Waste Heat Recovery for Power Valorisation with Organic Rankine Cycle Technology in Energy Intensive Industries”

Analysis of the replicability of the developed technology to other sectors through LCA methodology

Roberta Manariti[1a], Giorgio Urbano[1a], Eros Faraci[1b], Pedro Egizibal[2], Inigo Unamuno[3], Paolo Belotti[4], Nazarena Spinelli[4], Davide Carando[5]

[1]RINA S.p.A. ([1a] Rina Consulting; [1b] Rina Consulting – Centro Sviluppo Materiali)

[2] TECNALIA Research & Innovation; [3] Sidenor; [4] Turboden; [5] Cementirossi

Email: roberta.manariti@rina.org

Abstract

The installation of a Waste Heat Recovery Systems (WHRS) based on the Organic Rankine Cycle (ORC) technology with a Direct Heat Exchanger (DHE) into Energy Intensive Industries (EII) could provide significant environmental benefits, in particular in terms of Greenhouse Gases (GHG) emissions reduction and primary energy demand decrease, and economic savings for the end-user. The Life Cycle Assessment (LCA) methodology is used in the frame of the co-funded EU project TASIO (“Waste Heat Recovery for Power Valorisation with Organic Rankine Cycle Technology in Energy Intensive Industries”), in order to investigate the replicability of the technology developed within the TASIO project in multiple industrial sectors. In particular, the analysis is performed for four “virtual” case studies, considering the potential installation of the technology in three industrial plants, i.e. the cement plant Holcim, the glass plant Vidrala, the steel plant Sidenor and in a pilot plant of petrochemical sludge treatment, installed during the project in the Rina Consulting - Centro Sviluppo Materiali (RINA) plant. Furthermore, a “real” case study is also taken into account: the Cementirossi cement plant, where the demonstrator of the TASIO project was installed during the project. Data are collected regarding these five case studies on the basis of the information provided by the project partners Holcim, Sidenor, Vidrala, Rina Consulting – CSM and Cementirossi. The functional unit of the study is the treatment of the exhaust gases coming from the above mentioned five plants, related to 1 ton of product, i.e. 1 ton of cement, glass, and steel produced and 1 ton of petrochemical sludge treated, respectively. The achieved environmental benefits are calculated and provided per functional unit, per year and per life span of the system (estimated of 15 years).

1. Introduction

The project TASIO, “Waste Heat Recovery for Power Valorisation with Organic Rankine Cycle Technology in Energy Intensive Industries” (H2020-EE-2014-2015/H2020-EE-2014-1-PPP, Grant Agreement No. 637189) involves 7 partners from 3 European countries, i.e Tecnalia (the project coordinator), Cementi Rossi, Geonardo, RINA, Sidenor, Turboden, and Vidrala.

The main objective of the TASIO project is to develop a Waste Heat Recovery Systems (WHRS) based on the Organic Rankine Cycle (ORC) technology. This technology is able to recover and transform the thermal energy of the flue gases of Energy Intensive Industries (EII) such as cement, glass, steelmaking and petrochemical industries, into electric power for internal or external use. In order to reach this objective, several challenging innovative aspects are approached by the project consortium. A multi sectorial Direct Heat Exchanger (DHE) to transfer heat directly from the flue gases to the organic fluid of the ORC system is designed and developed and new heat conductor and anticorrosive materials to be used in parts of the heat exchanger in contact with the flue gases are developed. These aspects are completed by the design and modelling of a new integrated monitoring and control system for the addressed sectors. Furthermore, the project addresses the implementation of a full demonstration of a direct exchange heat recovery system for electrical energy generation at the Cementirossi cement plant, in Italy.

This paper has the aim to highlight the potential benefits that the TASIO system could provide in the EII from the environmental point of view.

2. Goal and Scope

The potential environmental benefits that the installation in the EII of the Waste heat Recovery system developed within the TASIO project could provide are investigated in this paper. In particular, four "virtual" case studies and one "real" case study are taken into account. The virtual ones are related to the potential installation of the TASIO technology in four plants, the Holcim cement plant, the Vidrala glass plant, the Sidenor steel plant, and the pilot plant of petrochemical sludge treatment installed during the project in Rina Consulting – Centro Sviluppo Materiali (RINA) facilities'. The real case study is related to the Cementirossi cement plant, where the demonstrator of the project is installed.

