

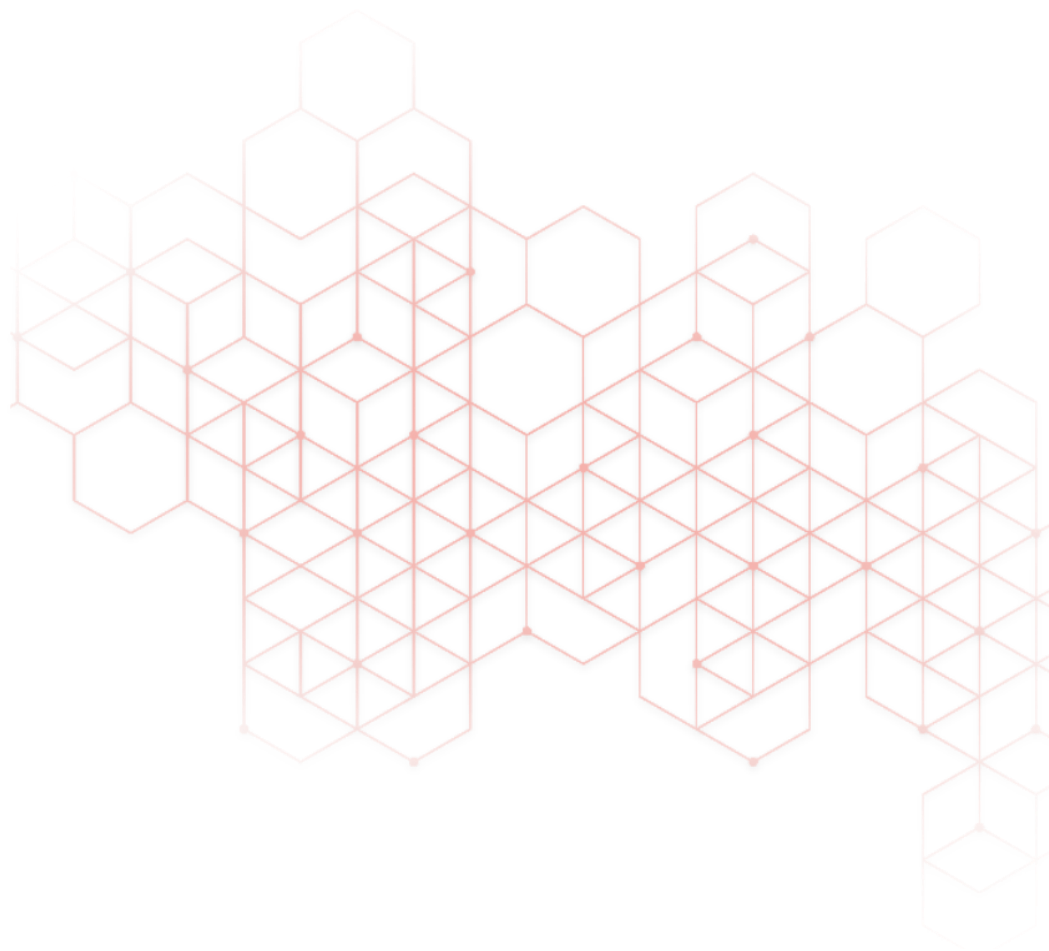
Report on the LCAs of the developed technologies in industrial plant environment

Elsa Busson, Andrés Ramírez Sánchez | RWTH IOB

Leo Cailliau, Magdalena Coventry | TME

Xingqiang Song | SWE

August 2026



Credits

Copyright © 2026 HyInHeat project

Disclaimer

The sole responsibility of this publication lies with the author.
The European Union is not responsible for any use that may be
made of the information contained therein.



This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101091456.

Technical references

Grant Agreement N°	101091456	Acronym	HyInHeat
Full Title	Hydrogen technologies for decarbonization of industrial heating processes		
Work Package (WP)	WP7		
Authors	Andrés Ramírez Sánchez (RWTH IOB), Magdalena Coventry (TME), Xingqiang Song (SWE), Elsa Busson (RWTH IOB) and Leo Cailliau (TME)		
Leading organisation	RWTH IOB		
Date of publication	14.08.2026		
Contributors	Felix Kaiser (RWTH IOB), Moritz Langhorst (NTNU), Lukas Sankowski (RWTH-IOB)		
Document Type	R – Report		
Document Title	Report on the LCAs of the developed technologies in industrial plant environment		
Dissemination Level	Public		

Document history

Version	Date	Partner	Author
1	19.01.2026	RWTH-IOB	Andrés Ramírez Sánchez (RWTH IOB)
2	21.07.2026	RWTH-IOB, TME and SWE	Andrés Ramírez Sánchez, Elsa Busson (RWTH IOB), Magdalena Coventry (TME), Leo Cailliau (TME) and Xingqiang Song (SWE)
3	31.07.2026	RWTH-IOB and NTNU	Felix Kaiser (RWTH IOB) and Moritz Langhorst (NTNU),
Final	14.08.2026	RWTH-IOB	Andrés Ramírez Sánchez (RWTH IOB)

Table of contents

List of Figures	6
List of Tables	9
List of Abbreviations	11
1 Introduction.....	13
2 Case 1: LCA on the trials of the ladle preheater from METLEN	14
2.1 Scope and goal	14
2.2 Life cycle inventory	14
2.3 Impact assessment	15
2.4 Interpretation	19
3 Case 2: LCA on the trials of the rotary furnace from BEF	23
3.1 Scope and goal	23
3.2 Life cycle inventory	23
3.3 Impact assessment	25
3.4 Interpretation	30
4 Case 3: LCA on the trials of the reverberatory furnace from CTEC	34
4.1 Scope and goal	34
4.2 Life cycle inventory	34
4.3 Impact assessment	36
4.4 Interpretation	41
5 Case 4: LCA on the study of the reverberatory furnace from METL	44
5.1 Scope and goal	44
5.2 Life cycle inventory	44
5.3 Impact assessment	45
5.4 Interpretation	51
6 Case 5: LCA on the study of the pusher furnace from SPE	55
6.1 Scope and goal	55
6.2 Life cycle inventory	55
6.3 Impact assessment	56
6.4 Interpretation	61
7 Case 6: LCA on the trials of the annealing furnace from TME	65
7.1 Scope and goal	65
7.2 Life cycle inventory	65
7.3 Impact assessment	66
7.4 Interpretation	69
8 Case 7: LCA on the trials of the walking beam furnace from SWE & SSAB	70
8.1 Scope and goal	70
8.2 Life cycle inventory	70
8.3 Impact assessment	72
8.4 Interpretation	75
9 Case 8: LCA on the trials of Ladle Preheater from 7Steel	79
9.1 Scope and goal	79

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

9.2	Life cycle inventory	79
9.3	Impact assessment	80
9.4	Interpretation	81
10	Framework for future NO_x regulation in hydrogen-fired industrial furnaces	84
10.1	Introduction.....	84
10.2	Current NO _x Reporting and Measurement Framework	84
10.3	Challenges of Current NO _x Reporting for Hydrogen Combustion.....	86
10.4	Alternative Reporting Approaches	89
10.5	Measurement and Monitoring Requirements for Alternative Approaches	93
10.6	Demonstrator Results.....	95
10.7	Conclusions.....	103
11	Bibliography	105
12	Annex.....	107
12.1	Annex A: Umberto 11 [®] model from baseline of case 1	107
12.2	Annex B: Umberto 11 [®] model from scenario 1 of case 1.....	108
12.3	Annex C: Umberto 11 [®] model from baseline of case 2.....	109
12.4	Annex D: Umberto 11 [®] model from scenario 1 of case 2	110
12.5	Annex E: Umberto 11 [®] model from the baseline of case 3	111
12.6	Annex F: Umberto 11 [®] model from scenario 1 of case 3	112
12.7	Annex G: Umberto 11 [®] model from baseline of case 4.....	113
12.8	Annex J: Umberto 11 [®] model from scenario 1 of case 4.....	114
12.9	Annex K: Umberto 11 [®] model from scenario 2 of case 4.....	115
12.10	Annex L: Umberto 11 [®] model from baseline of case 5	116
12.11	Annex M: Umberto 11 [®] model from scenario 1 of case 5	117
12.12	Annex N: Sphera LCA Expert model for Case 6	118

List of Figures

Figure 2.1: Electricity mix for electricity production in Greece in 2025. Data taken from [3].....	15
Figure 2.2: Percentage of IA of each process from the case 1 baseline (ReCiPe 2016 Midpoint-H)	16
Figure 2.3: Mean values distribution for all the processes and environmental impacts under the case 1 baseline	16
Figure 2.4: Mean values distribution for all the processes and environmental impacts from the case 1 scenario 1.....	17
Figure 2.5: Percentage of IA of each process from the case 1 scenario 1 (ReCiPe 2016 Midpoint-H).....	18
Figure 2.6: Relative change for all impact categories with respect to baseline for case 1.....	19
Figure 2.7: Sensitivity analysis for the NG and electricity demand for baseline from case 1	20
Figure 2.8: Sensitivity analysis for the H ₂ and electricity demand for scenario 1 from case 1.....	22
Figure 3.1: Electricity mix for electricity production in Spain in 2024. Data taken from [4]	24
Figure 3.2: Percentage of IA of each process from the case 2 baseline (ReCiPe 2016 Midpoint-H)	26
Figure 3.3: Distribution of the mean values among the considered processes for all the environmental impacts under the baseline scenario	26
Figure 3.4: Percentage of IA of each process from the case 2 scenario (ReCiPe 2016 Midpoint-H).....	27
Figure 3.5: Distribution of the mean value among the processes for all the environmental impacts under the hydrogen oxycombustion scenario	28
Figure 3.6: Relative change for all impact categories with respect to baseline for case 2.....	29
Figure 3.7: Sensitivity analysis for the NG and electricity demand for baseline from case 2	30
Figure 3.8: Sensitivity analysis for the H ₂ and electricity demand for scenario 1 from case 2.....	32
Figure 4.1: Electricity mix for electricity production in France in 2024. Data taken from [5]	35
Figure 4.2: Percentage of IA of each process from the case 3 baseline (ReCiPe 2016 Midpoint-H)	37
Figure 4.3: Distribution of the mean value among the processes for all the environmental impacts under the baseline scenario.....	37
Figure 4.4: Percentage of IA of each process from the case 3 scenario 1 (ReCiPe 2016 Midpoint-H).....	38
Figure 4.5: Distribution of the mean value among the processes for all the environmental impacts under the scenario 1	39
Figure 4.6: Relative change for all impact categories between baseline (reference) and scenario 1 for case 3	40
Figure 4.7: Results on the sensitivity analysis for the NG and electricity demand for baseline from case 3..	41
Figure 4.8: Results on the sensitivity analysis for hydrogen and electricity demand on the scenario 1 from case 3.....	42
Figure 5.1: Percentage of IA of each process from the case 4 baseline (ReCiPe 2016 Midpoint-H)	46
Figure 5.2: Distribution of the mean value among the processes for all the environmental impacts under the baseline scenario for case 4	46
Figure 5.3: Percentage of IA of each process from the case 4 scenario 1 (ReCiPe 2016 Midpoint-H).....	48

