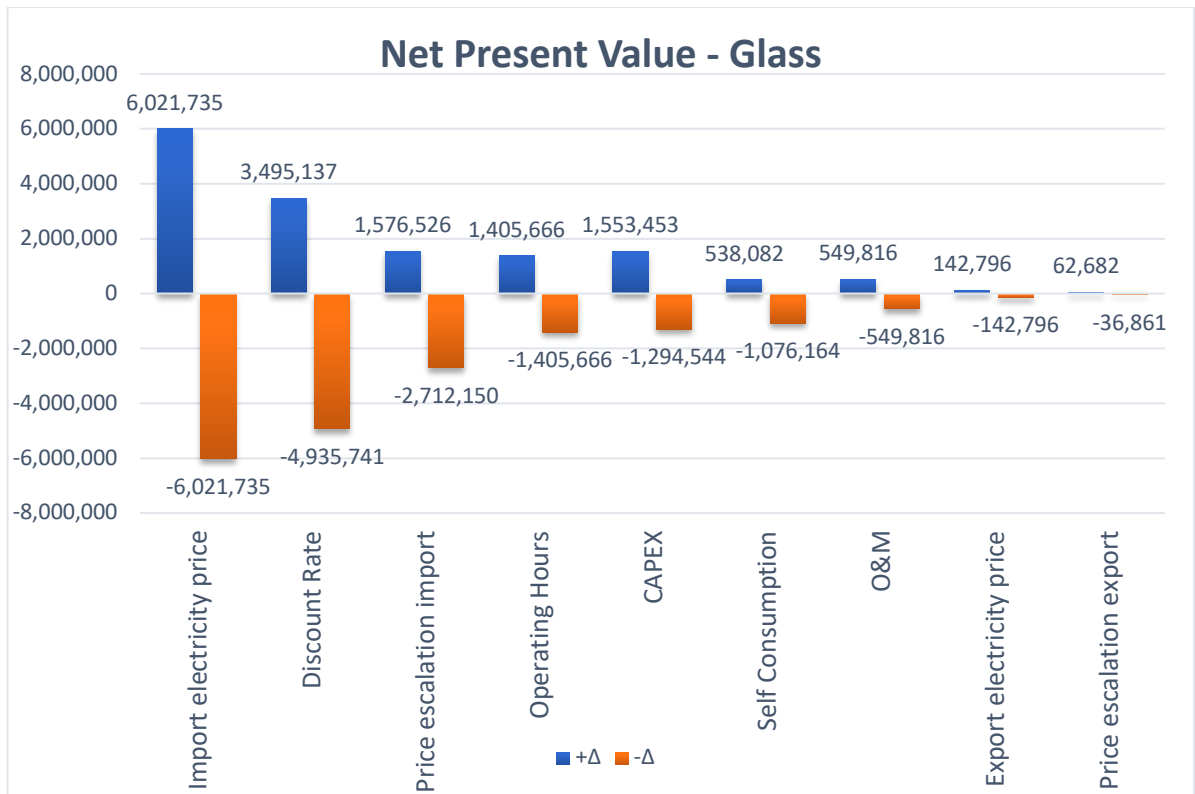


Figure 16. Tornado analysis for the net present value in the glass reference plant showing the most influential factors.

3.5.2 Monte-Carlo Setup

By performing a tornado one-at-a-time analysis of each parameter it was possible to determine the magnitude of influence each variable has on the NPV and on the payback period individually. The Monte-Carlo simulation performed in a second step focusses on the payback period, since this parameter is the most crucial parameter for decision makers, when deciding to perform or not perform the project on a short term. A Monte-Carlo simulation is carried out to assess the uncertainty of outcome by altering all the parameters simultaneously. But different from the tornado analysis, the values in the Monte-Carlo simulation can adapt any of the values between the best and worst case, which are defined in Table 9 in Section 3.3. For this thesis the Monte-Carlo simulation is performed for both the cement and the glass plant with focussing on the payback period, as this metric is the key decision criteria when it comes to investment feasibility for the firm. The Monte-Carlo analysis can quantify the combined effects of all the parameter uncertainties and allows for the investing party to assess the variation ranges the project can take under realistic circumstances.

The Monte-Carlo simulation is performed in multiple iterations. Each iteration randomly creates a set of parameter values that lay between their best- and worst-case values. The model performed for this thesis undergoes 2,000 iterations, which provide a sufficiently large sample size for stable statistical evaluation, while keeping the computational demand moderate. Each of the iterations computes the payback period with the randomized mix of input parameters individually, to attain a distribution of results.

The values of the input parameters are chosen randomly but inside a triangular distribution. The triangular distribution is a simple probabilistic distribution. It can be defined when only limited information about a variable is available. It is defined by the minimum, maximum and most likely (base) value. The probability of choosing a value increases linearly from the minimum to the base value and decreases again towards the maximum, forming a triangular shape. This means, values closer to center are more probable to be chosen. This is a realistic assumption made for the Monte-Carlo simulation for ORC applications.

The parameters for which random values are created are the following: Electricity Import Price, Electricity Export Price, Discount Rate, CAPEX, Operating Hours, Self-Consumption share, O&M, and the Price escalation factors (Import/Export).

The Monte-Carlo simulation creates a distribution of the payback period which describes the range of all outcomes under the above conditions. The distribution can be used in a second step to attain the following metrics: Mean payback period, standard deviation, 5th percentile (optimistic boundary), 95th percentile (conservative boundary).

3.5.3 Monte-Carlo Results

The results of the Monte-Carlo simulation (Figure 17) reveal the simulated payback period which form a bell-shaped distribution with the center laying at the 3-year range. The histogram is relatively symmetrical, but with a small tendency to the right (elevated payback period). The lowest value archived in the 2000 iterations sits at around 1.9 years and the largest value stretches up to 6 years.

Diving deeper into the metrics that can be attained from the histogram (Table 12) a calculated mean payback period of 3.25 years can be observed. The previously estimated payback period in the best case (Section 3.3. Table 10) is at 2.96 years. The 0.3-year offset between the estimated mean and the initial base value, can be explained by the asymmetrical lower and upper bounds chosen for the uncertainty. In this case, upper limits tend to reach out further than lower limits causing the mean value to shift to the right. The standard deviation sits at around 0.6 years, indicating limited dispersion around the mean. The 5th percentile is at 2.41 years and the 95th

percentile is at 4.34 years, meaning that 90 percent of all simulated results fall into the range between these values. No severe outliers exist. Overall, the distribution is tight and stable, suggesting that the cement case shows moderate uncertainty and rather clustered outcomes.