Table 1 includes information related to each of the five case studies.

Table 1: Estimated electricity production per each case study

Case studies	Source of the heat recovery	Data source	Plant size	Net ORC electric power	Electricity production (year)	Electricity production (life span)
Holcim cement plan	Kiln exhausted gases	Holcim	5.000 t/d	1.715 kWe	1,37E+07 kWh	2,06E+08 kWh
Vidrala glass plant	Flue gases of the melting furnace after electrofilter	Vidrala	400 t/d	565 kWe	4,52E+06 kWh	6,78E+07 kWh
Sidenor steel plant	Reheating furnace in the rolling mill	Sidenor	85 t/h	580 kWe	4,64E+06 kWh	6,96E+07 kWh
RINA CSM petro-chemical pilot plant	Petrochemical sludge	RINA (CSM)	2 t/h	1.255 kWe	1,00E+07 kWh	1,51E+08 kWh
Cementi rossi cement plant (Demosite)	Kiln exhausted gases	Cementi rossi	2.300 t/d	1,945 kWe	9,73E+06 kWh	1,46E+08 kWh

The electricity amount that could be produced through the Organic Rankine Cycle (ORC) technology with a Direct Heat Exchanger (DHE) in the four virtual case studies is calculated on the basis of the thermal power available (kWt) from the source of the heat recovery. Two time references are considered: 1 year and 15 years (i.e. the estimated life span of the system). A period of 8.000 working hours/year is considered for the virtual case studies, while 5.000 hours/year is taken into account for the real case study.

The LCA is performed according to the internationally recognized guidelines, i.e. “ILCD Handbook: General guide for Life Cycle Assessment – Detailed guidance”, and to specific standards, i.e. ISO 14040 and 14044. The boundary limits for the LCA include the use phase of the TASIO technology; a gate-to-gate LCA analysis is performed.

The analysis does not support any business decisions. This LCA study is classifiable in the situation C2 – Accounting, excluding interactions with other systems. The system is into a foreground system under the specificity perspective. The processes are inventoried based on data provided by the owners of the technologies. The functional unit is the cooling down of the exhaust gases, coming from the four plants investigated, related to the amount of 1 ton of product, i.e.1 ton of cement, glass and steel produced and 1 ton of petrochemical sludge treated, respectively. The conditions of the exhaust gases in the five case studies are described in Table 2.

Table 2: Exhaust gases conditions

	Holcim	**Vidrala**	**Sidenor**	**RINA CSM**	**Cementi rossi**
Flow rate [Nm³/h]	125.000	43.000	34.000	35.000	180.000
Temperature [°C]	330	380	425	600	300
Composition	N_2 78% O_2 20% H_2O 2% CO_2 0%	N_2 68% O_2 7% H_2O 15% CO_2 10%	N_2 78,3% O_2 13,6% H_2O 4,6% CO_2 3,5%	N_2 75% O_2 15% H_2O 6,5% CO_2 3,5%	N_2 69% O_2 10% H_2O 6% CO_2 15%
Cooled down to [°C]	120	200	180	200	135

2.1. Products description

The aim of the TASIO project is to develop an innovative waste heat recovery system for the **recovery** of the **waste heat** deriving from the **Energy Intensive Industries**, such as cement, glass and steelmaking. The TASIO project is based on a new generation of Organic Rankine Cycle based on the **direct heat exchange**.

The project addresses the implementation of a full demonstration of a direct exchange heat recovery system for electrical energy generation at Cementirossi cement plant in Italy.

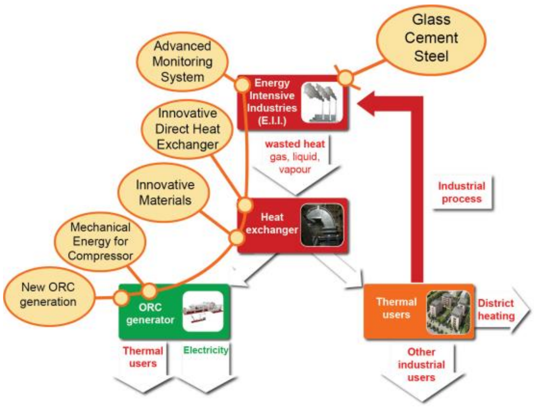

Figure 1: TASIO overview

In order to give an overview of the TASIO system, this chapter describes the innovative elements of the direct exchange heat recovery system installed in the cement plant. In the TASIO scheme, no heat transfer loop is needed: the liquid organic fluid is pre-heated and evaporated in a heat exchanger where the hot gas passes through. The organic vapour is then sent to the turbine where it expands, generating mechanical power that drives the electric generator. After the turbine, the expanded fluid firstly releases its sensible heat in the regenerator and then condenses, returning to liquid form and closing the loop.