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Figure 5.4: Distribution of the mean value among the processes for all the environmental impacts under the scenario 1 for case 4	48
Figure 5.5: Percentage of IA of each process from the case 4 scenario 2 (ReCiPe 2016 Midpoint-H).....	49
Figure 5.6: Distribution of the mean value among the processes for all the environmental impacts under the scenario 2	49
Figure 5.7: Relative change for all impact categories among baseline (reference), scenario 1 and scenario 2	50
Figure 5.8: Sensitivity analysis on the NG and electricity demand for the baseline from case 4	51
Figure 5.9: Sensitivity analysis on the Hydrogen and electricity demand for the scenario 1 from case 4	52
Figure 5.10: Sensitivity analysis on the Hydrogen and electricity demand for the scenario 2 from case 4	53
Figure 6.1: Electricity mix for electricity production in Germany for 2025. Data taken from [10]	56
Figure 6.2: Percentage of IA of each process from the case 5 baseline (ReCiPe 2016 Midpoint-H)	57
Figure 6.3: Distribution of the mean value among the processes for all the environmental impacts under the baseline scenario for case 5	58
Figure 6.4: Distribution of the mean value among the processes for all the impact categories under scenario 1 for case 5	59
Figure 6.5: Percentage of IA of each process from the case 5 scenario 1 (ReCiPe 2016 Midpoint-H).....	59
Figure 6.6: Relative change for all impact categories between baseline (reference) and scenario 1 for case 5	60
Figure 6.7: Results on the sensitivity analysis for NG and electricity demand on the baseline from case 5 ..	61
Figure 6.8: Results on the sensitivity analysis for H ₂ and electricity demand on the baseline from case 5	63
Figure 7.1 Impact categories for all cases	67
Figure 7.2 Global Warming Potential analysis.....	68
Figure 10.1: Differences in minimum off-gas volume moist $v_{og,min,moist}$ and dry $v_{og,min,dry}$ ($\lambda = 1$) for the combustion of natural gas H and hydrogen with air. [31]	87
Figure 10.2: Calculated moist off-gas composition for the combustion of natural gas H and hydrogen with air (a) and oxygen (b) for different air ratios λ (bal. N ₂). [31]	87
Figure 10.3: Schematic for NO _x emission calculation; current standards and regulations (a) and proposed universal limit definition (b) [31].....	95
Figure 10.4: Comparison of a) NO _x values and b) O ₂ values and c) H ₂ O values of the different analysers at the CTEC demonstrator	98
Figure 10.5: Comparison of different NO _x reporting approaches for the analyser 3 at the CTEC demonstrator a) on a moist basis and b) on a dry basis.....	99
Figure 10.6: Comparison of a) NO _x values for the analysers 1 and 3 and b) O ₂ values of the analysers 1 and 4 and c) H ₂ O values for the analyser 2 at the SWERIM demonstrator	102
Figure 10.7: Comparison of different NO _x reporting approaches for the Analyser 3 at the SWERIM demonstrator	103
Figure 12.1: Model from the software Umberto 11® for the baseline in case 1	107
Figure 12.2: Model from the software Umberto 11® for the hydrogen combustion in case 1	108

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Figure 12.3: Model from the software Umberto 11® for the baseline in case 2	109
Figure 12.4: Model from the software Umberto 11® for the scenario 1 in case 2	110
Figure 12.5: Model from the software Umberto for the baseline in case 3	111
Figure 12.6: Model from the software Umberto 11® for the scenario 1 in case 3	112
Figure 12.7: Model from the software Umberto 11® for the baseline of case 4	113
Figure 12.8: Model from the software Umberto 11® for the H2/air combustion of case 4	114
Figure 12.9: Model from the software Umberto 11® for the hydrogen oxycombustion scenario in case 4	115
Figure 12.10: Model from the software Umberto 11® for the baseline in case 5	116
Figure 12.11: Model from the software Umberto 11® for the scenario 1 in case 5	117
Figure 12.12 Model from Sphera LCA Expert 2026 for case 6 (Annealing Furnace).....	118
Figure 12.13 Model from Sphera LCA Expert 2026 for case 6 for electricity supply	118

List of Tables

Table 1.1: Case description of LCAs performed throughout the study	13
Table 2.1: Input and output parameters for baseline from case 1 based on trials from METL.....	14
Table 2.2: Input and output parameters for hydrogen oxycombustion from case 1 provided by METL	14
Table 2.3: Values on the IA for the NG combustion scenario of case 1 (ReCiPe 2016 Midpoint-H).....	15
Table 2.4: Values on the IA for the Hydrogen combustion of case 1 (ReCiPe 2016 Midpoint-H)	17
Table 2.5: Percentage deviation of all impact categories in reference to baseline for case 1	18
Table 2.6: Results on the sensitivity analysis for the NG and electricity demand for baseline from case 1	20
Table 2.7: Results on the sensitivity analysis for the H ₂ and electricity demand for scenario 1 from case 1..	21
Table 3.1: Input and output parameters for baseline from case 2 provided by BEF	23
Table 3.2: Input and output parameters for hydrogen oxycombustion from case 2 provided by BEF	23
Table 3.3: Values on the impact assessment on the baseline case of case 2 (ReCiPe 2016 Midpoint-H)	25
Table 3.4: Values on the IA on the scenario 1 of case 2 (ReCiPe 2016 Midpoint-H)	27
Table 3.5: Percentage deviation of all impact categories in reference to baseline for case 2	28
Table 3.6: Results on the sensitivity analysis for the NG and electricity demand for baseline from case 2	31
Table 3.7: Results on the sensitivity analysis for the H ₂ and electricity demand for scenario 1 from case 2..	32
Table 4.1: Input and output parameters for modelling the baseline case from case 3 provided by CTEC	34
Table 4.2: Input and output parameters for modeling the retrofitted case from case 1 provided by CTEC...	35
Table 4.3: Values on the IA for the baseline of case 3 (ReCiPe 2016 Midpoint-H)	36
Table 4.4: Values on the IA for the hydrogen oxycombustion scenario of case 3 (ReCiPe 2016 Midpoint-H)	37
Table 4.5: Percentage deviation of all impact categories from the scenario 1 from case 3 (ReCiPe 2016 Midpoint-H)	39
Table 4.6: Results on the sensitivity analysis for the NG and electricity demand for baseline from case 3	42
Table 4.7: Results on the sensitivity analysis for hydrogen and electricity demand on the scenario 1 from case 3.....	43
Table 5.1: Input and output parameters for the baseline case from case 4.....	44
Table 5.2: Input and output parameters for the Hydrogen/air combustion from case 4	44
Table 5.3: Input and output parameters for the Hydrogen oxycombustion case from case 4	45
Table 5.4: Values on the IA for the NG combustion case of case 4 (ReCiPe 2016 Midpoint-H).....	45
Table 5.5: Values on the IA for the H ₂ /air combustion of case 4 (ReCiPe 2016 Midpoint-H)	47
Table 5.6: Values on the IA for the NG combustion case from case 4 (ReCiPe 2016 Midpoint-H)	48
Table 5.7: Percentage deviation of all impact categories in reference to baseline for case 4 under scenario 1 and 2	50
Table 5.8: Results on the sensitivity analysis for the NG and electricity demand for baseline from case 4	51
Table 5.9: Results on the sensitivity analysis for the H ₂ and electricity demand for scenario 1 from case 4..	52
Table 5.10: Results on the sensitivity analysis for the H ₂ and electricity demand for scenario 2 from case 4	53
Table 6.1: Input and output parameters for modelling the NG combustion with air for case 5	55

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 6.2: Input and output parameters for modelling the H ₂ combustion with air for case 5.....	55
Table 6.3: Values on the IA for the baseline scenario of case 5 (ReCiPe 2016 Midpoint-H)	56
Table 6.4: Values on the IA for the scenario 1 of case 5	58
Table 6.5: Percentage deviation of all impact categories from the scenario 1 from case 5 (ReCiPe 2016 Midpoint-H)	60
Table 6.6: Results on the sensitivity analysis for the NG and electricity demand for baseline from case 5	62
Table 6.7: Results on the sensitivity analysis for H ₂ and electricity demand on the baseline from case 5	63
Table 7.1: Input and output parameters for modelling the baseline case from TME	65
Table 7.2: Input parameters for modelling the hydrogen scenarios from TME	65
Table 7.3 Baseline results	66
Table 7.4 EU electricity mix results	67
Table 7.5 Renewable electricity scenario.....	68
Table 10.1: Overview of NO _x emission reporting frameworks in the steel and aluminium sectors.....	85
Table 10.2: Calculated NO _x concentrations on a moist basis for different fuel-oxidiser combinations assuming a constant NO _x mass flow of 300 mg/h	90
Table 10.3: Calculated NO _x emissions expressed in mg/kWh for different fuel-oxidiser combinations assuming a constant NO _x mass flow of 300 mg/h.....	91
Table 10.4: Different NO _x limit specifications for the combustion of NG and H ₂ with air, based on a measured concentration of 180 ppmv _{dry} ; reference O ₂ concentrations in the off-gas: 3.0 vol% (dry) and 2.5 vol% (moist) [31].....	92
Table 10.5: Different NO _x limit specifications for the combustion of NG and H ₂ with pure oxygen, based on a measured concentration of 180 ppmv _{moist} ; reference O ₂ concentration in the off-gas: 2.5 vol% (moist) [31]	93
Table 10.6: Comparison of NO _x emission reporting approaches for industrial combustion systems	93
Table 10.7: Overview of the available data from the demonstrators	96
Table 10.8: Overview of specifications of relevant analysers used at the CTEC demonstrator for NO _x and O ₂ measurements.....	97
Table 10.9: Overview of operating conditions during the trials at the CTEC demonstrator	98
Table 10.10: Overview of specifications of relevant analysers used at the SWERIM demonstrator for NO _x and O ₂ measurements.....	100
Table 10.11: Overview of operating conditions during the trials at the SWERIM demonstrator	101

List of Abbreviations

Abbreviations	Explanation
AEC	Alkaline Electrolysis Cell
ASU	Air Separation Unit
BEF	Befesa Aluminio SLU
CO ₂	Carbon Dioxide
CTEC	Constelium Technology Center
FD	Fossil Depletion Potential
FET	Freshwater Eutrophication
FU	Functional Unit
e.g.	exempli gratia (for example)
et al.	Et alii/aliae (and others)
GWP	Global Warming Potential
H ₂ O	Water
H ₂	Hydrogen
HTP	Human Toxicity Potential
i.e.	id est (that is)
IA	Impact Assessment
IOB	Institut für Industrieofenbau und Wärmetechnik
IR	Ionizing Radiation
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LFO	Light Fuel Oil
METL	Metlen Energy and Metals
MET	Marine Eutrophication Potential
MD	Metal Depletion
NA	Not Available
NG	Natural Gas
NO _x	Nitrogen oxides
NTNU	Norwegian University of Science and Technology
O ₂	Oxygen
OFh	Ozone formation, human health

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Oft	Ozone formation, terrestrial ecosystems
OD	Stratospheric Ozone Depletion
PMF	Fine Particulate Matter Formation
POF	Photochemical Ozone Formation
Resp.	Responsible
RWTH	Rheinisch-Westfälische Technische Hochschule Aachen
R&D	Research and Development
SA	Sensitivity Analysis
SMR	Steam Methane Reforming
SPE	Speira GmbH
SWE	Swerim AB
TRL	Technology Readiness Level
TME	Toyota Motor Europe
TAP	Terrestrial Acidification
WD	Water depletion
WP	Work Package

1 Introduction

Throughout this report, the **Life Cycle Assessment (LCA)** for **6 cases in the aluminium industry** (cases 1 to 6, Table 1.1) and **2 cases from the steel industry** (cases 7 and 8, Table 1.1) will be conducted. Furthermore, primary data obtained from the demonstration will be completed with calculations, especially regarding off-gas composition. Subsequently, Table 1.1 presents the description of each case and the conditions applied in the following LCA.