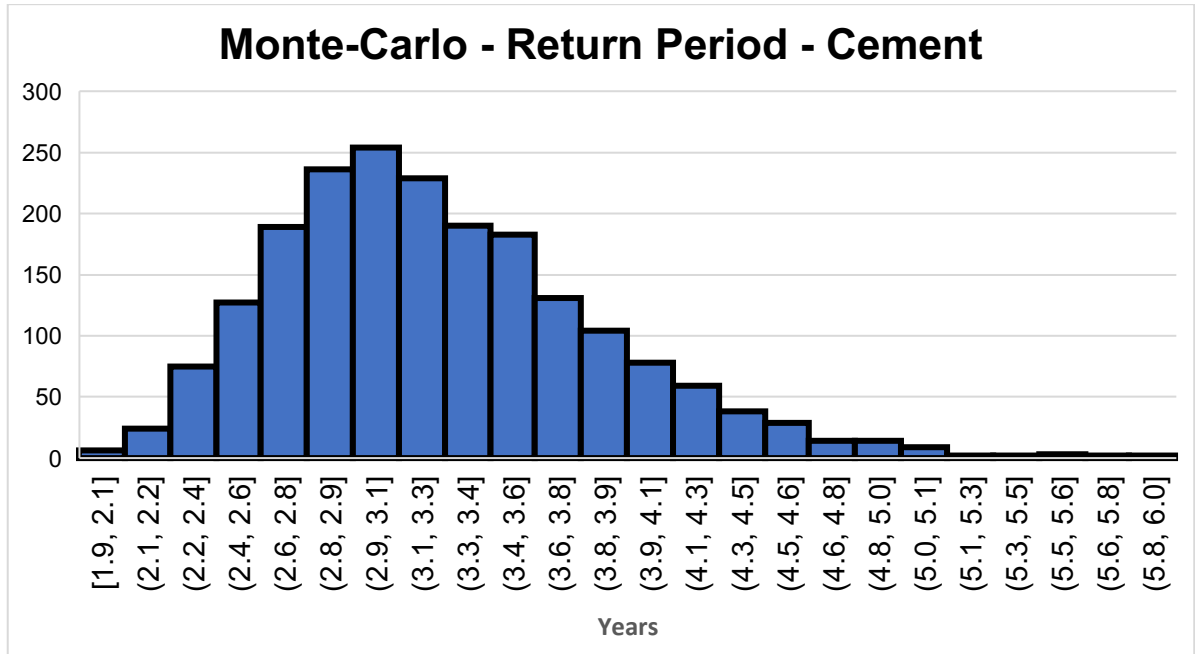


Figure 17. Monte-Carlo simulation for the return period of the ORC-installation in the cement plant.

Table 12. Metrics to derive from the Monte-Carlo payback calculation – cement.

Mean	Standard. Dev.	5 th percentile	95 th percentile
3.249	0.599	2.405	4.341

The glass plant Monte-Carlo simulation (Figure 18) reveals similar results as the cement one. Also, here a bell-shaped distribution can be observed, with the center shifted slightly to the right. Under the used parameter conditions, also here a slightly right-tendency in the distribution can be observed, indicating possible longer payback outcomes.

The spread of the glass plant distribution is slightly higher compared to the one of cement. There are some further-outreaching outliers up to a value of 7.4 years. This can be confirmed when checking the metrics that go along with the histogram (Table 13). The standard deviation is at 0.72 years, indicating this larger spread compared to the cement case. The mean value lays at 3.64 years, which is only slightly larger than the previously derived base value of 3.46 years payback (Table 11) for this case.

The 5th percentile is located at around 2.65 years and the 95th one is at 4.98 years. This shows that right tail extends further out than the one of cement, indicating a higher sensitivity to the uncertainty parameters.

Overall, both distributions indicate a clear concentration in the range of 2 to 5 years payback, but the glass plant entails a slightly larger dispersion. The cement plant has a slightly narrower spread and a mean value that lays below the one of glass.

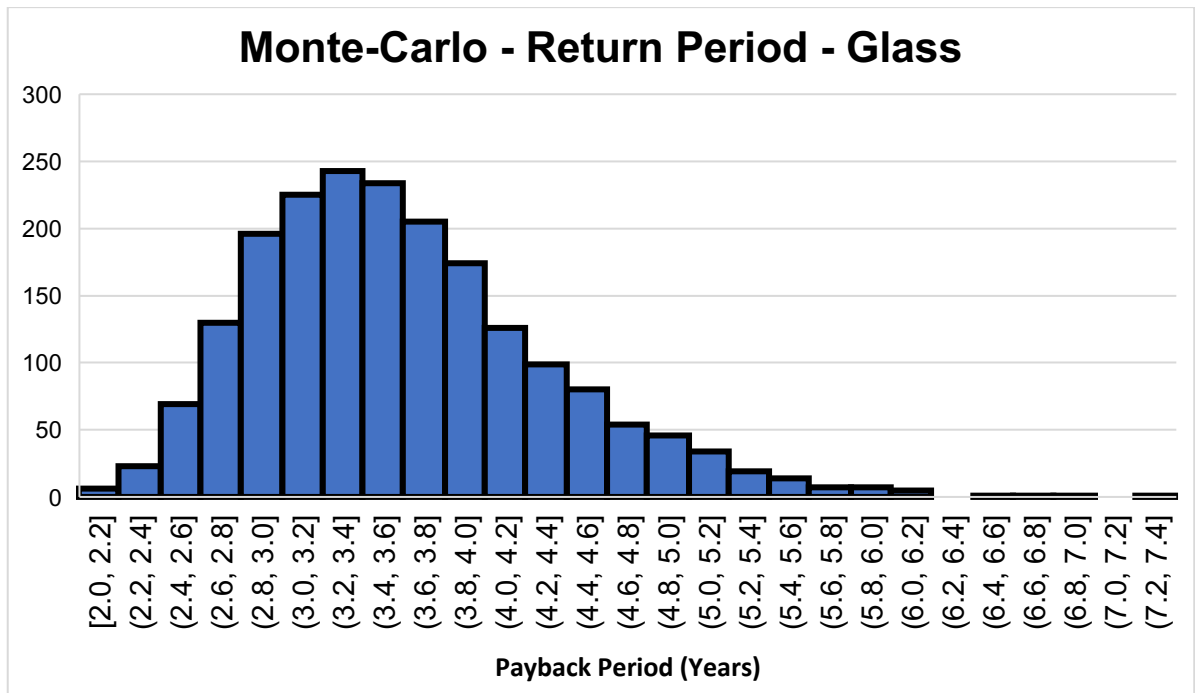


Figure 18. Monte-Carlo simulation for the return period of the ORC-installation in the glass plant.

Table 13. Metrics to derive from the Monte-Carlo payback calculation – glass.

Mean	Standard. Dev.	5 th percentile	95 th percentile
3.635	0.721	2.650	4.985

3.6 Interpretation of Stage 2 Findings

With the given results it is now possible to conclude and interpret the findings of stage two. The first interpretation to perform is the one of overall economic attractiveness of installing the ORC-turbine in the given settings. Both reference plants reveal pronounced economic performance. Payback periods and net present values find themselves in similar magnitude for the two reference plant installation, with the mean performance of the cement case to be estimated marginally better. Projects with payback periods which lay at around 3 years are financially

attractive to be carried out in the modern economy. The projects both entail net present values from 14 to 15 million €, which is exceptionally high relative to the initial CAPEX of 5 million €. The IRR are accordingly high between 30 and 40%, again confirming the financial attractiveness of the ORC. It should equally be considered that the assumptions made, also for the base values, are rather conservative than optimistic in this study.

Comparing the two installations and finding the advantages of the cement plant, it becomes visible that cement plants show slightly faster payback. This can be explained by the lower CAPEX/kw. Equally the cement plant performs slightly better in the uncertainty analysis, especially the Monte-Carlo simulation. With more stable operating conditions the spread of payback period is lower than in the case of glass. The explanation for this could lay in the more robust output that was analysed already in Stage 1. The cement plant uses lower temperature but at the same time constant flows of off heat.

The advantages of installing the ORC in the glass plant include higher specific electric yields, which were already observed in Stage 1. Together with the slightly longer operating hours and despite the same 2 MW ORC plant, the glass plant can save up slightly more carbon dioxide than the cement one. It generates a solid cashflow, but the higher CAPEX leads to a slightly later payback than in the case of cement. The uncertainty analysis finds a wider distribution of outcomes for the glass plant, highlighting that glass ORC-projects are slightly more sensitive to variations in the market parameters.

The Tornado Analysis reveals that across both plants the same dominant drivers are found. The most important one is the import electricity price, which indicates the highest impact for both payback and NPV. The variation in discount rate is the factor that specially in the long term (NPV) causes a major impact. The initial investment (CAPEX) is the factor that has major impact on short-term evaluation of the project (payback period). The third most dominant and influential factor are the operating hours, demonstrating how important the constant usage of the ORC is. Less relevant factors for the ORC are export prices and export price escalation. This underlines the statement that ORC value is driven by self-consumption and not by selling electricity.

Analysing the Monte-Carlo results in detail in the case of cement a mean payback of 3.25 years and a narrow distribution of ± 0.6 years (standard deviation) can be achieved. Only a 5% chance was found that the payback exceeds the value of 4.3 years. With no extreme outliers this result suggests the high robustness of installing an ORC-turbine inside a cement plant under the given conditions.