Traditional scheme includes a thermal oil loop between gas and organic fluid: there is a waste heat recovery system that is a heat exchanger fed by thermal oil without any phase change. Downstream, thermal oil feeds one or more heat exchangers in order to preheat, evaporate and potentially superheat organic fluid. All these heat exchangers are replaced with only one WHRS, where organic fluid is directly preheated and evaporated. The new ORC developed during the project shows several innovative aspects in comparison with a standard configuration with thermal oil.

An important innovation is the use of a refrigerant, nor toxic, nor flammable and with low Global Warming Potential (GWP) as working fluid in the ORC for heat recovery. The new fluid could be used also for high temperature applications, maintaining good performances. The use of this innovative alternative fluid permits to reduce the Global Warming Potential of the working fluid used in the Organic Rankine Cycle, contributing also to the compliance with the Fluorinated Gases Regulation. Another innovative aspect is constituted by the WHRS design, able to efficiently recover heat from gases, maintain the organic fluid temperature below decomposition limits and remove dust from exchange surfaces; the WHRS material is able to resist high temperatures and dust, and it is also cheap enough to be economically sustainable. Thermal oil is no needed, therefore the environmental impact of the new technology is lower than the conventional one. From the technical point of view, the recovered thermal power of this new ORC is higher in comparison to the conventional ones. Additionally, it is the first worldwide application of an ORC with direct heat exchange in the cement sector.

3. Life Cycle Inventory

The Life Cycle Inventory (LCI) is the LCA phase that foresees a qualitative and quantitative identification and compilation of the inputs and outputs for a given product along its life cycle. The dedicated software GaBi 8 is used for the LCA.

Information for performing the LCA is provided mainly by the owners of the case studies plants, partners of the project, i.e. Holcim (partner of the project during only the first period), Vidrala, Sidenor, Rina Consulting – Centro Sviluppo Materiali (RINA) and Cementirossi.

The models in Gabi are related to the electricity production from grid mix for all the case studies analysed, and also to the water consumption for the real case study. The aim of the LCA study is indeed to investigate the environmental benefits provided by TASIO project through the waste heat recovery and its transformation into electricity. The environmental impacts due to the electricity production is therefore calculated in order to understand the environmental impacts that TASIO permits to avoid to the owners of the plants considered. The electricity production datasets are taken into account. In particular, the electricity production from Romania (Holcim installation country), Spain (Vidrala and Sidenor installation country) and Italy (Rina Consulting – Centro Sviluppo Materiali and Cementirossi installation countries) grid mix are considered. Regarding the real case study, the other important information achieved from Cementirossi is related to the water saving permitted by the installation of the waste heat recovery system based on the ORC with the direct heat exchanger in the cement plant. Indeed, the WHRS permits to not use the cooling tower for the cooling of the exhaust gases, saving consequently water. The water saving is approximately estimated equal to 100,000 m^3 per year. Also this benefit will be calculated and evaluated from the environmental point of view during this analysis.

4. Life Cycle Impact Assessment

The Life Cycle Impact Analysis (LCIA) is the LCA phase that calculates the amount and significance of the environmental impacts arising for the LCI. The environmental impacts are hereinafter showed. Data inventoried during the LCI are assigned to impact categories and their potential impacts quantified according to characterization factors. The PEF (Product Environmental Footprint) recommendation (2013/179/EU) is used as reference for impact assessment method. Sixteen indicators are calculated.

The LCA results are reported in
Table 3, referred to the functional unit of the study, i.e. the heat recovery of the exhaust gases coming from the five plants investigated. In particular, the "savings" of the use step are provided, per ton of product. They are negative values due to the fact that they are savings generated through the electricity production that permits to avoid the "ex-novo" production of the same amount of electricity. The ex-novo production impacts are calculated considering the energy grid mix of the installation countries of the analysed plants.