As stated in report D1.2, these assessments have been performed by three different individuals applying the LCA methodology based on ReCiPe 2016 (Midpoint-H) but with different impact categories. For that purpose, the first 5 Aluminium cases have been conducted according to the impact categories presented in report D1.2 in section A.2.2.4. These impact categories were selected based on recommendations from European Aluminium Agency and the results from Santero and Hendry [1,2]. Furthermore, to the aforementioned categories, the categories FD, FET, HTP, MD, LU, POF and WD have been added in order to have a detailed analysis into the effect of NO_x and CO₂ emissions into the environment. The full ecological profile was discarded, because there were some categories which did not provide any value in relation to the objective of this project presented in the proposal. Finally, a full ecological profile according to ReCiPe 2016 (Midpoint-H) have been conducted for the steel cases.

Table 1.1. Case description of LCAs performed throughout the study

Case	Partner	Process	Type of furnace	Demo/ Study	Baseline	Scenario 1	Resp.
1	METL	Holding	Ladle preheater	Demo	NG oxyfuel combustion	H2 oxyfuel	IOB
2	BEF	Melting	Rotary furnace	Demo	NG oxyfuel combustion	H2 oxyfuel	IOB
3	CTEC	Melting	Reverb. Furnace	Demo	NG/air combustion	H2 oxyfuel	IOB
4	METL	Melting	Reverb. Furnace	Study	NG/air combustion	H2/air combustion + H2 oxyfuel	IOB
5	SPE	Preheating	Pusher furnace	Study	NG/air combustion	H2/air combustion	IOB
6	TME	Annealing	Annealing furnace	Demo	NG/air combustion	H2/air combustion	TME
7	SSAB	Reheating	W. beam furnace	Study	NG/coke oven gas	H2 oxyfuel	SWE
8	7Steel	Reheating	Ladle preheater	Demo	CO	H2 oxyfuel	SWE

In addition, the deliverable assesses the **suitability of current and alternative NO_x reporting approaches for hydrogen-based industrial combustion systems** in Section 10. The analysis covers air-fuel, oxygen-enriched and oxyfuel combustion and considers both the current regulatory framework and alternative approaches proposed in the literature. The different approaches are then applied to available demonstrator results from the project. This assessment builds on the review of existing emission regulations provided in D1.2 and will serve as input to D8.8, which will propose concepts for future NO_x limit definitions, emission reporting methodologies and standardisation activities.

2 Case 1: LCA on the trials of the ladle preheater from METLEN

2.1 Scope and goal

The scope and goal applied for this case is described in section A.2.2.4 from report D1.2. Nevertheless, some modifications need to be clarified. In this case a “cradle-to-gate” LCA is going to be performed in which the H₂ source is a Steam Methane Reforming (SMR) process. Furthermore, in this case the refractories from the ladle are not going to be considered. Also, as a clarification the Functional Unit (FU) is going to be the aluminium held in the furnace and the oxidant during the combustion process is oxygen instead of air. Finally, the emissions to air of Nitrogen and CO will not be considered.

2.2 Life cycle inventory

The following data represents the ladle preheater in the factory in Agios Nikolaos (Greece), which is modelled for the trials performed in 2025 and described in D5.1. More into detail, Table 2.1 presents the data for the modelling of the Natural gas (NG) and oxygen trials performed in this case. The data shown was calculated manually based on the data from the trials with $\lambda = 1$. These trials were performed with the full ladle of molten aluminium during 3h with a burner power of 25 kW. Finally, the NO_x values were taken from the trials on the 1.5 t reverberatory furnace from SPE on delivery D2.1. The electricity consumption in this type of trial was not considered.

Table 2.1: Input and output parameters for baseline from case 1 based on trials from METL

	Parameter	Unit	Value	Comment
Input	Volume NG	Nm ³	7.02	Calculated
	Oxygen	m ³	15	Calculated
	Molten aluminium	t	4.2	Measured
Output	Molten aluminium	t	4.2	Measured
	NO _x	mg/MJ	81	Measured*
	CO ₂	kg	14.14	Calculated
	H ₂ O	m ³	14.78	Calculated

*Measured in different burner

Subsequently Table 2.2 presents the data for the modelling of the hydrogen oxycombustion trials. The data given from the trials and the data calculated is shown in the table below respectively. Similar as in the previous table, the NO_x values were taken from deliverable D2.1, as no measurements were performed in this case.

Table 2.2: Input and output parameters for hydrogen oxycombustion from case 1 provided by METL

	Parameter	Unit	Value	Comment
Input	Hydrogen	kg	3.1	Measured
	Oxygen	m ³	19.4	Calculated
	Molten aluminium	t	4.2	Measured
Output	Molten aluminium	t	4.2	Measured
	NO _x	mg/MJ	209	Measured*
	CO ₂	kg	0	Calculated
	H ₂ O	m ³	41.86	Calculated
	O ₂	kg	0	Calculated

*Measured with in burner

Figure 2.1: Electricity mix for electricity production in Greece in 2025. Data taken from [3] presents the mix of electricity production sources in Greece in 2025. This data was taken from the source [3]. This electricity mix will be applied in the model.

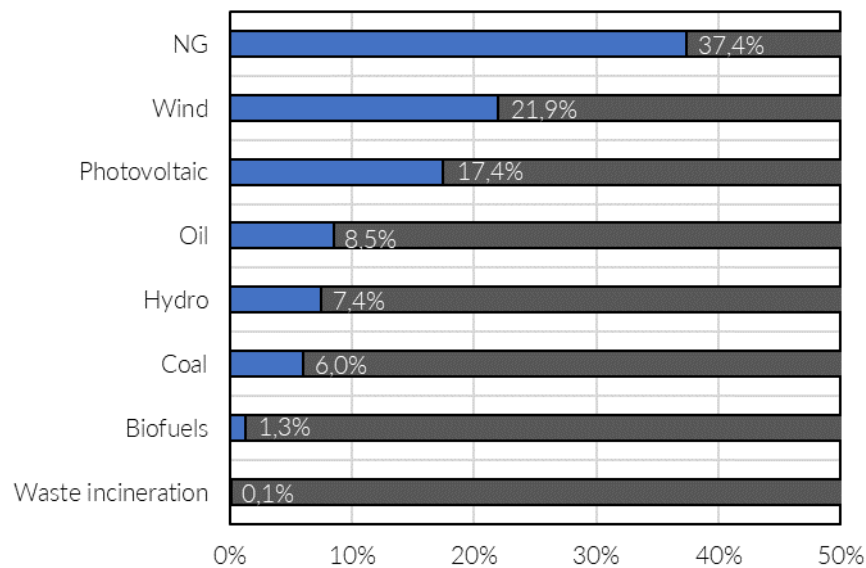


Figure 2.1: Electricity mix for electricity production in Greece in 2025. Data taken from [3]

2.3 Impact assessment

2.3.1 Baseline case

Table 2.3 presents the values on the Impact Assessment (IA) for the NG combustion case on the ladle preheater case. In this case, the following process have been considered: NG, electricity (shown in Figure 2.1) and oxygen production and NG combustion. Based on the input data presented in Table 2.1, this case led to $6.5 \cdot 10^{-3} \text{ tCO}_2/\text{tal}$, from which 51% of this quantity is generated on the combustion process in the furnace. The model applied in the software Umberto 11® to obtain this value is presented in Figure 12.1 in Annex A.

Table 2.3: Values on the IA for the NG combustion scenario of case 1 (ReCiPe 2016 Midpoint-H)

Impact category	Acronym	Unit	Value
Fossil depletion Potential	FD	kg oil-eq/tal	2.36
Freshwater Eutrophication	FET	kg P eq/tal	$1.7 \cdot 10^{-3}$
Global Warming Potential	GWP	kg CO ₂ eq/tal	6.58
Human Toxicity Potential	HTP	kg 1.4 DB/tal	2.79
Ionizing radiation	IR	kBq Co-60 eq/tal	$20.1 \cdot 10^{-3}$
Land use	LU	Annual crop eq/tal	$8.4 \cdot 10^{-3}$
Metal Depletion	MD	kg Cu-eq/tal	$43.4 \cdot 10^{-3}$
Marine Eutrophication	MET	kg N eq/tal	$0.25 \cdot 10^{-3}$
Stratospheric Ozone Depletion	OD	kg CFC-11-eq/tal	$1.55 \cdot 10^{-6}$
Fine Particulate Matter Formation	PMF	kg PM _{2.5} -eq/tal	$3 \cdot 10^{-3}$
Photochemical Ozone Formation	POF	kg NO _x eq/tal	$10.7 \cdot 10^{-3}$
Terrestrial Acidification	TAP	kg SO ₂ -eq/tal	$7 \cdot 10^{-3}$
Water depletion	WD	m ³ water -eq/tal	3.6

Figure 2.2 presents the percentage of each process on each impact category for case 1. In this case, although no electricity consumption was measured in the process per se, only the electricity used for the production of NG and oxygen was considered. Consequently, the value of 7 out of 13 impact categories was higher than 50% in this process. Nevertheless, NG production also plays an important role in the environmental impact, since the value of 3 out of 13 categories are over 40% in this process as well. Therefore, both aforementioned processes are significant for the environmental impact in this case. The dominance of these two processes will be analysed in the Sensitivity Analysis (SA). Finally, the remaining processes have less influence in the

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

impact categories, except the combustion process in the furnace, which has special impact on WD, due to the water emissions.