For the glass plant the mean payback, also analysed earlier is at 3.64 years. With a wider spread of ± 0.72 years (standard deviation) and a longer right tail that extends up to 7.4 years the investment risk margin here is to be found larger than in the cement plant. Still 90% of outcomes lie between 2.65 and 4.98 years, which represents a highly relevant business case.

Both plants can individually save between 3,000 and 4,500t CO₂ each year, contributing meaningfully to decarbonization, and this under rather conservative assumptions, considering that Germany's higher grid intensity would benefit the CO₂ savings even larger, compared to the one of Italy, which was used here. Over the 20-year total project lifespan, the cement plant can save 73,000 tons CO₂ and the one of the glass plants up to 75,000 tons CO₂.

While stage 1 demonstrates high national technical potential, stage 2 suggests high economic relevance of installing an ORC plant for off heat created by both the glass and cement plant. Combining the two results it is implied that there exists a large unused economic opportunity which is the case for both Germany and Italy. The limiting factor does not lie in the financials of the project but could rather be linked to awareness of the technology and resource allocations (investment decisions). The uncertainty analysis indicates that for both plants a low-risk situation exists, meaning that decision makers can plan with high returns when performing an installation of such an ORC-plant under the given parameters. As analysed earlier, the most sensitive parameter is the electricity price. As the trend of this parameter is unknown for the coming years, the ORC is a relevant method for industry decision makers to hedge against this price volatility. When comparing the plant-level findings to the literature it becomes visible that that for older studies the attained results in this thesis lay at the lower range of reported values, where payback periods range between 3 and 6 years [4], [5], [31]. More recent case studies in the cement and glass industry find paybacks between 2.7 and 4 years to be a realistic timeframe [10], [18], [26], which is in strong alignment with the attained data presented here. This downward trend can be explained by specific CAPEX values dropping in dynamics like economies of scale and improvement of the technology. This study confirms this improvement trend over the past years.

4 Co-Benefits of ORC Deployment

Up to this point of the ORC analysis two major beneficial aspects have been highlighted. The first one regards the possibility of monetizing off heat, through electricity generation. The second benefit lays in the CO₂ saving which equally results from the electricity generation, as it does not need to be generated by fossil heavy production methods.

This section focuses on three additional benefits, which come with the installation of the ORC devices. The first aspect deals with baseload and energy-system stability. The second aspect introduces the usage of carbon credits, and the third aspect introduces potential labour opportunities for large scale ORC deployment. These benefits partly reach further than common installation arguments and become especially meaningful on a macro scale.

4.1 Baseload & Energy-System Stability

The first co-benefit of implementing an ORC-turbine is the one of baseload and energy-system stability. The baseload describes the minimum continuous amount of power production required to maintain a stable grid. The baseload is an important factor in the case of transition to renewable energy sources, as the variability of the commonly implemented technologies, solar and wind, entail high variability as they are dependent on weather conditions and sun availability. The benefit present in the ORC-turbine is a constant energy production, which is independent of external conditions. This can help to substitute carbon intensive energy production methods previously used to provide for a constant baseload.

In this section an overview of the current situation is provided to depict the potential of ORC implementation. To archive this the full energy production of the week 07. – 13. July 2025 is analysed in Germany. July is a month of significant solar output with strong daily variability and therefore an optimal exemplary timeframe to analyse the situation. This analysis depicts the fluctuation of renewable sources and gives an overview of the baseload.

The ENTSO-E Transparency platform [39] is used in this analysis to attain data of the energy mix. The platform holds information on the exact production (MW) of each energy source within a timespan of 15 minutes. Different countries possess different baseline conditions which make up unique electricity grid mixes in each country. For this analysis it is important to differentiate between fossil technologies and non-fossil technologies.

For this thesis the following energy sources are included to be fossil technologies: Brown coal/lignite, hard coal, coal derived gas, fossil gas, and fossil oil. The following technologies are

non-fossil: Geothermal, Hydro pump storage, hydro source, solar, waste, wind offshore and onshore and other renewables. Germany does not generate any energy with a nuclear source. Figure 19, directly taken from the Website of ENTSO-E Transparency [39] shows the stacked power generation pattern for the full week 07. – 13. July 2025 in Germany. In the graph the production variation through the 7 days can be seen. Each peak presents the midday, and each low point represents nighttime. The peak production lays at circa 60,000 MW and the low points are at around 30,000 MW. Each colour represents an individual production source. It becomes evident, that solar creates high midday peaks. Wind is also fluctuating but contributes a significant output share. The fossil components are represented by the lower band of the stacked graphic. This indicates, that even in a week of strong solar production, Germany still relies on a baseload, partly consisting of fossil related energy sources.

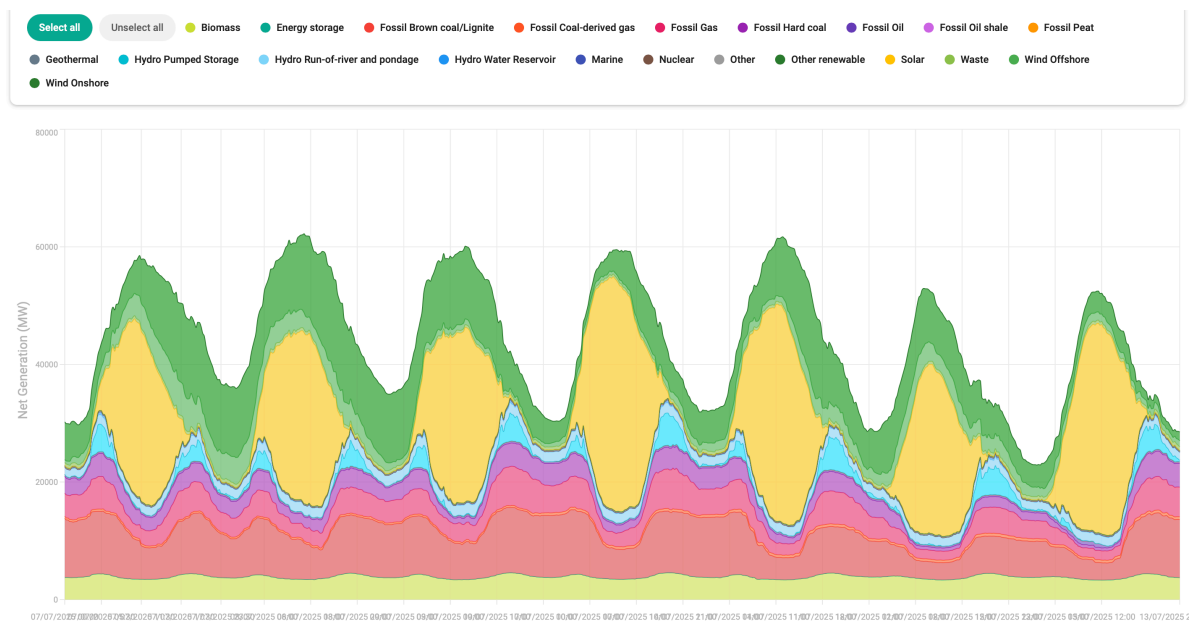


Figure 19. Total electricity generation by production type in Germany (07 to 13 July 2025) split up by source of energy, represented by different colours (Adapted from ENTSO-E Transparency Website [39]).

In the next step it makes sense to group the fossil and non-fossil related sources and directly compare them to identify the baseload. Figure 20, constructed with the data of the previous analysis, entails the grouping of fossil (grey) and non-fossil (green) related energy sources. It becomes evident that fossil generation appears to be more stable than non-fossil production over a 24-hour timespan, throughout the whole week. During the daytime the fossil generation drops down but never disappears.

From the graph it becomes evident that fossil generation forms a clearly visible night-time plateau. This plateau typically lays at around 20GW hours each night. The analysed plateau can be interpreted as the structural baseload dependency of the German power system. This is exactly the segment where ORC could replace some of the current fossil productions.