Table 3: TASIO global avoided impacts per functional unit (ton of product)

	CEMENT Holcim	GLASS Vidrala	STEEL Sidenor	PETRO CHEMICAL Rina CSM	CEMENT CementiR (demosite)
Installation country	Romania	Spain	Spain	Italy	Italy
Acidification midpoint (v1.09) [Mole of H+ eq.]	-4,07E-02	-3,39E-02	-7,51E-03	-5,80E-01	-1,88E-02
Climate change midpoint, excl biogenic carbon (v1.09) [kg CO2 eq.]	-4,13E+00	-1,05E+01	-2,32E+00	-2,82E+02	-9,13E+00
Ecotoxicity freshwater midpoint (v1.09) [CTUe]	-2,00E-01	-4,28E-01	-9,48E-02	-1,51E+00	-4,89E-02
Eutrophication freshwater midpoint (v1.09) [kg P eq.]	-1,05E-06	-1,39E-05	-3,08E-06	-1,35E-03	-4,36E-05
Eutrophication marine midpoint (v1.09) [kg N eq.]	-2,94E-03	-7,89E-03	-1,75E-03	-1,52E-01	-4,93E-03
Eutrophication terrestrial midpoint (v1.09) [Mole of N eq.]	-3,18E-02	-8,35E-02	-1,85E-02	-1,47E+00	-4,77E-02
Human toxicity midpoint, cancer effects (v1.09) [CTUh]	-3,78E-09	-1,16E-08	-2,58E-09	-2,97E-07	-9,60E-09
Human toxicity midpoint, non-cancer effects (v1.09) [CTUh]	-1,84E-07	-1,03E-07	-2,28E-08	1,24E-05	4,02E-07
Ionizing radiation midpoint, human health (v1.09) [kBq U235 eq.]	-7,50E-01	-2,51E+00	-5,55E-01	-2,87E+01	-9,30E-01
Land use midpoint (v1.09) [kg C deficit eq.]	-2,22E-01	-3,88E+00	-8,60E-01	-3,31E+02	-1,07E+01
Ozone depletion midpoint (v1.09) [kg CFC-11 eq.]	-1,47E-09	-4,28E-09	-9,48E-10	-1,06E-08	-3,43E-10
Particulate matter/Respiratory inorganics midpoint (v1.09) [kg PM2.5 eq.]	-2,44E-03	-1,59E-03	-3,51E-04	-2,40E-02	-7,75E-04
Photochemical ozone formation midpoint, human health (v1.09) [kg NMVOC eq.]	-9,88E-03	-2,21E-02	-4,89E-03	-3,88E-01	-1,26E-02
Resource depletion water, midpoint (v1.09) [m³ eq.]	-5,70E-02	-1,32E+00	-2,91E-01	-9,98E+00	-3,23E-01
Resource depletion, mineral, fossils and renewables, midpoint (v1.09) [kg Sb eq.]	-1,11E-05	-4,65E-05	-1,03E-05	-8,85E-04	-2,86E-05
Primary energy demand from ren. and non ren. resources (gross cal. value) [MJ]	-9,22E+01	-3,36E+02	-7,44E+01	-7,15E+03	-2,31E+02

In order to provide an indication for non-LCA expert readers, these benefits are normalized to the yearly impacts generated by an average European citizen. The International Organization Standardization (ISO) Standards defines Normalisation as the process of calculating indicator results relative to reference information. In this study, as reference information the impact of a European citizen across one year is selected. The European Person equivalent (2010), as defined in PEF, is selected as normalization factor.

The normalized results, i.e. the avoided normalized impacts per year, are resumed in Table 4, following the PEF impact indicators proposed for the assessment. Only for land use no normalization factor is available.