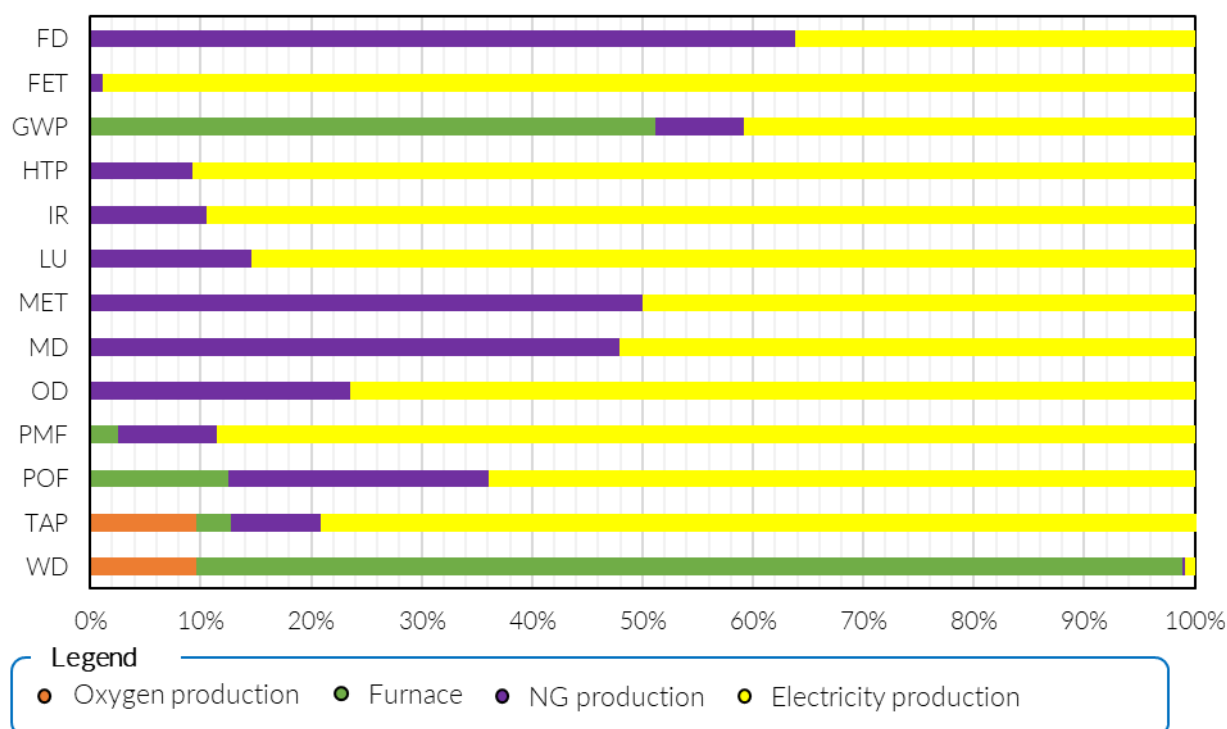


Figure 2.2: Percentage of IA of each process from the case 1 baseline (ReCiPe 2016 Midpoint-H)

Figure 2.3 represents the distribution of the impact categories mean values among the processes under the baseline scenario. In particular, it shows the influence of each process individually. More into detail, the aforementioned influence of the electricity and NG production processes is represented on this figure with 69.2% and 21.3% respectively. However, the value of 8.7% obtained for the NG combustion process (i.e. "Furnace", Figure 2.3), is due to the high value on WD. Finally, the environmental impact in the oxygen production is below 2%. Therefore, based on the results presented in Figure 2.2 and Figure 2.3, it can be stated that the influence of the oxygen production process on the environmental impact is minimal, and thus, could be neglected.

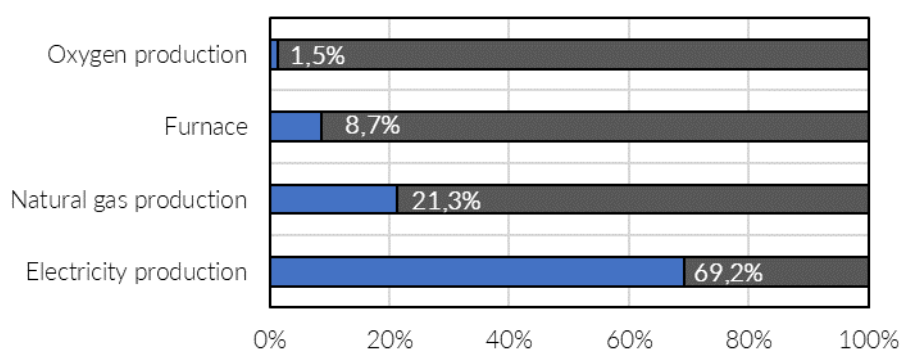


Figure 2.3: Mean values distribution for all the processes and environmental impacts under the case 1 baseline

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

2.3.2 Scenario 1: Hydrogen oxycombustion

Table 2.4 presents the results on the IA for the hydrogen oxycombustion scenario for case 1. This evaluation was done based on the data from Table 2.2. As result, these trials led to 0.037 tCO₂/tal, from which 90.6% was generated on the hydrogen production process, which in this case is SMR process. The rest was generated on the electricity production process, whose production mix was presented in section 2.2. Then, the model used for the calculation of these values is presented in Figure 12.2 from Annex B.

Table 2.4: Values on the IA for the Hydrogen combustion of case 1 (ReCiPe 2016 Midpoint-H)

Impact category	Acronym	Unit	Value
Fossil depletion Potential	FD	kg oil-eq/tal	13.82
Freshwater Eutrophication	FET	kg P eq/tal	3*10 ⁻³
Global Warming Potential	GWP	kg CO ₂ eq/tal	37.08
Human Toxicity Potential	HTP	kg 1.4 DB/tal	11.17
Ionizing radiation	IR	kBq Co-60 eq/tal	0.18
Land use	LU	Annual crop eq./tal	0.7*10 ⁻³
Metal Depletion	MD	kg Cu-eq/tal	0.35
Marine Eutrophication	MET	kg N eq/tal	67.4*10 ⁻³
Stratospheric Ozone Depletion	OD	kg CFC-11-eq/tal	4.13*10 ⁻⁶
Fine Particulate Matter Formation	PMF	kg PM ₂₅ -eq/tall	9.9*10 ⁻³
Photochemical Ozone Formation	POF	kg NO _x eq./tal	58.8*10 ⁻³
Terrestrial Acidification	TAP	kg SO ₂ -eq/tal	25.4*10 ⁻³
Water depletion	WD	m ³ water -eq/tal	6.87

Figure 2.4 shows distribution of the mean values among the processes for all the environmental impacts under the scenario 1. This figure emphasizes the high influence of the SMR process over the model, which led to a 77.3% on the impact categories mean values. More into detail, as result of the use of H₂, the environmental impact of the combustion process is reduced, due to its influence on the category GWP. Similar as the case before and, as shown in Figure 2.3 and Figure 2.5, the influence of oxygen production is minimal, based on the value of 0.1% of their impact categories mean values. Therefore, it could be stated that the effect of the oxygen production process can be neglected.

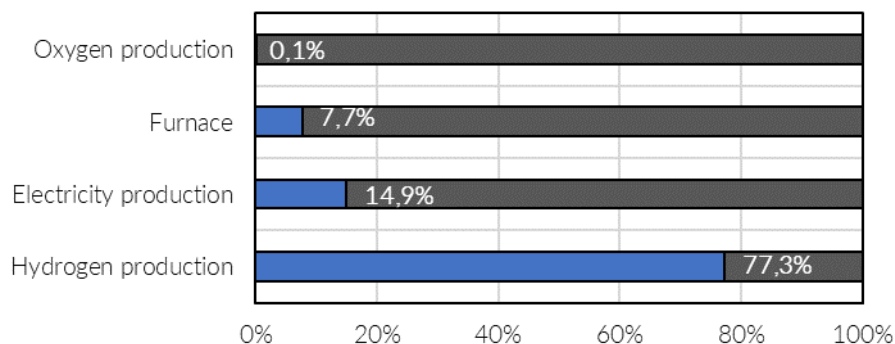


Figure 2.4: Mean values distribution for all the processes and environmental impacts from the case 1 scenario 1

Figure 2.5 represents the percentage of IA of each process from case 1 under the Hydrogen scenario. In this case, the SMR process has the most influence in the environmental impact, as 11 out of 13 impact categories are over 50%, due to this process. The only exceptions are WD and FET, which are influenced by the combustion and electricity production process respectively. Furthermore, although the oxygen demand for this case is higher in comparison to the NG case, due to the hydrogen combustion conditions, the influence of oxygen production still resulted in less than 1%, thus, its effect can be considered negligible.

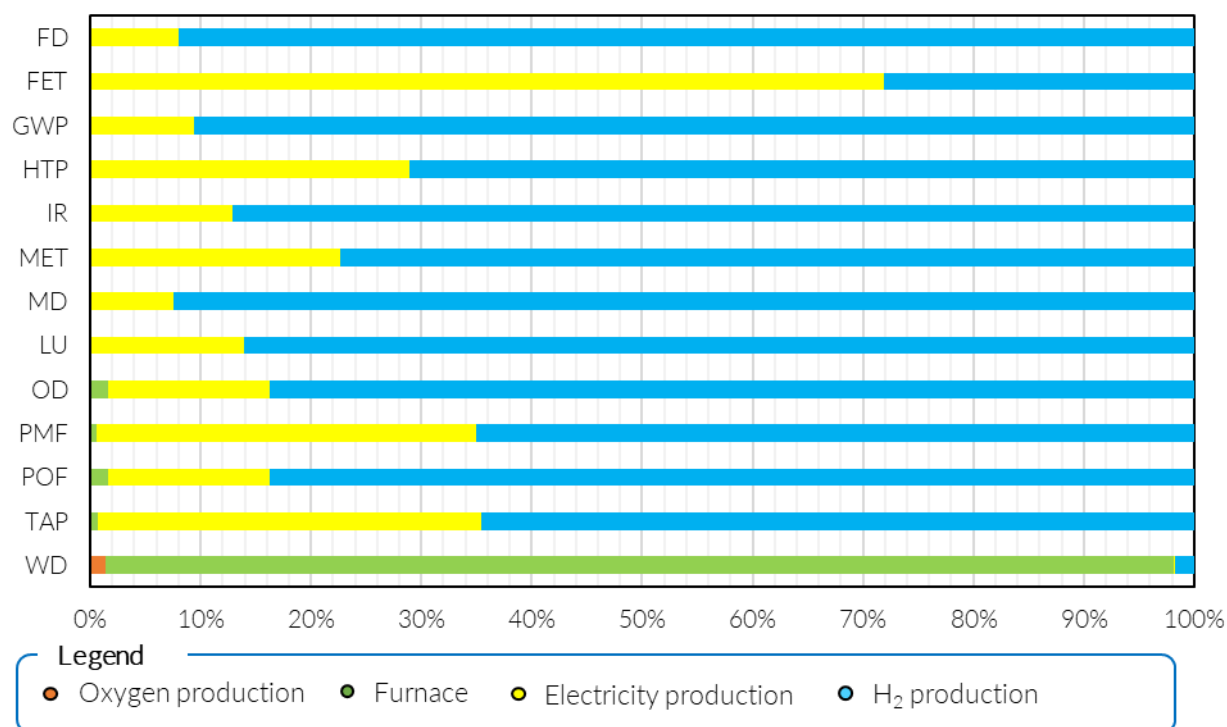


Figure 2.5: Percentage of IA of each process from the case 1 scenario 1 (ReCiPe 2016 Midpoint-H)

2.3.3 Results comparison

Table 2.5 shows the values for the comparison on all the impact categories between the NG combustion and H₂ combustion cases. The values presented in this table are graphically shown in Figure 2.6. Consequently, all the impact categories analysed in the hydrogen combustion case led to a worse environmental impact, in comparison to the baseline. In particular, the category FET obtained a value 77% higher. Then, the categories MET, OD, PMF, POF and TAP resulted on values between 2 and 3 times higher in comparison to the baseline. Finally, the rest of the categories obtained values up to 8.6 times higher. The impact categories with highest values are MD, WD and IR. The high variation of this case is based on the SMR process, which has higher environmental impact as the extraction of NG per se, since for the SMR process requires NG for producing Hydrogen. Therefore, in this process not only the use of NG is considered, but also the emissions generated on the SMR for the production of H₂ are taken into account. Furthermore, the higher values on WD are based on the chemical reaction of H₂ with oxygen.