The non-fossil generation never drops down to zero, due to wind, biomass and hydro in the mix of renewable energy sources, which can be used also at nighttime. With the implementation of ORC-technologies the current visible 60% fossil and 40% non-fossil split at nighttime, can be improved towards an even more carbon neutral ratio.

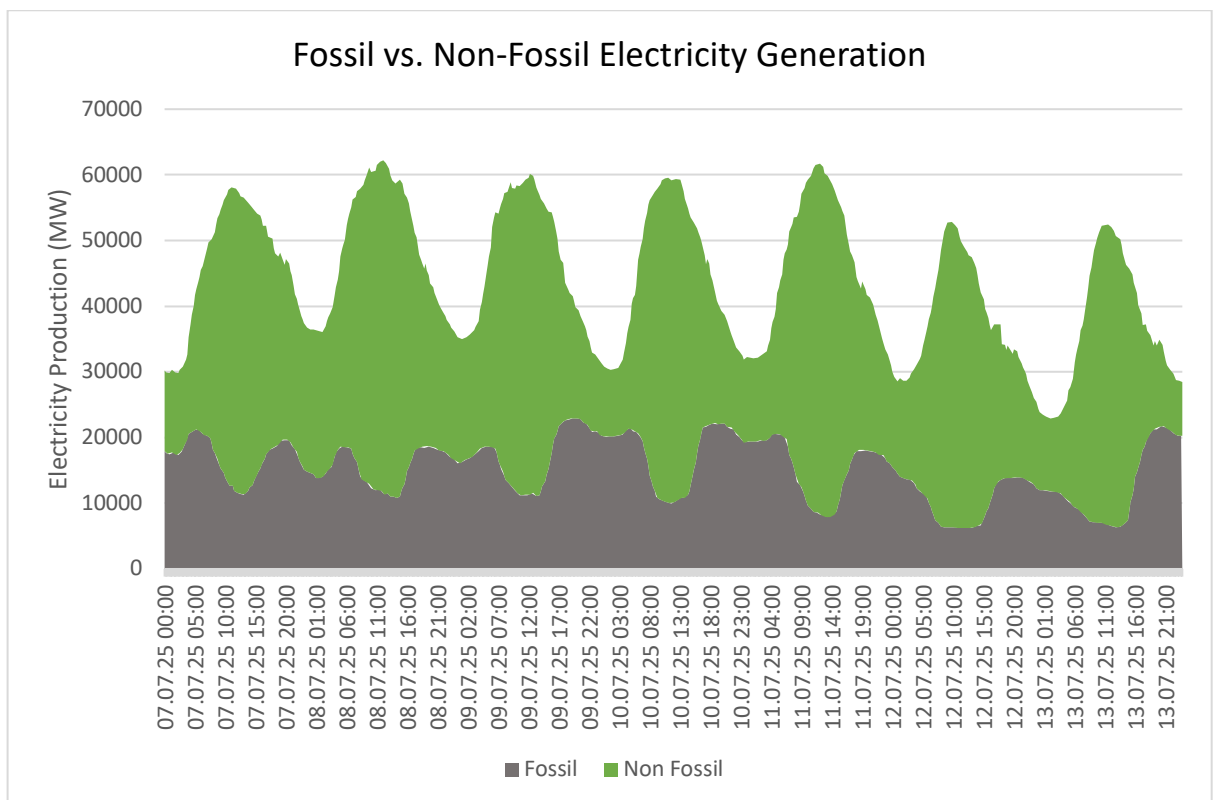


Figure 20. Fossil (grey) vs. non-Fossil (green) electricity generation, Germany (07–13 July 2025).

In a third step of analysis the parameter of residual load is introduced. This parameter describes the amount of non-fluctuating generation which is required in the grid, excluding wind and solar energy sources. The same data can be used to construct the residual load over the same time span, and it can be found in Figure 21. The curve suggests a stable nighttime production between 22 and 30 GW. During the day a dip is seen, due to the solar surplus. The evening shows a high increase of residual load, with values increasing from 17 GW to 30 GW. This steep ramp is seen thought all days in the observed timespan. It is caused by constant demand and drastic decrease

in supply of solar energy in the evening. In this period the residual demand rises drastically. These ramps are not avoidable if the system relies on solar energy.

As the ORC can replace part of the baseload, the fossil related energy plants would only need to ramp from a lower usage point. This can decrease the height of the ramp. Additional advantages lay in the diversification of the baseload. A diversified portfolio of sources decreases the risk of price peaks and shortcomings.

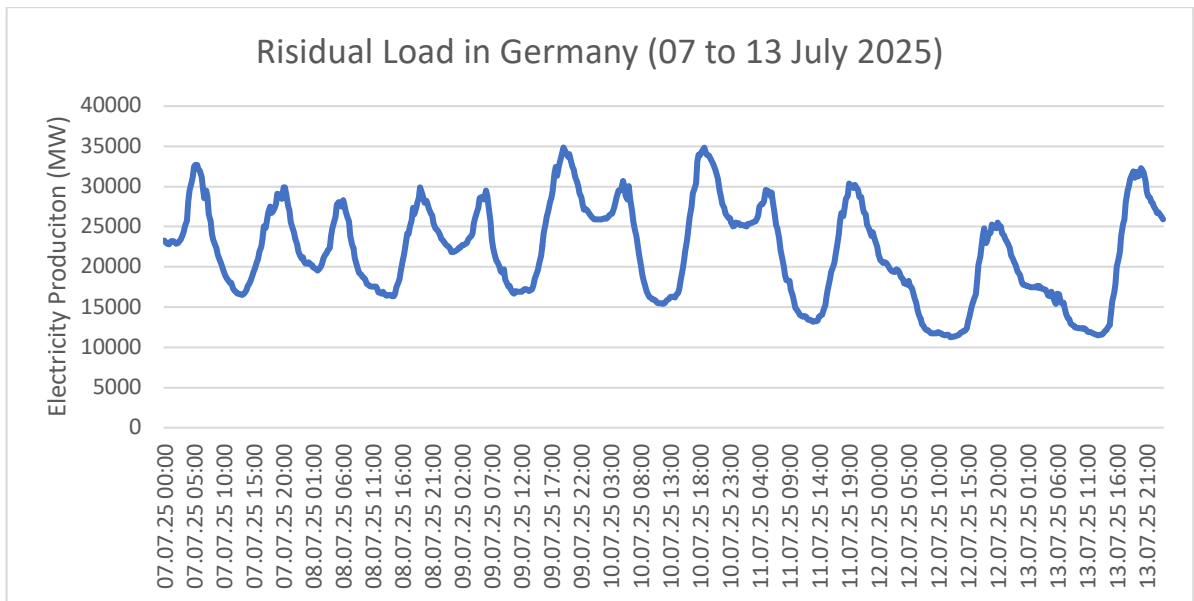


Figure 21. Residual load in Germany (07–13 July 2025).

This short analysis has shown that the ORC has a unique position in the field of energy supply. As analysed previously, ORCs generate power with constant availability (7000-8200 h/year). For this reason, they act as additional reliable baseload, that can substitute part of the fossil baseload, especially at night, without causing additional variability or ramping. As solar and wind energy will in the future have an even larger share of energy production, having a stable carbon neutral energy source becomes even more strategic on a national level.

4.2 Carbon Credits

Both the cement and glass sector belong to the fields where large amounts of emissions come from unavoidable high temperature processes [38]. The recovery of heat which would otherwise be wasted allows for electricity generation without adding additional natural resources and are therefore categorised to be carbon neutral. As this process is in the interest of society, it is possible to quantify the emission reduction in terms of financial benefits. The purpose of this

section is to describe how the CO₂ reduction can be evaluated through emission pricing mechanisms such as the EU ETS.