Table 4: TASIO normalized avoided impacts per year

	CEMENT Holcim	GLASS Vidrala	STEEL Sidenor	PETRO CHEMICAL Rina CSM	CEMENT CementiR (demosite)
Installation country	Romania	Spain	Spain	Italy	Italy
Acidification midpoint (v1.09) [Person equivalent]	-1.432,70	-105,12	-107,91	-196,34	-192,21
Climate change midpoint, excl biogenic carbon (v1.09) [Person equivalent]	-746,75	-166,68	-171,11	-490,02	-478,34
Ecotoxicity freshwater midpoint (v1.09) [Person equivalent]	-38,11	-7,19	-7,38	-2,77	-3,71
Eutrophication freshwater midpoint (v1.09) [Person equivalent]	-1,18	-1,38	-1,42	-14,59	-15,93
Eutrophication marine midpoint (v1.09) [Person equivalent]	-289,82	-68,47	-70,29	-144,36	-141,97
Eutrophication terrestrial midpoint (v1.09) [Person equivalent]	-300,90	-69,60	-71,45	-134,06	-131,46
Human toxicity midpoint, cancer effects (v1.09) [Person equivalent]	-170,66	-46,30	-47,53	-128,70	-132,60
Human toxicity midpoint, non-cancer effects (v1.09) [Person equivalent]	-576,60	-28,32	-29,08	372,97	356,11
Ionizing radiation midpoint, human health (v1.09) [Person equivalent]	-1.106,10	-325,20	-333,83	-406,93	-395,82
Ozone depletion midpoint (v1.09) [Person equivalent]	-0,11	-0,03	-0,03	-0,01	-0,01
Particulate matter/Respiratory inorganics midpoint (v1.09) [Person equivalent]	-1.072,33	-61,26	-62,88	-100,93	-99,13
Photochemical ozone formation midpoint, human health (v1.09) [Person equivalent]	-519,37	-102,09	-104,80	-196,05	-192,16
Resource depletion water, midpoint (v1.09) [Person equivalent]	-11.66,37	-2.371,06	-2.434,00	-1.961,13	-2.110,90
Resource depletion, mineral, fossils and renewables, midpoint (v1.09) [Person equivalent]	-183,39	-67,58	-69,37	-140,16	-135,82
Primary energy demand from ren. and non ren. resources (gross cal. value) [Person equivalent]	-529,51	-169,77	-174,28	-394,40	-384,22

5. Conclusions

Generally, the possible installation of the waste heat recovery system (WHRS) based on the Organic Rankine Cycle (ORC) technology with a direct heat exchanger (DHE) developed within TASIO project in Holcim cement plant, Vidrala glass plant, Sidenor steel plant and RINA petrochemical sludge treatment, seems a convenient choice from the environmental point of view, as well as the installation of the demonstrator of the project in Cementirossi cement plant.

The results, calculated through the recommendations of Product Environmental Footprint (2013/179/EU) show impressive values in all the sixteen impacts categories analysed, due to the significant amount of electricity produced through the Waste Heat Recovery system based on the Organic Rankine Cycle (ORC) technology with a Direct Heat Exchanger. In particular, concerning the Climate Change category, an avoided impact per year comprises between 1,54E+06 and 6,89E+06 kg of CO_2 eq., as well as, concerning the Primary Energy Demand category, between 4,93E+07 and 1,54E+08 MJ is permitted.

In order to provide an indication for non-LCA expert readers, these benefits are normalized to the yearly impacts of a European citizen. The normalization results show that the Waste Heat Recovery system based on the Organic Rankine Cycle (ORC) technology with a Direct Heat Exchanger is able to avoid the environmental impacts produced in a year by a range of 167 until around 747 person equivalents, considering the climate change midpoint indicator.

The environmental benefits permit to the owners of the plants also huge economic savings due to the possibility to produce electricity within their plants. In particular, the economic benefit is estimated for the virtual case studies; a cost reduction per year of 8,64E+05 € for the cement case, 4,07E+05 € for the glass case, 2,78E+05 € for the steel case and, finally, 7,03E+05 € for the petrochemical case is achieved.

ACKNOWLEDGEMENTS

The Authors wish to thank Project Partners Holcim (Mr. Andrea Barbieri), Vidrala (Mr Liher Irizar), Sidenor (Mr Inigo Unamuno), Rina Consulting – Centro Svilupo Materiali (Mr Eros Faraci) and Cementirossi (Davide Carando) for data providing. The result presented in this paper is part of the TASIO project (http://www.tasio-h2020.eu/) co-funded by the European Commission in H2020-EE-2014-2015/H2020-EE-2014-1-PPP, Grant Agreement No. 637189.

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