Table 2.5: Percentage deviation of all impact categories in reference to baseline for case 1

Impact category	Baseline	Scenario	Unit
Fossil depletion Potential	100%	530.9%	kg oil-eq/t _{al}
Freshwater Eutrophication	100%	177.7%	kg P eq/t _{al}
Global Warming Potential	100%	562%	kg CO ₂ eq/t _{al}
Human Toxicity Potential	100%	400%	kg 1.4 DB/t _{al}
Ionizing radiation	100%	880.5%	kBq Co-60 eq./t _{al}
Marine Eutrophication	100%	264.8%	kg N eq/t _{al}
Metal Depletion	100%	824.2%	kg Cu-eq/t _{al}
Land use	100%	777.8%	Annual crop eq./t _{al}
Stratospheric Ozone Depletion	100%	266.1%	kg CFC-11-eq/t _{al}
Fine Particulate matter formation	100%	309.7%	kg PM25-eq/t _{al}
Photochemical Ozone formation potential	100%	219.2%	kg NO _x eq./t _{al}
Terrestrial Acidification	100%	303.6%	kg SO ₂ -eq/t _{al}
Water depletion	100%	858.8%	m ³ water -eq/t _{al}

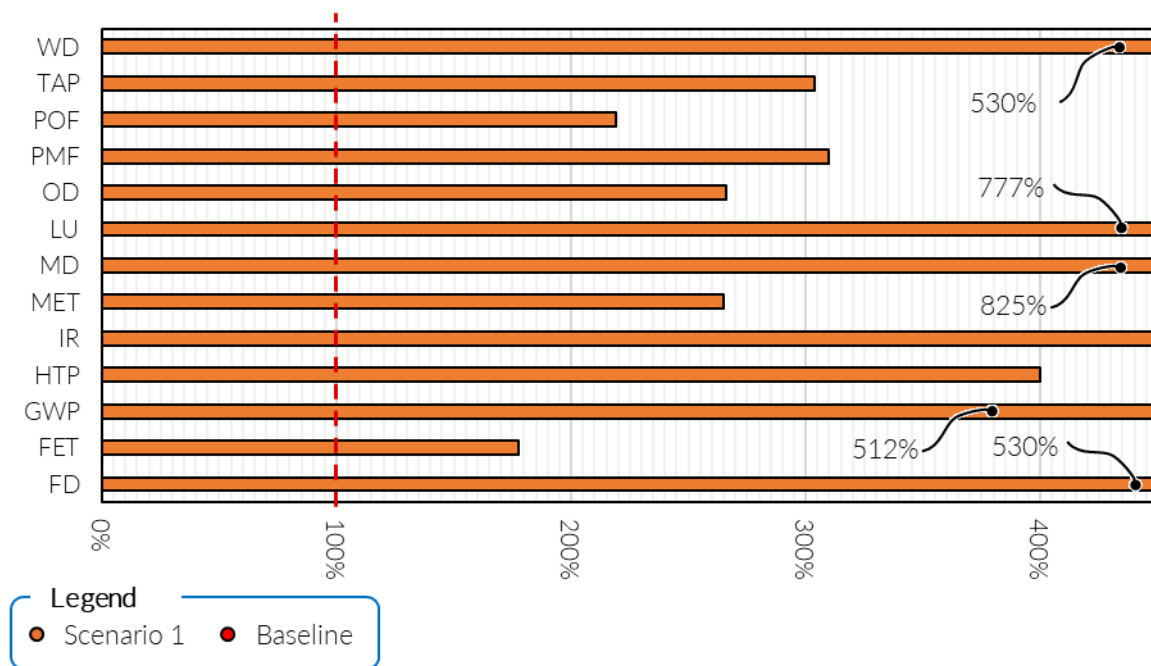


Figure 2.6: Relative change for all impact categories with respect to baseline for case 1

2.4 Interpretation

2.4.1 Sensitivity analysis in the baseline case

Table 2.6 presents the results on the SA for the NG combustion scenario for case 1. In this case, the variables of NG and electricity demand have been modified. As mentioned in section 2.3.1, these are the variables with higher influence in the model. Throughout this section it will be examined the robustness and independency of the model from the aforementioned variables. Furthermore, the output data of the SA has been represented in Figure 2.7.

Regarding the NG production process, Figure 2.7 presents in dark and light purple the results on the SA for the NG demand for the baseline case. Based on the subtracted value from the baseline, the SA show a mean value of 0.015 and a median value of $8.3 \cdot 10^{-3}$. Therefore, as a general overview, these values demonstrate that the sensitivity of the NG demand over the model is low, as the maximal achievable value possible is 0.05. Furthermore, these results show that the data distribution obtained for the SA in this case is dragged to the left (closer to zero). Nevertheless, the impact categories of FD and GWP still slightly influence the model, as their values remain between 3% and 3.5%. Finally, the impact category WD is not influenced by the NG production process, as did not vary in this part.

The SA conducted on the electricity demand is represented in Figure 2.7 with dark and light-yellow lines. In this case, the SA show values closer to the upper limit of 0.05. In particular, a mean value of 0.032 and a median value of 0.035, which demonstrate a remarkable influence of this process over the model. Also, the standard deviation on this analysis is 0.0138, which indicates a significant dispersion. Therefore, the values obtained from the SA are dispersed and high and, thus, leading to a high variability of the electricity demand over the model. Especially in categories such as FET, HTP, IR, LU, PMF and TAP in which values remained equal and over 4%. Similar as before, WD remains invariable.

Consequently, as described in 2.3.1 and aforementioned, the electricity production process has high influence over the model, especially in the categories FET, HTP, IR, LU, PMF and TAP. Then, based on the mean value on impact categories (subchapter 2.3.1) and the results on the SA conducted on the NG production process, it can be inferred that the model is less dependent from NG demand, except in the FD and GWP categories. Also, the impact category WD, and, thus, the model, is only dependent on the NG combustion process.

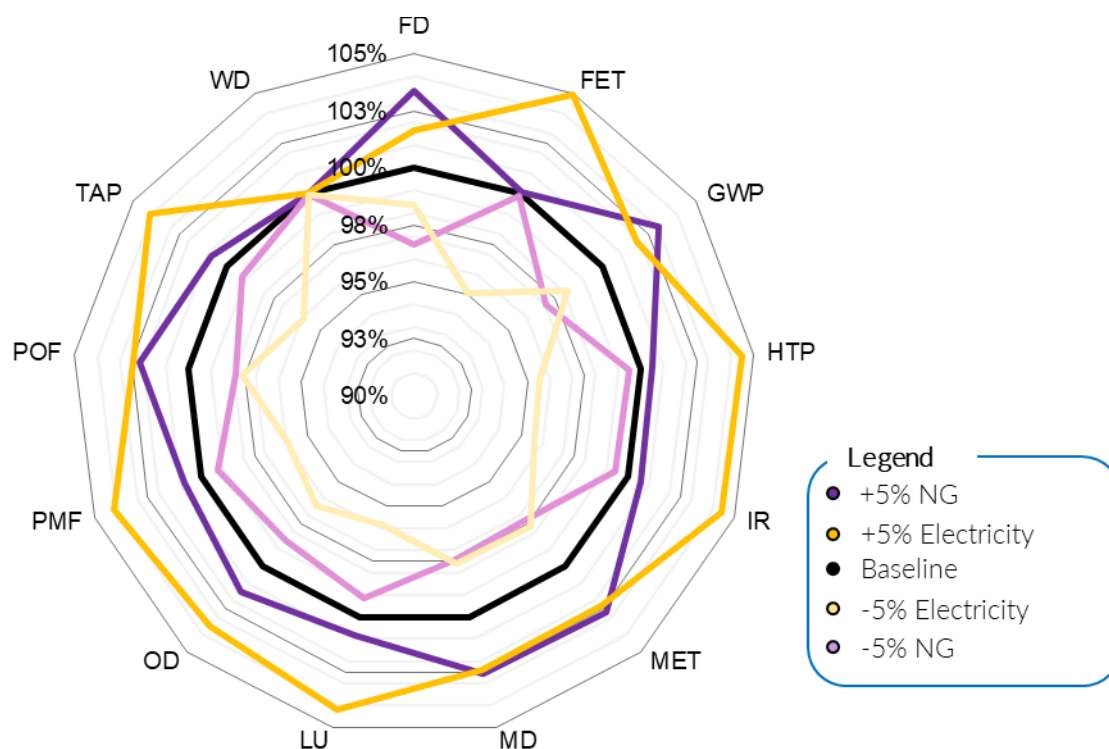


Figure 2.7: Sensitivity analysis for the NG and electricity demand for baseline from case 1

Table 2.6: Results on the sensitivity analysis for the NG and electricity demand for baseline from case 1

Impact category	Baseline	+5% NG demand	-5% NG demand	+5% Electricity demand	-5% Electricity demand
FD	100%	103%	97%	102%	98%
FET	100%	100%	100%	105%	95%
GWP	100%	103%	97%	102%	98%
HTP	100%	101%	99%	104%	96%
IR	100%	101%	99%	104%	96%
MET	100%	103%	97%	102%	98%
MD	100%	103%	97%	102%	98%
LU	100%	101%	99%	104%	96%
OD	100%	101%	99%	104%	96%
PMF	100%	101%	99%	104%	96%
POF	100%	102%	98%	102%	98%
TAP	100%	101%	99%	104%	96%
WD	100%	100%	100%	100%	100%

2.4.2 Sensitivity analysis in the hydrogen case

Table 2.7 presents the SA for case 1 on the hydrogen combustion scenario, in which the hydrogen and electricity demand have been modified on $\pm 5\%$. The results obtained from the SA are graphically presented in Figure 2.8. The selection of these variables was done according to the arguments presented in section 2.3.2, in which it was demonstrated that the aforementioned process showed high influence over the process. However, the independence and robustness of the model will be examined throughout this section.

With respect to the H_2 production process, Figure 2.8 shows in dark and light blue the results obtained for the $\pm 5\%$ modification on the Hydrogen demand applied in the model. As result, a mean value of 0.035 and a median value of 0.0389 were obtained. Based on these values, it can be concluded that this process has high influence on the model, as the values obtained are closer to 0.05, which is the maximum variability possible. This fact is presented especially in categories like FD, GWP, IR, MD, LU and POF. Furthermore, the standard deviation obtained for this analysis is 0.013, which represents that the values are dispersed. This result is mainly influenced by the values on WD and FET, which drag the data distribution opposite to the maximum

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

value (0.05). Therefore, based on the previously described results, it can be stated that the hydrogen production process has high influence on the model, and thus creates a dependency over the model.

Regarding the electricity production process, Figure 2.8 presents in dark and light yellow the results on the SA for the $\pm 5\%$ modification on the electricity demand applied in the model. For that purpose, this analysis led to a mean value of 0.011, a median value of $7 \cdot 10^{-3}$ and a maximal value of 3.7% in FET. Therefore, these figures represent a data distribution located closer to 0 rather than 0.05. As result, it can be inferred that this process has less influence on the model, except for the impact category FET. Furthermore, the standard deviation led to $9 \cdot 10^{-3}$, which indicates a low dispersion. Also, there are some impact categories which were barely affected on this modification. In particular, FD, GWP, MD, LU and POF resulted with values below 1%. Similar as before, the WD impact category was not modified during the SA. Therefore, based on the reasons aforementioned, the electricity production process has low influence over the process.

In conclusion, based on the rationale previously described, the hydrogen production process via SMR has high influence on the model, due to all the emissions to air derived from this process, which represented a 77.3% of the impact categories mean values. This fact confirms the hypothesis proposed in section 2.3.2 regarding this process. In contrast, the electricity production process has lower influence over the model. Finally, it is possible to state that the WD impact category is independent from the electricity and Hydrogen production processes.