In Section 2.4.2 the grid emission factors were introduced. They are used for determining the amount of CO₂ that can be saved for every MWh produced with a carbon neutral technology. With the logic being that the grid electricity would otherwise come to a certain factor from fossil generation sources. Since the electricity grid composition varies between countries, the index is defined for every region differently. The value for Germany lays at 0.36 tCO₂/MWh [40] and for Italy at 0.30 tCO₂/MWh [41]. This calculation method is standard across all waste heat recovery and ORC literature [4], [16], [26]. With this baseline, in Section 3.4.4 it was calculated that for a typical 2MW ORC in the glass and cement industry, the CO₂ emissions avoided can be at around 4,000-5,000t per year.

In the EU Emission Trading System (ETS), every ton of CO₂ emitted must be covered by an emission allowance (EUA). Firms in the EU are under strict emission regulation and can receive a limited number of free allowance and can additionally buy more carbon allowance, if needed. As seen, a significant amount of CO₂ can be saved by implementing the ORC generator. This avoidance of carbon dioxide can be translated into cost avoidance, which reduces operational cost. If there is a surplus the additional carbon credits can be sold to the carbon market, which represents a real surplus. This demonstrates that ORCs do not just reduce emissions but also create a carbon related quantifiable monetary value. There is a market existing which trades carbon credits and therefore assigns them a quantifiable dynamic value [18], [42], [43].

The EUA prices have historically risen in the past year and are expected to rise even further in the future. Today a typical value for a carbon credit is 80€/tCO₂ [44]. For avoidance of 4,000 to 5,000 tCO₂/year as in the representative project, this makes for 320,000 to 400,000 €/year in carbon value. Over the 20-year lifespan, this is a gain of 6 to 8 million Euro for each of the two projects.

The literature consistently finds that carbon value increases the attractiveness of implementing a waste heat recovery method [8], [16], [26].

In earlier steps, where financial calculations were performed (Section 3.4), carbon credits have not been included. This is because the revenue is not universally guaranteed and can vary by country or even region. Part of the reasoning for this is that free CO₂ allocations can differ between regions and can also be shaped by political situations, which make comparability difficult. Additionally, the evolution of carbon credits in the next 20 years is still uncertain, making a precise estimation for such projects difficult.

4.3 Labour & Economic Development Opportunities

The third co-benefit of the ORC introduced in this thesis is the one of labour opportunities. The ORC deployment requires a large value chain, which requires the creation of jobs. These jobs lay in different sectors like research and development, manufacturing, transport and installation, and operation and maintenance.

The job creation can be found to occur both temporarily during the project rollout, but also permanently for ongoing engineering, operation, and service of installed ORC units. The manufacturing of ORC is an intensive undertaking, just as the installation requires skilled personal, which must be trained to have the capabilities of installing such technology. Deployment in large scale could, particularly in countries with large amounts of industrial waste heat like Italy, Germany, Poland, or France, stimulate regional peaks of industrial activity [18].

The CE Delft report [18] introduces two methods of estimating the job creation linked to ORC technology. The first one is directly linked to the CAPEX and OPEX spent by firms which implement such technology. In this first method a share of 5 and 15% of the CAPEX is directly assumed to be connected to ORC labour. 40 and 60% of OPEX are seen as labour expenditure. This method estimates labour opportunities directly along the full project lifecycle.

Applying these introduced estimates for previous financial estimations (Section 3.4), where the glass plant alone caused O&M costs of 170,000€ per year. A labour share of 40 to 60% lead to 70,000€ and 100,000€ per year in labour cost. At a wage of 70.000€ this would mean 1 to 1.4 full-time equivalent permanent jobs, from a single project alone, not even considering the 5M€ expenditure in CAPEX.

The second method introduced by the CE Delft report [18] focusses on temporary jobs. It is based on labour coefficients from fossil electricity generation, which can be seen as closest to ORCs. It entails the labour demand in previously named sectors: research and development, manufacturing, transport, and installation. It does not account for O&M as this aspect differs from fossil plants and is therefore not stretching throughout the whole process lifespan.

Applying these methods and assuming a large ORC rollout across the EU, with 19GWel across all industries the literature estimates a combined creation of 4,000 jobs on the lower bound and 41,000 jobs as the optimistic upper bound for the temporary work demand. The same study shows that permanently up to 10,000 workers could be required on a long term across the whole EU to archive this technology implementation. These roles are linked to monitoring, inspection, replacement of components, and technical support. Since the projects have long operational lifetimes from 20 to 25 years, these opportunities are set for long-term [18].

As seen, the ORC deployment strengthens Europe's industrial competitiveness as such job opportunities are largely created inside its borders. The job creation is spread across different skill levels. High skilled workers like engineers, thermodynamic specialists and software personal are required. Medium skilled workers are needed for mechanical work or welding. Low skilled workers take support roles and are required for transportation. The creation of such jobs helps regions to move human capital from fossil-intensive production to this clean technology. The ORC deployment aligns strongly with EU industrial plans, which support the manufacturing, and innovation in this technology.

5 Discussion

5.1 Integration of Stage 1 and Stage 2

This thesis performs a two-level analysis of the ORC industry in Germany and Italy. The first stage evaluates the national technical potential in a macro perspective. Stage 2 evaluates the micro perspective with the goal to evaluate the economic feasibility on an individual plant level. Therefore, both stages regard different but complementary questions. It is now possible to perform an integration of both perspectives to allow for the identification of the technical ORC-potential that can realistically be exploited.

Stage 1 quantifies the ORC waste heat potential in the cement and glass sectors. The results that are found in this stage demonstrate significant electricity generation potential in both Germany and Italy. Where the cement sector reveals lower specific yields but large absolute potential due to the high level of production leading to a potential up to 545 GWh/a in Germany. The glass sector on the other side shows higher specific power outputs, because of its higher exhaust temperatures with a potential electricity production up to 249 GWh/a in Germany. The amount of current ORC installations is generating much less energy than the estimated technical potential. In stage two the economic attractiveness of ORC installations for individual plants is quantified. Both the reference cases of a representative cement and glass case in Germany and Italy find strong economic performance with payback periods that lay out around three years, under base assumptions. With the help of a Monte-Carlo analysis the robustness of these results is underlined with a common range between 2 and 5 years. The net present value of these investments is strongly positive over a project lifetime of 20 years (from 14 to 15 Mio €) and the internal rates of return reach beyond typical thresholds of the industry (from 35 to 40%). A sensitivity analysis suggests that the most important factors which lead to profitable projects are the electricity prices, the CAPEX, and operating hours.

The combined findings of stage 1 and stage 2 suggests that large portions of the identified potential could also be financially exploitable under realistic industrial conditions. Therefore, the relatively low levels of current deployment in both sectors and industries are not explainable by primarily technological or economic limitations. Instead, the gap between potential and actual deployment may result from non-technical factors. Possible factors that prevent industry decision makers from performing such investment include limited awareness of the ORC technology in the industry. Equally the complexity of integrating such waste heat recovery system into existing industrial processes may be a factor when it comes to the decision making. Financially, such new

investments inside a company are competing against other investments with different priorities within different firms. This may lead to situations where a budget is chosen to be spent for alternative projects. Another factor that could possibly explain the deployment gap are long investment cycles in such heavy industry fields like cement and glass. Such large investments are agreed on long in advanced and take time until they are ready to operate. All these factors may slow down the ORC adoption, despite favourable economic conditions.

These findings carry a valuable implication for decision makers in the industry. The results demonstrates that ORC deployment is suitable for energy-intensive industries with continuous thermal processes such as cement or glass. The installation of an ORC can lead to reduced electricity purchase costs. This is a method to hedge against increasing electricity prices, as their future trends remains unknown and are expected to continue to increase. Equally it must be considered that ORC adoptions contribute to reaching emission reduction targets. As ORC systems provide continuous electricity generation based on existing industrial waste heat flows, it allows for emission reduction without changing the core production process. Therefore, ORCs represent a complementary decarbonization strategy alongside process innovation.

5.2 Comparison with Literature

A comparison of the literature and found results highlights the relevance of this thesis and briefly emphasize the plausibility of the findings from Stage 1 and Stage 2. By comparing the previously performed studies in the literature with the results in this work, the scientific importance and contribution of this study is depicted and can be elaborated on.