Table 2.7: Results on the sensitivity analysis for the H₂ and electricity demand for scenario 1 from case 1

Impact category	Baseline	+5% H ₂ demand	-5% H ₂ demand	+5% Electricity demand	-5% Electricity demand
FD	100%	105%	95%	100%	100%
FET	100%	101%	99%	104%	96%
GWP	100%	105%	96%	101%	100%
HTP	100%	104%	96%	101%	99%
IR	100%	104%	96%	101%	99%
MET	100%	104%	96%	101%	99%
MD	100%	105%	95%	100%	100%
LU	100%	104%	96%	101%	99%
OD	100%	103%	97%	102%	98%
PMF	100%	103%	97%	102%	98%
POF	100%	104%	96%	101%	99%
TAP	100%	103%	97%	102%	98%
WD	100%	100%	100%	100%	100%

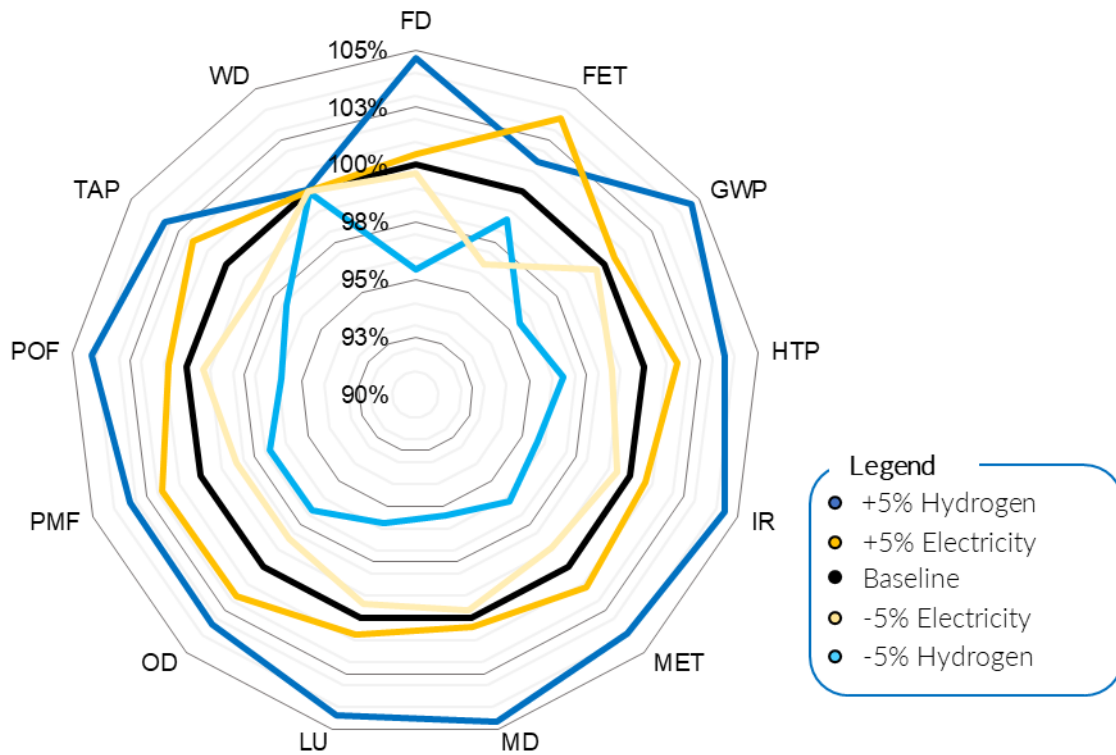


Figure 2.8: Sensitivity analysis for the H₂ and electricity demand for scenario 1 from case 1

2.4.3 Overall interpretation

Although the implementation of Hydrogen for decarbonizing the ladle preheating process removed all the CO₂ emissions from the ladle, the overall process led to a worse environmental impact in comparison to the NG combustion process. As explained in section 2.3.2, this reason is based on the quantity of emissions to air generated during the SMR process. As result, this process shows high influence over the model. These results demonstrate that the use of hydrogen as a retrofit in the ladle preheating process eliminates the CO₂ emissions. Also, it has been proven that the production of H₂ and its subsequent use has worse environmental impact in comparison to the use of NG.

The Greek electricity production mix was presented in section 2.2. From this graph it is possible to infer the influence on impact categories like GWP, MD or IR, as result of the application of fossil fuels sources (e.g. NG, oil, coal...). Although the electricity consumption in these cases is lower in comparison to others cases analysed throughout this report, this influence is still present and, thus, has an influence on it. On the NG combustion case, is low, this model showed high sensitivity as described in section 2.4.1. Nevertheless, the H₂ combustion case show low sensitivity as mentioned in section 2.4.2, due to the higher dominance of the SMR process in comparison to the electricity production process.

Based on the aforementioned results from sections 2.3.1 and 2.3.2, oxygen production showed an environmental impact lower than 1% in their impact categories mean values. Therefore, it can be neglected. Finally, WD is an impact category totally dependent on the combustion process, as the oxygen production process has not an environmental impact in both models, and this impact category remained constant under the SA on the NG, H₂ and electricity production processes.

3 Case 2: LCA on the trials of the rotary furnace from BEF

3.1 Scope and goal

Based on the goal and scope from report D1.2 in section A.2.2.4 in the following will be explained the modifications applied in this analysis. First, this analysis did not consider in the product system the hydrogen and NG production. Then, the system boundary for this analysis is “cradle-to-gate” instead of a “gate-to-gate”. More into detail, the following elements initially considered in the trials have not been taken into account. On one side, the inputs shavings, incinerator bottom ash, refractories and water. On the other side, regarding the outputs, CO, SO₂, PCD/F, HCL, TVOC, HF, N₂ and refractories. Furthermore, the LCIA methodology is the same as presented, but the following impact categories were added to the ones mentioned: FD, FET, HTP, MD, LU, POF and WD. Finally, the considerations presented in the aforementioned report remain the same in this analysis.

3.2 Life cycle inventory

This model represents the tilting rotary furnace in the factory in Valladolid, which is modelled from the trials performed in 2025 presented in D5.1. More into detail, Table 3.1 presents the data used for the baseline case. Furthermore, this Table represents the input and output flow for the trials performed with this furnace for NG oxycombustion. The NO_x was measured by TEC. This table represent the trials for 100% NG.

Table 3.1: Input and output parameters for baseline from case 2 provided by BEF

	Parameter	Unit	Value	Comment
Input	Volume NG	Nm ³	39	Measured
	Electricity consumption	kWh	384.15	Measured
	Oxygen	m ³	87.5	Measured
	Aluminium concentrates	t	0.9	Measured
	Salt	t	0.083	Measured
Output	Aluminium	t	0.592	Measured
	Salt slag	t	0.386	Measured
	CO	t	0	Assumed
	NO _x	mg/MWh	7.524	Measured
	CO ₂	kg	78.57	Calculated
	H ₂ O	m ³	82.134	Calculated
	O ₂	kg	0	Calculated

Similar as the table aforementioned, Table 3.2 shows the input and output parameters for the modelling of the hydrogen oxycombustion trials performed. In this case, a mixture of Hydrogen and NG trials were performed. Nevertheless, this table shows the trials for 100% Hydrogen. Furthermore, the quantity of electricity considered for the hydrogen production via Chlor-alkali electrolysis and oxygen production is not shown in this table but considered in the model.

Table 3.2: Input and output parameters for hydrogen oxycombustion from case 2 Table 3.1 provided by BEF

	Parameter	Unit	Value	Comment
Input	Hydrogen	m ³	125.4	Measured
	Electricity consumption	kWh	376.2	Measured
	Oxygen	m ³	75.5	Measured
	Aluminium concentrates	t	0.9	Measured
	Salt	t	0.083	Measured

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Output	Aluminium	t	0.603	Measured
	Salt slag	t	0.351	Measured
	CO	t	0	Assumed
	NO _x	mg/MWh _{wet}	6.363	Measured
	CO ₂	kg	0.0084	Measured
	H ₂ O	m ³	125.4	Calculated
	O ₂	kg	0.2	Measured

Figure 3.1: Electricity mix for electricity production in Spain in 2024. Data taken from [4] presents the mix of electricity production sources in Spain in 2024. This data was taken from the source [4]. In this graph, the “other sources” are related to Tidal.

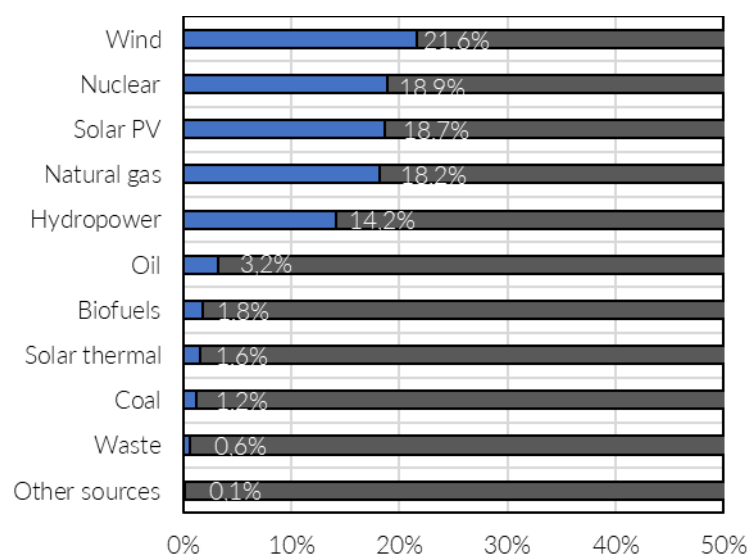


Figure 3.1: Electricity mix for electricity production in Spain in 2024. Data taken from [4]

3.3 Impact assessment

3.3.1 Baseline case

Table 3.3 presents the results for the IA for case 2. These results were obtained based on the data provided by BEF presented in Table 3.1 and minimally modified in order to fit them in the Software Umberto 11[®]. Furthermore, these trials led to 0.3 t_{CO2}/t_{al}, from which 18.2% are generated from the combustion process. Furthermore, the electricity mix applied in this model was presented in the previous phase. Finally, the processes considered in this evaluation are oxygen production, NG production, electricity production and the combustion process that occurs in the furnace. The model used for the calculation of these values is presented in Figure 12.3 in [Annex C](#).

Table 3.3: Values on the impact assessment on the baseline case of case 2 (ReCiPe 2016 Midpoint-H)

Impact category	Acronym	Unit	Value
Fossil depletion Potential	FD	kg oil-eq/t _{al}	152.3
Freshwater Eutrophication	FET	kg P eq/t _{al}	62.8·10 ⁻³
Global Warming Potential	GWP	kg CO ₂ eq/t _{al}	300
Human Toxicity Potential	HTP	kg 1.4 DB/t _{al}	11.6
Ionizing radiation	IR	kBq Co-60 eq./t _{al}	137.25
Land Use	LU	Annual crop eq./t _{al}	0.06
Metal Depletion	MD	kg Cu-eq/t _{al}	18.9
Marine Eutrophication	MET	kg N eq/t _{al}	0.3
Stratospheric Ozone Depletion	OD	kg CFC-11-eq/t _{al}	2.2·10 ⁻⁵
Particulate matter formation	PMF	kg PM25-eq/t _{al}	0.47
Photochemical oxidant formation potential	POF	kg NOx eq./t _{al}	0.9
Terrestrial Acidification	TAP	kg SO ₂ -eq/t _{al}	1.15
Water depletion	WD	m ³ water -eq/t _{al}	1.62

Figure 3.2 presents the percentage of each impact category for each process. Although it was considered in the assessment, the influence of oxygen production resulted in less than 1%. Furthermore, this figure demonstrates the influence of the NG production process, with special interest on FD and HTP. Nevertheless, the highest part falls into the electricity production, based on the electricity consumption.