Several studies have previously investigated the technical potential of Organic Rankine Cycle systems for industrial waste heat recovery. In these studies, specifically heat intensive industries like the cement and steel industry have been identified as ones with high potential. Campana et al. [4] provide an estimation of the heat recovery potential in the 27 states of the European Union. The study finds installable ORC capacities in the cement, steel, glass, and oil and gas industries in all of the EU of around 2705 MW. Campana et al. [4] estimate an electricity generation potential for the German cement industry between approximately 351 GWh/year and 562 GWh/year depending on the operational hours. The results obtained in this thesis are close to this estimated range and most optimistic values lie at 545 GWh/year. This validates the scaling approach used in Stage 1.

A study by Tartière and Astolfi [5] reveal in a global market report a worldwide ORC installed capacity of 2700 MW across more than 700 projects. However, only 376 MW belong to waste

heat recovery undertakings, indicating that industrial ORC deployment still represents a small fraction of the overall ORC market despite the technical potential of this technology. The results in this thesis confirm this observation, as the estimated waste heat recovery potential is significantly larger than the currently installed ORC capacity.

Several studies have analysed economic feasibility of ORC systems for industrial waste heat recovery by considering payback period, internal rate of return, and net present value of the projects. Regarding the payback, typical return periods found in the literature range between approximately 2.5 and 6 years. The CE Delft report [18] estimates payback periods in the glass industry of 3.0 to 4.8 for a new ORC installation while the cement industry finds itself with estimated paybacks between 2.8 and 6.7. Pilli et al. [31] find paybacks of roughly 3 to 6 years for German industry ORC installations. The results found in this thesis lie at the lower end of this range. The payback for both the cement and the glass industry is positioned at 3.0 and 3.5 years respectively in the baseline situation, while the uncertainty analysis in form of a Monte Carlo simulation shows that these values can reach up to 5 years. Therefore, we can assume that the estimations of this thesis lie in similar orders of magnitude as the ones of the literature, especially because more recent studies have shown lower payback periods compared to older ones [10], [18], [26]. The same analogy can be performed when looking at the IRR. This study finds values of 35-40 % which is closely similar to the studies of previous research. Mokarram et al. [10] find this value to be at around 33% for waste heat recovery ORC systems, just like the CE Delft report [18].

The key economic drivers which cause the fluctuation in the literature exactly match the ones of this study found in the sensitivity analysis. The electricity price, the CAPEX, and operating hours are the largest drivers of alteration. This confirms the plausibility of these results.

Comparing the methods of this study to previously performed ones points out the major differences in the approach and therefore the contribution which this specific study performs. Many of the previous studies focus either on national assessment or on individual plant case studies. Only few studies combine a macro-level and micro-level analysis. This specific study merges a database of existing ORC installations, sector-level scaling and plant-level economic modelling. Additionally, uncertainty analysis in form of Monte-Carlo and Tornado-analysis is performed which adds robustness to the economic results. Therefore, this thesis contributes a more comprehensive perspective on ORC deployment potential than previously performed analysis. The combined approach allows for a more realistic and complete evaluation of the ORC installation potential.

Altogether, the comparison with the literature highlight that the results of this work are consistent with the ones obtained in the literature, while this thesis extends the analysis by combining a macro and micro perspective.

5.3 Main Uncertainties and Limitations of this Research

Every study that involves modelling of potential and uses data to scale global results, relies on the use of simplifications which lead to uncertainties in the results. While this thesis aims to provide a complete assessment of technical and economic potential of ORC systems for waste heat recovery, multiple simplifications are performed. These simplifications lead to limitations and uncertainty in the results and need to be addressed.

The first limitation to address is the fact that Stage 1 is based on a sector specific scaling approach within the two industries. Reference values from the dataset are translated onto the whole sector. The difficulty with this approach is the lack of comparability within the plants within one sector. The plant size, kiln configuration (cement), furnace type (glass), and operating hours could differ significantly between different cement or glass plants, leading to uncertainty in the scaling approach. Also, the penetration rate of realistic near-future installations can only be estimated, leading to uncertainties when relying on this factor. The results should therefore be interpreted as sector estimates, rather than precise predictions for individual industrial facilities.

In Stage 2 a typical plant is being modelled, this is not a real individual plant but one based on representative reference plants. A real modelling approach would consider the real waste heat temperature, flow rate, and integration constraints. The installation of an ORC is influenced by multiple factors which are not considered in this study. The system size would influence the plant layout and could lead to factors not considered in this study.

As found out in the uncertainty analysis (Section 3.5), the electricity price represents one of the most important economic drivers and is therefore a crucial input parameter. The electricity price is modelled with an escalation factor over the next 20 years. But in reality, the electricity price is extremely volatile. Energy crises or policy changes make it difficult to model the financial future. The uncertainty analysis is performed to cover at least part of the remaining risk.

Another limitation to address is the one of a simplified emission factor assumption. The calculated avoided CO₂ in this study is based on constant grid emission factors over the future time period. In reality, a statically decarbonized energy system increases the percentage of renewable energy which leads to a decrease in CO₂ avoidance over time. The oversimplification of the EF factor could therefore lead to reduced climate benefit compared to the calculated value.

The next simplification to discuss is the one of the CAPEX values, which consist of literature cost estimations. The CAPEX used in the cost calculations of this thesis is made up by a specific CAPEX and the installed system size. This value is a crucial factor to precisely estimate the payback period but is only attained by performing an estimation. The costs at a plant can significantly vary depending on plant size, integration costs, infrastructure modifications, or installation complexity. All these factors are not considered inside the representative plant in Stage 2. Instead, a range of values should help to precisely reach an estimation.

The final simplification to be addressed, regards the scope of this work. This thesis focusses on the technical and economic perspective but does not include the modelling of barriers to integrate a new ORC system in a running industrial process. Investments in companies are highly complex and depend on multiple factors which include investment priorities, organisational decision processes, operational risks, or lack of awareness for the technology. Such barriers are not modelled or further analysed in the thesis but may explain the low deployment to the current day.

6 Conclusion and Outlook

This thesis analysed technical and economic potential of Organic Rankine Cycle (ORC) systems for waste heat recovery in the cement and glass sectors in Germany and Italy. An approach of two stages was performed, in which a macro-level analysis of technical potential was combined with a micro-level economic evaluation of a representative industrial application. In a third section the resulting co-benefits of the ORC implementation are addressed, focussing on aspects benefitting society. The following chapter summarises the key findings of this research and answers the previously defined research question. Lastly, it outlines future research directions which extend the work of this thesis.

6.1 Key Findings and Contribution of this Thesis

The first research question in this thesis addresses the potential of ORC systems in the cement and glass sector in Germany and Italy. Stage 1 identified a large unused national waste heat recovery potential in both countries and industries. The cement sector reveals the largest absolute potential recoverable within a near future timeframe, up to 545 GWh/year in Germany and 296 GWh/year in Italy. The glass industry shows values which are below the ones of cement with potential that reaches up to 249 GWh/year. This additional ORC electricity is estimated to lead to substantial CO₂ reductions for both of the sectors and regions.

The second research question regards the structural difference of ORC potentials in the cement and glass industry, indicating that sector characteristics strongly shape the performance of such installations. The analysis finds that that strong thermodynamic differences between the two industries exist, caused by higher exhaust temperatures in the glass industry, leading to higher specific electric yields. Cement kilns operate at lower temperatures but reach much larger production volumes. As a result, glass industry applications achieve higher specific electricity generation, while the larger heat flows in cement plants result in greater total electricity generation potential. Additionally, from an economic perspective, the larger scale of cement plants may also favour ORC deployment in this sector due to economies of scale.

The third research question examines the economic and technical feasibility of a representative ORC system in the cement and glass industry. The results suggest strong economic performances in both cases with baseline payback periods of 3 years in the cement and 3.5 years in the glass industry. The internal rate of return of these projects is between 35 and 40% with a strongly positive NPV value (up to 15 million euros) in a project scope of 20 years. These values demonstrate that ORC systems represent financially attractive investments for industrial plants.