Figure 3.3 presents the distribution of the mean values obtained for each process for all the environmental categories considered. These values are calculated based on data from Figure 3.2. More into detail, it can be stated the hypothesis that the process of electricity production has the highest influence on the environmental impact. Nevertheless, this fact needs to be proved in subsequential sections by the application of the SA. Subsequently, the combustion process and all its byproducts have also an influence over the environmental. Furthermore, the process of oxygen production was removed from the graph as the mean value obtained was less than 1%. This reason was based on the low oxygen demand in these trials.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

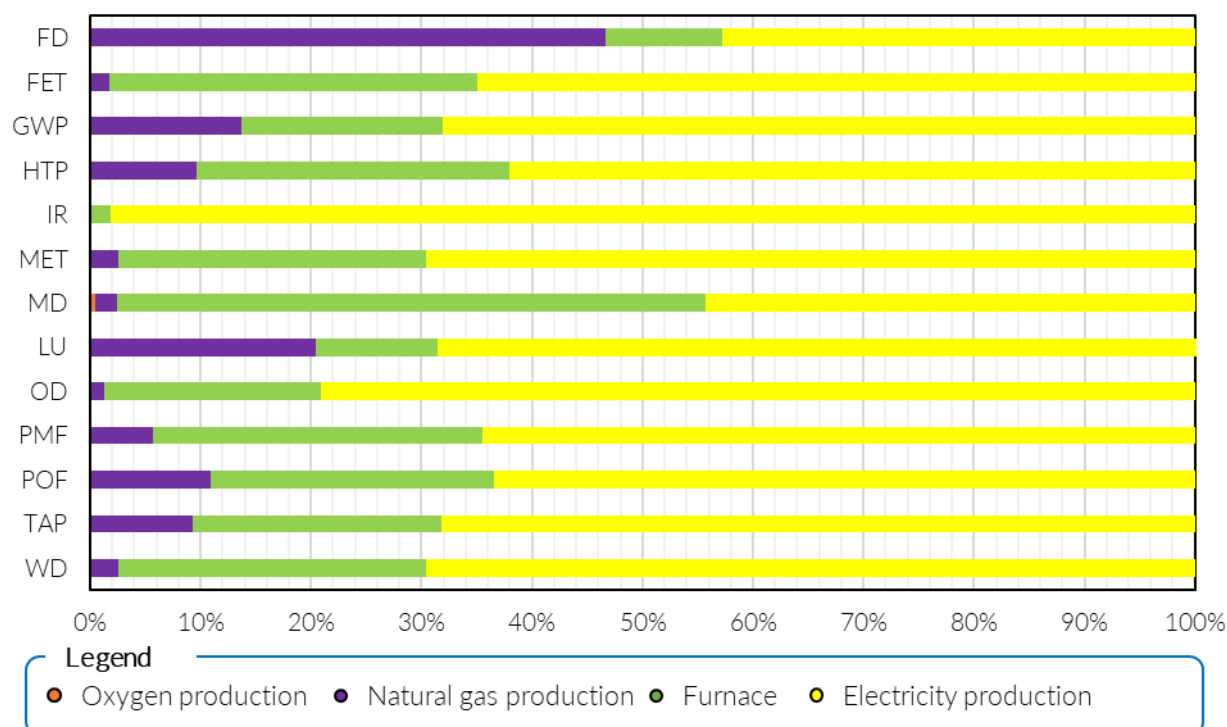


Figure 3.2: Percentage of IA of each process from the case 2 baseline (ReCiPe 2016 Midpoint-H)

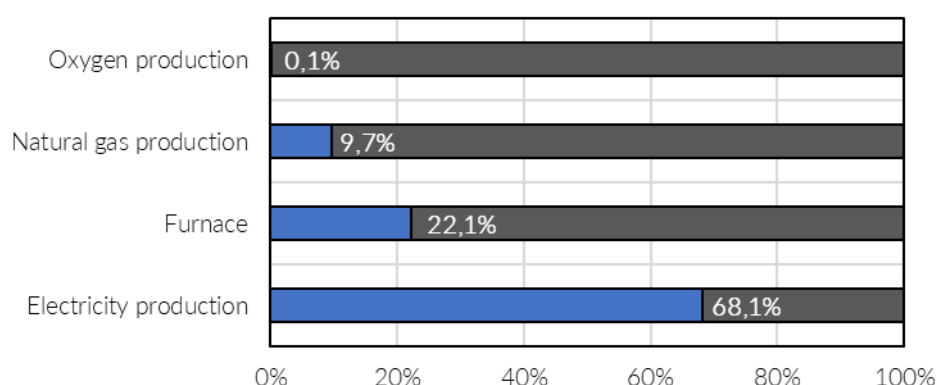


Figure 3.3: Distribution of the mean values among the considered processes for all the environmental impacts under the baseline scenario

3.3.2 Scenario 1: Hydrogen oxycombustion

Table 3.4 shows the values obtained for the IA for the trials of hydrogen oxycombustion of case 2. Similar as before, these results were obtained the Software Umberto, in which the data was given by BEF and presented in Table 3.2. These data were also modified in order to fit them in the program. As result, this assessment evaluated the processes of oxygen production, hydrogen production via chlor-alkali electrolysis, electricity production and the combustion process that occurs in the furnace were considered. These values resulted in $0.38 \text{ tCO}_2/\text{t}_{\text{al}}$, from which 18% is generated in the furnace. The electricity mix applied in this model is the one represented in Figure 3.1: Electricity mix for electricity production in Spain in 2024. Data taken from [4]. Furthermore, the model used in this section is presented in [Annex D](#).

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 3.4: Values on the IA on the scenario 1 of case 2 (ReCiPe 2016 Midpoint-H)

Impact category	Acronym	Unit	Value
Fossil depletion Potential	FD	kg oil-eq/t _{al}	114.5
Freshwater Eutrophication	FET	kg P eq/t _{al}	0.12
Global Warming Potential	GWP	kg CO ₂ eq/t _{al}	384.4
Human Toxicity Potential	HTP	kg 1.4 DCB/t _{al}	19.6
Ionizing radiation	IR	kg U235 eq/t _{al}	188.17
Marine Eutrophication	MET	kg N eq/t _{al}	0.45
Metal Depletion	MD	kg Fe-eq/t _{al}	36.3
Land use	LU	m ² /t _{al}	92.5·10 ⁻³
Stratospheric Ozone Depletion	OD	kg CFC-11-eq/t _{al}	0.2·10 ⁻³
Particulate matter formation	PMFP	kg PM10-eq/t _{al}	0.7
Photochemical Ozone formation potential	POFP	kg NMVOC-E/t _{al}	1.16
Terrestrial Acidification	TAP	kg SO ₂ -eq/t _{al}	1.62
Water depletion	WD	m ³ water-eq/t _{al}	2.08

Figure 3.4 presents the percentage values for the IA of each process considered in this section. In particular, the effect of the electricity production is dominant, as 11 out of 13 impact categories (except MD and OD) fall into this process with values higher or equal to 50%. Similar as before, the influence of oxygen production resulted in less than 1%, thus its effect it is possible to be considered negligible. As result of the fuel change, the influence of hydrogen production increased with the result of reducing the effect of the combustion process with maximum values of 25%.

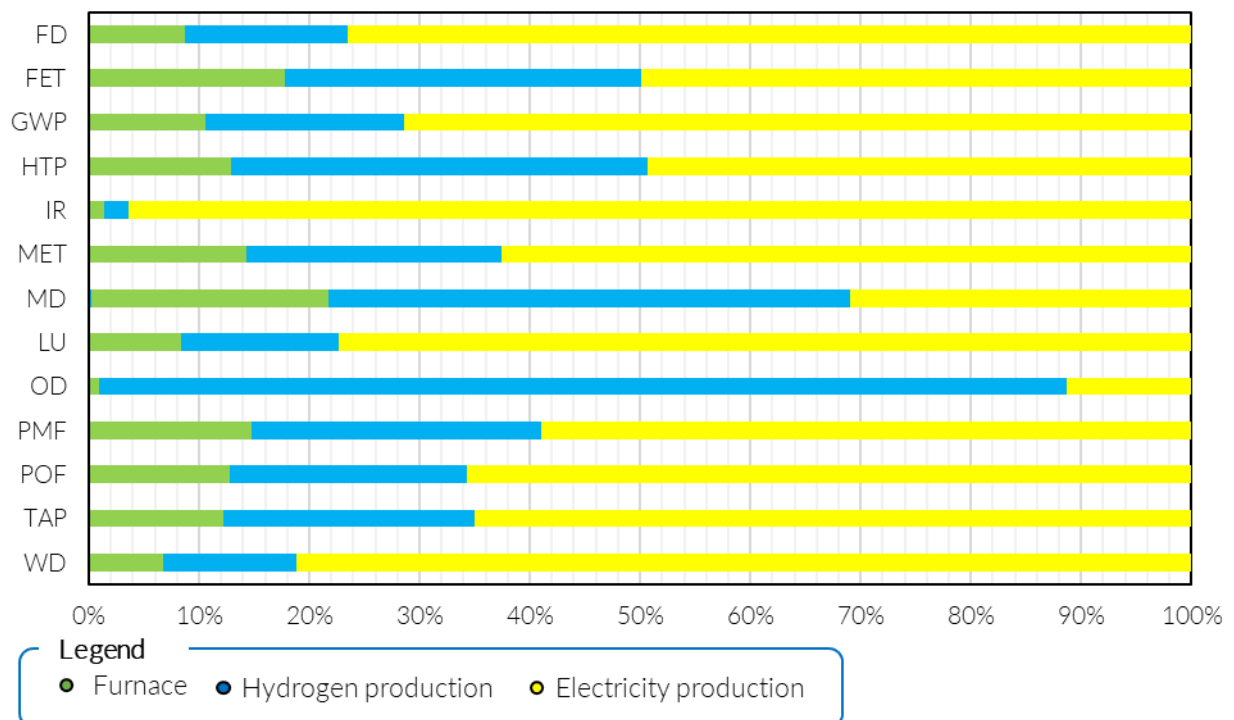


Figure 3.4: Percentage of IA of each process from the case 2 scenario (ReCiPe 2016 Midpoint-H)

Figure 3.5 shows the distribution of the mean values corresponding to all the impact categories divided by process. These values from which this figure is created are represented in Figure 3.4. As previously mentioned, the electricity production is the most dominant process in the environmental impact, due to the electricity production from coal. Furthermore, this process has been more influential, due to the increase of

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

electricity demand from the chlor-alkali electrolysis process. As less emissions affecting the environment are generated on the combustion process, the influence of this process is reduced. Then, the process of hydrogen production gains higher presence in the environmental impact (especially in MD and OD), due to the emission of R-10 (methane tetrachloro-) for OD and sodium chloride in powder for MD. Finally, as aforementioned, the effect of oxygen production is not influential in this evaluation.