The fourth research question aims at finding the uncertainty of results and finding the parameters which most influence the profitability in a new ORC installation. A Monte Carlo simulation reveals a payback range between 2 and 6 years for both plants, where results remain robust across parameter variations. The sensitivity analysis identifies the strongest drivers of variation in performed projects to be the electricity price, the CAPEX and the operating hours. This leads to the conclusion, that a successful project is most depended on the future energy supply situations and operational on-site conditions.

The last research question asked in this thesis addresses the extent to which the ORC can beyond electricity generation for the individual plant operator contribute to grid stability and labour opportunities. This work demonstrates that ORC electricity generation is continuous and therefore contributes to the baseload electricity supply. This holds the benefit of improved grid stability in industrial regions. The benefits for society of implementing more ORC plants continues when considering the overall CO₂ emission reduction, which support industrial decarbonization goals. Additionally, this work demonstrates that job creation in manufacturing, logistics, and maintenance fields is found. Up to 41,000 jobs could be created with an increase in ORC demand. Overall, it is found that ORC system generates economic and system-level co-benefits which reach beyond electricity production.

Beyond answering the individual research questions, this thesis contributes to the existing literature by combining a macro-level and micro-level perspective on ORC installations. This thesis combines a global ORC installation database with sector-level scaling and plant level economic modelling to reach an assessment of both economic and technical potential. By performing a sensitivity analysis and Monte Carlo simulation the results are further strengthened and made robust. This integrative approach of two stages allows for a more comprehensive understanding of the overall potential of ORC systems when it comes to waste heat recovery in energy intensive industries. The results found in this work are not only relevant for industrial decision makers but also for policy discussions.

6.2 Future Research Directions

While this work provides a detailed assessment of the technical and economic potential of ORC systems in the cement and glass industries, several aspects remain open for future research.

This research has highlighted large technical potential and strong economic feasibility for ORC systems. Yet, limited real world installations are to be found to the present day. Future research should analyse this deployment gap by investigating organizational barriers, investment decision

processes, and risk perception from the point of view of decision makers. This goal could be reached by performing interviews with plant operators.

As a second future research direction the work of this thesis could be extended by performing a study in a real industrial facility instead of a representative imaginary plant. The study could include a detailed thermodynamic assessment with detailed flow data and hourly operational profiles. This would allow for a precise ORC potential assessment and would further demonstrate the integration process with possible integration difficulties.

A third approach to further extend the performed research is one of precisely modelling the electricity price market, as the electricity price represents one of the most crucial parameters in a project lifespan. Where this thesis takes a simplified model, a future work could include dynamic electricity pricing modelling and include time-of-use pricing. A detailed modelling approach, also regarding further future pricing could significantly alter the profitability of ORC installations.

As this thesis focusses mainly on the cement and glass industry, a final recommendation implies extending the research and method on other industries like steel, chemical, paper, or ceramics. This enables for more accurately estimating the overall cumulated national ORC potential.

Including these research aspects could further improve the understanding of industrial waste heat recovery and support the broader instalment of Organic Rankine Cycle technologies in such energy intensive industries.

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Appendix A

Table 14. Cement plants with ORC installations and their corresponding production capacities and electrical output

Name	City	Country	Production (t/day)	ORC Power (MW)	Specific Power (MW/1000t/day)
Untervaz	Untervaz	Switzerland	2100	1.9	0.90
Wildeg	Wildeg	Switzerland	2000	1.9	0.95
Cementi Rossi	Pederobba	Italy	2500	3.6	1.44
HeidelbergCement	Triefenstein, Bayern	Germany	3000	1.5	0.50
AP Cement	Andhra Pradesh	India	15000	4	0.27
Ait Baha	Ait Baha	Morocco	4400	2	0.45
Medcem	Akdere, Mersin	Turkey	20000	10	0.50
Alesd	Aleşd	Romania	4000	4	1.00
Alhandra	Alhandra	Portugal	6300	6	0.95
Riyadh Cement Company	Al-Muzahmiya	Saudi Arabia	11000	13	1.18
Eclépens	Eclépens	Switzerland	2000	1.3	0.65
CTN Makina	Eskişehir	Turkey	2500	5.9	2.36
Fieni	Fieni, Dâmbovița County	Romania	4000	3.8	0.95
Lafarge	Fujairah	United Arab Emirates	12100	10	0.83
Holcim Belgium	Mons	Belgium	6000	7.5	1.25
Möriken-Wildeg	Möriken-Wildeg	Switzerland	2000	2.3	1.15
Narli	Narli	Turkey	7500	7	0.93
Outão, Setubal	Outão, Setubal	Portugal	5500	7.2	1.31
Piacenza	Piacenza	Italy	2200	2	0.91
Rohoznik	Rohožník	Slovakia	3600	5	1.39
Souselas	Souselas	Portugal	6500	8	1.23
Yumurtalik, Erzin / Hatay	Yumurtalik, Erzin / Hatay	Turkey	5500	7.3	1.33

Table 15. Glass plants with ORC installations and their corresponding production capacities and electrical output

Name	City	Country	Production (t/day)	ORC Power (MW)	Specific Power (MW/1000t/day)
Bangkok Glass	Kabin Buri	Thailand	600	1.8	3.00
Yenisehir	Yenisehir	Turkey	725	3.2	4.41
Mersin	Mersin	Turkey	1000	5.5	5.50
SISECAM TARGOVISHTTE	Targovishte	Bulgaria	740	4.8	6.49
Manferdonia-Sangalli	Puglia	Italy	600	2.2	3.67
Beykoy - Duzce	Beyköy - Düzce	Turkey	1500	6.2	4.13
Cuneo	Cuneo	Italy	600	1.3	2.17
Vetreria Piegarese	Piegaro (PG)	Italy	918	2.3	2.51
Pisa	Pisa	Italy	830	1.2	1.45
Asahi India Glass	Roorkee, District Haridwar, Uttarakhand	India	1250	1.7	1.36
AGC Thailand	Samut Prakan	Thailand	500	1.9	3.80
AGC Seingbouse	Seingbouse	France	600	1	1.67
Asahi India Glass	Soniyana, District Chittorgarh, Rajasthan	India	700	1.5	2.14
Sriperumbudur	Sriperumbudur	India	1500	1.2	0.80
VDN Srl	Udine	Italy	410	1,1	2.68
Euroglas Polska	Ujazd	Poland	1000	5	5.00
Villotta di Chions (PN)	Villotta di Chions (PN)	Italy	300	0.5	1.67
Piacenza	Piacenza	Italy	180	0.2	1.11

Appendix B

Table 16. Cash flow analysis of the reference ORC installation in the cement plant case

Year	Age (yr)	Net capacity (kW)	Load factor	Hours/year	Degradation	Net gen (kWh)	Import price (€/kWh)	Export price (€/kWh)	Revenue (€)	O&M (€)	Net Cash flow (€)	Discount factor	Discounted Cash flow (€)	Cumulative DCF (€)
0	0	2000	1	7500	0.00	0	0	0	0	0	-4800000	1	-4800000	-4800000
2025	1	2000	1	7500	0.98	14700000	0.140	0.080	2013900	144000	1869900	0.926	1731389	-3068611
2026	2	2000	1	7500	0.96	14406000	0.144	0.081	2031966	144000	1887966	0.857	1618627	-1449984
2027	3	2000	1	7500	0.94	14117880	0.149	0.082	2050207	144000	1906207	0.794	1513209	63224
2028	4	2000	1	7500	0.92	13835522	0.153	0.084	2068624	144000	1924624	0.735	1414656	1477880
2029	5	2000	1	7500	0.90	13558812	0.158	0.085	2087218	144000	1943218	0.681	1322522	2800402
2030	6	2000	1	7500	0.89	13287636	0.162	0.086	2105992	144000	1961992	0.630	1236388	4036789
2031	7	2000	1	7500	0.87	13021883	0.167	0.087	2124946	144000	1980946	0.583	1155863	5192653
2032	8	2000	1	7500	0.85	12761445	0.172	0.089	2144084	144000	2000084	0.540	1080583	6273236
2033	9	2000	1	7500	0.83	12506216	0.177	0.090	2163405	144000	2019405	0.500	1010205	7283441
2034	10	2000	1	7500	0.82	12256092	0.183	0.091	2182913	144000	2038913	0.463	944411	8227852
2035	11	2000	1	7500	0.80	12010970	0.188	0.093	2202608	144000	2058608	0.429	882902	9110754
2036	12	2000	1	7500	0.78	11770751	0.194	0.094	2222493	144000	2078493	0.397	825398	9936152
2037	13	2000	1	7500	0.77	11535336	0.200	0.096	2242569	144000	2098569	0.368	771640	10707792
2038	14	2000	1	7500	0.75	11304629	0.206	0.097	2262838	144000	2118838	0.340	721382	11429174
2039	15	2000	1	7500	0.74	11078537	0.212	0.099	2283303	144000	2139303	0.315	674397	12103571
2040	16	2000	1	7500	0.72	10856966	0.218	0.100	2303963	144000	2159963	0.292	630473	12734044
2041	17	2000	1	7500	0.71	10639826	0.225	0.102	2324822	144000	2180822	0.270	589409	13323452
2042	18	2000	1	7500	0.70	10427030	0.231	0.103	2345882	144000	2201882	0.250	551019	13874471
2043	19	2000	1	7500	0.68	10218489	0.238	0.105	2367143	144000	2223143	0.232	515129	14389600
2044	20	2000	1	7500	0.67	10014120	0.245	0.106	2388609	144000	2244609	0.215	481577	14871177

Table 17. CO₂ emission reduction and associated carbon revenue for the reference cement plant case

Year	Net gen (MWh)	Grid EF (tCO ₂ /MWh)	Baseline Emissions (tCO ₂)	Project Emissions (tCO ₂)	Emission Reduction (tCO ₂)	Cum. Emission Reduction (tCO ₂)	CO ₂ Revenue (€)
2025	14700	0.3	4410	22	4388	4388	351036
2026	14406	0.3	4322	22	4300	8688	344015
2027	14118	0.3	4235	21	4214	12902	337135
2028	13836	0.3	4151	21	4130	17032	330392
2029	13559	0.3	4068	20	4047	21080	323784
2030	13288	0.3	3986	20	3966	25046	317309
2031	13022	0.3	3907	20	3887	28933	310963
2032	12761	0.3	3828	19	3809	32742	304743
2033	12506	0.3	3752	19	3733	36475	298648
2034	12256	0.3	3677	18	3658	40134	292675
2035	12011	0.3	3603	18	3585	43719	286822
2036	11771	0.3	3531	18	3514	47233	281086
2037	11535	0.3	3461	17	3443	50676	275464
2038	11305	0.3	3391	17	3374	54050	269955
2039	11079	0.3	3324	17	3307	57357	264555
2040	10857	0.3	3257	16	3241	60598	259264
2041	10640	0.3	3192	16	3176	63774	254079
2042	10427	0.3	3128	16	3112	66887	248997
2043	10218	0.3	3066	15	3050	69937	244018
2044	10014	0.3	3004	15	2989	72926	239137

Table 18. Cash flow analysis of the reference ORC installation in the glass plant case

Year	Age (yr)	Net capacity (kW)	Load factor	Hours/year	Degradation	Net gen (kWh)	Import price (€/kWh)	Export price (€/kWh)	Revenue (€)	O&M (€)	Net cash flow (€)	Discount factor	Discounted cash flow (€)	Cumulative DCF (€)
0	0	2000	1	7700	0.00	0	0	0	0	0	-5600000	1	-5600000	-5600000
2025	1	2000	1	7700	0.98	15092000	0.140	0.080	2067604	168000	1899604	0.926	1758893	-3841107
2026	2	2000	1	7700	0.96	14790160	0.144	0.081	2086152	168000	1918152	0.857	1644506	-2196601
2027	3	2000	1	7700	0.94	14494357	0.149	0.082	2104879	168000	1936879	0.794	1537557	-659044
2028	4	2000	1	7700	0.92	14204470	0.153	0.084	2123787	168000	1955787	0.735	1437562	778518
2029	5	2000	1	7700	0.90	13920380	0.158	0.085	2142877	168000	1974877	0.681	1344068	2122586
2030	6	2000	1	7700	0.89	13641973	0.162	0.086	2162152	168000	1994152	0.630	1256654	3379240
2031	7	2000	1	7700	0.87	13369133	0.167	0.087	2181612	168000	2013612	0.583	1174923	4554163
2032	8	2000	1	7700	0.85	13101751	0.172	0.089	2201259	168000	2033259	0.540	1098507	5652670
2033	9	2000	1	7700	0.83	12839716	0.177	0.090	2221096	168000	2053096	0.500	1027059	6679729
2034	10	2000	1	7700	0.82	12582921	0.183	0.091	2241124	168000	2073124	0.463	960257	7639986
2035	11	2000	1	7700	0.80	12331263	0.188	0.093	2261344	168000	2093344	0.429	897800	8537786
2036	12	2000	1	7700	0.78	12084638	0.194	0.094	2281760	168000	2113760	0.397	839403	9377189
2037	13	2000	1	7700	0.77	11842945	0.200	0.096	2302371	168000	2134371	0.368	784804	10161993
2038	14	2000	1	7700	0.75	11606086	0.206	0.097	2323181	168000	2155181	0.340	733755	10895748
2039	15	2000	1	7700	0.74	11373964	0.212	0.099	2344191	168000	2176191	0.315	686026	11581774
2040	16	2000	1	7700	0.72	11146485	0.218	0.100	2365402	168000	2197402	0.292	641401	12223175
2041	17	2000	1	7700	0.71	10923555	0.225	0.102	2386818	168000	2218818	0.270	599677	12822852
2042	18	2000	1	7700	0.70	10705084	0.231	0.103	2408439	168000	2240439	0.250	560668	13383520
2043	19	2000	1	7700	0.68	10490982	0.238	0.105	2430267	168000	2262267	0.232	524195	13907714
2044	20	2000	1	7700	0.67	10281163	0.245	0.106	2452305	168000	2284305	0.215	490094	14397808

Table 19. CO₂ emission reduction and associated carbon revenue for the reference glass plant case

Year	Net gen (MWh)	Grid EF (tCO ₂ /MWh)	Baseline Emissions (tCO ₂)	Project Emissions (tCO ₂)	Emission Reduction (tCO ₂)	Cum. Emission Reduction (tCO ₂)	CO ₂ Revenue (€)
2025	15092	0.3	4527.6	23	4505	4505	360397
2026	14790	0.3	4437.0	22	4415	8920	353189
2027	14494	0.3	4348.3	22	4327	13246	346125
2028	14204	0.3	4261.3	21	4240	17486	339203
2029	13920	0.3	4176.1	21	4155	21642	332419
2030	13642	0.3	4092.6	20	4072	25714	325770
2031	13369	0.3	4010.7	20	3991	29704	319255
2032	13102	0.3	3930.5	20	3911	33615	312870
2033	12840	0.3	3851.9	19	3833	37448	306612
2034	12583	0.3	3774.9	19	3756	41204	300480
2035	12331	0.3	3699.4	18	3681	44885	294471
2036	12085	0.3	3625.4	18	3607	48492	288581
2037	11843	0.3	3552.9	18	3535	52027	282810
2038	11606	0.3	3481.8	17	3464	55492	277153
2039	11374	0.3	3412.2	17	3395	58887	271610
2040	11146	0.3	3343.9	17	3327	62214	266178
2041	10924	0.3	3277.1	16	3261	65475	260854
2042	10705	0.3	3211.5	16	3195	68670	255637
2043	10491	0.3	3147.3	16	3132	71802	250525
2044	10281	0.3	3084.3	15	3069	74871	245514