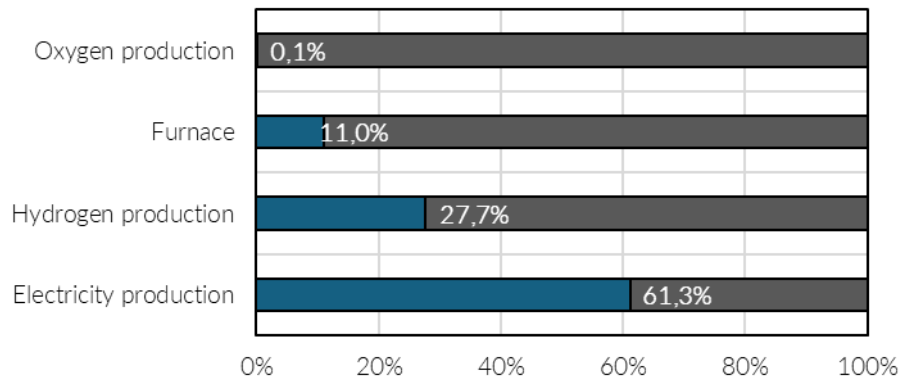


Figure 3.5: Distribution of the mean value among the processes for all the environmental impacts under the hydrogen oxycombustion scenario

3.3.3 Results comparison

Table 3.5 shows the deviation on the results presented in Table 3.3 and Table 3.4. These values are presented in reference to the baseline case, which in Figure 3.6 is represented by a red dotted line. The results presented show high variance. In particular, only 1 out of 13 categories (FD) provide a better environmental impact in comparison to the baseline. In contrast, the rest of the categories increase. Especially FET, HTP, LU, and OD are at least 50% higher than the reference. Then, OD is 450% higher than the reference. Nevertheless, in both cases the influence of oxygen production is negligible.

The high variation on this case is based on the influence of electricity production. As shown in section 3.3.1 and 3.3.2, electricity production is the process with higher environmental influence. Although both the percentages on the environmental impact do not fluctuate much for the electricity consumption (68% and 62% for baseline and hydrogen scenario respectively), the electricity consumption varies in 200 kWh between these two cases. This reason is based on the hydrogen production via chlor-alkali electrolysis. As result, more emissions are generated and more resources are consumed.

Furthermore, the influence of Hydrogen production is also noticeable in comparison with NG production. In particular, impact categories like MD and OD are mostly influenced by this process, due to the emission of R-10 (Methane tetrachloro-) and the use of sodium chloride.

Therefore, it can be stated that the worse environmental impact on the hydrogen combustion case is not due to the combustion process on the furnaces, whether to the electricity production. Nevertheless, this fact needs to be confirmed on the SA performed in the following section.

Table 3.5: Percentage deviation of all impact categories in reference to baseline for case 2

Impact category	Baseline	Scenario	Unit
Fossil depletion Potential	100%	75.4%	kg oil-eq./t _{al}
Freshwater Eutrophication	100%	175.6%	kg P eq./t _{al}
Global Warming Potential	100%	128.7%	kg CO ₂ eq./t _{al}
Human Toxicity Potential	100%	169.6%	kg 1.4 DB/t _{al}
Ionizing radiation	100%	137.4%	kBq Co-60 eq./t _{al}
Marine Eutrophication	100%	150.2%	kg N eq./t _{al}
Metal Depletion	100%	116.7%	kg Cu-eq./t _{al}
Land use	100%	158.1%	Annual crop eq./t _{al}
Stratospheric Ozone Depletion	100%	551.8%	kg CFC-11-eq./t _{al}
Particulate matter formation	100%	147.7%	kg PM25-eq./t _{al}
Photochemical Ozone formation potential	100%	130.3%	kg NO _x eq./t _{al}

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Terrestrial Acidification	100%	141.6%	kg SO ₂ -eq/t _{al}
Water depletion	100%	127.4%	m ³ water -eq/t _{al}

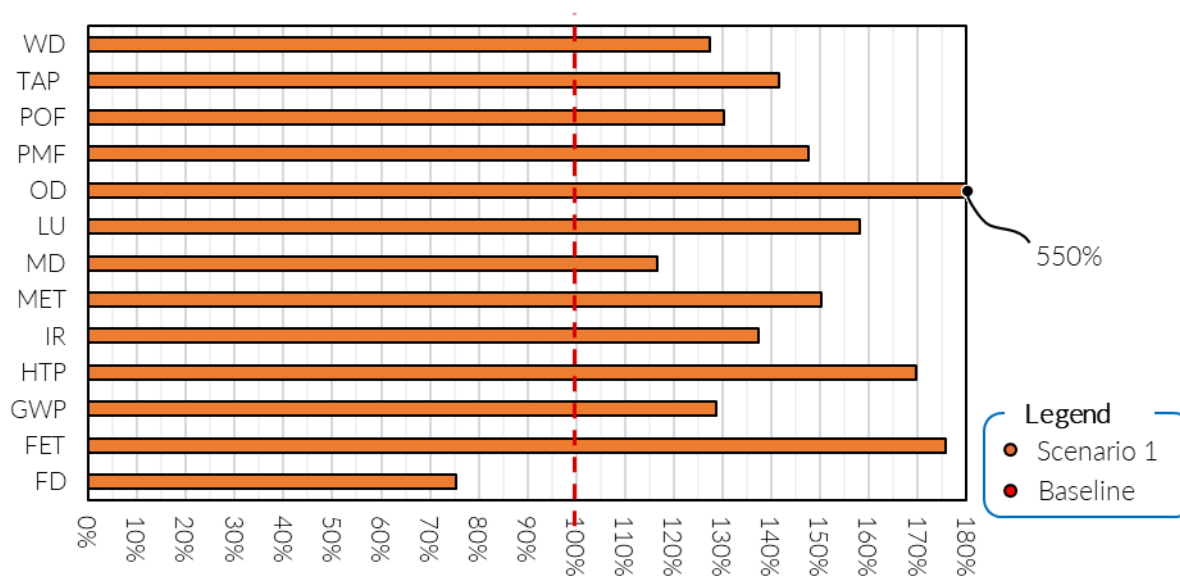


Figure 3.6: Relative change for all impact categories with respect to baseline for case 2

3.4 Interpretation

Throughout this subchapter a SA will be performed with the aim of evaluating the independence of the most influential variables of both the baseline and hydrogen oxycombustion models. In particular, as mentioned in section 3.3.1, hypothesis stated on the baseline case regarding the dominance of the electricity production will be analysed. For that purpose, in the following section 3.4.1, the variables of NG and electricity consumption will be modified. Similarly, as mentioned in paragraph 3.3.2, the dominance of the electricity production for the hydrogen case will be analysed. Therefore, most dominant variables from this case will be modified.

3.4.1 Sensitivity analysis baseline

Figure 3.7 presents graphically the results for the SA for baseline from case 2. These values are shown in Table 3.6. Furthermore, this analysis was performed based on the hypothesis in which electricity production is the most influential process in the environmental impact. Furthermore, this analysis was also conducted for the NG demand.

In particular, regarding the NG production process all the impact categories obtained values below 2%, except FD. In addition, the values obtained for mean and median are 0.005 and 0.003. These metrics represent that the dataset is shifted towards the lower limit. Furthermore, a standard variation value of 0.06 was obtained, which defines a minimal dispersion generated from the FD impact category. Nevertheless, based on aforementioned values, this model has low sensitivity on the NG demand. Therefore, it is possible to infer that all the analysed impact categories are independent of the NG production process.

In contrast, the electricity demand has higher influence in the impact categories than the NG production process. More into detail, an equal value of mean and median of 0.025 was obtained. This fact represents that the data distribution is centred in the middle of the data range. Additionally, the variation obtained is 0.05. This metric shows that the data is slightly dispersed from the centre, especially due to the values on LU and IR. Furthermore, except FD and MD, the rest of the impact categories vary more than a 2%. The highest value is obtained in IR, due to the influence of electricity production from nuclear sources. Finally, the rest of the categories stay between 2% and 3%. Therefore, based on these results, it has been demonstrated the independence of FD and MD from the electricity production and the dominance of this process over the rest of the impact categories.

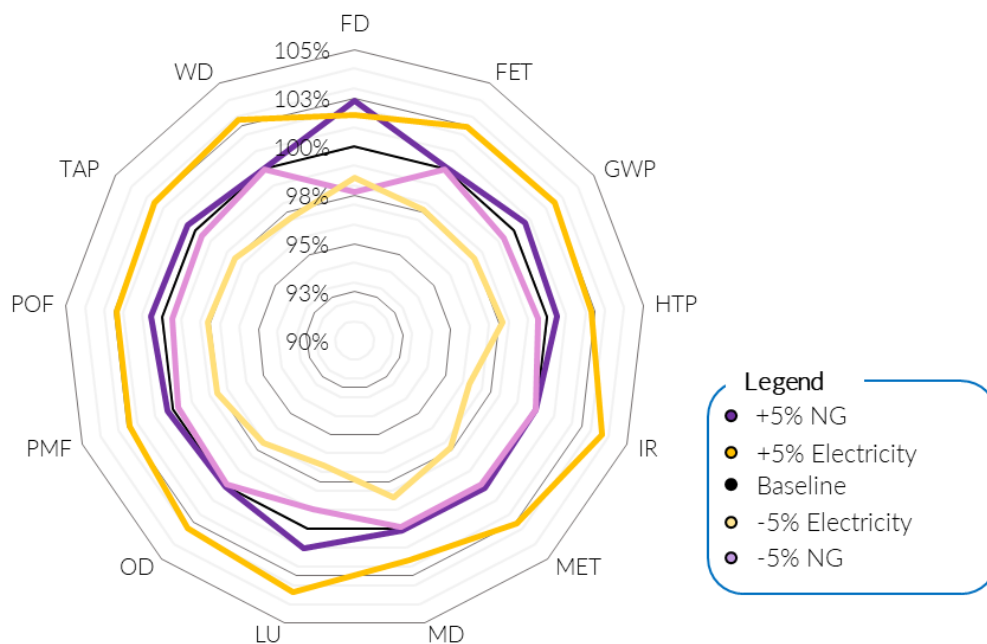


Figure 3.7: Sensitivity analysis for the NG and electricity demand for baseline from case 2

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 3.6: Results on the sensitivity analysis for the NG and electricity demand for baseline from case 2

Impact category	Baseline	+5% NG demand	-5% NG demand	+5% Electricity demand	-5% Electricity demand
FD	100%	102.3%	97.7%	101.6%	98.4%
FET	100%	100.1%	99.9%	102.4%	97.6%
GWP	100%	100.7%	99.3%	102.5%	97.5%
HTP	100%	100.5%	99.5%	102.3%	97.7%
IR	100%	100.0%	100.0%	103.7%	96.3%
MET	100%	100.1%	99.9%	102.6%	97.4%
MD	100%	100.1%	99.9%	101.6%	98.4%
LU	100%	101.0%	99.0%	103.4%	96.6%
ODE	100%	100.1%	99.9%	102.9%	97.1%
PMFP	100%	100.3%	99.7%	102.4%	97.6%
POFP	100%	100.5%	99.5%	102.4%	97.6%
TAP	100%	100.5%	99.5%	102.5%	97.5%
WD	100%	100.0%	100.0%	102.9%	97.1%

3.4.2 Sensitivity analysis scenario 1

Similar as the section before, Figure 3.8 presents the SA from the results obtained from the modification of the variables of NG and electricity demand. These values are numerically represented in Table 3.7. For that purpose, this analysis was conducted based on the same hypothesis as the SA performed in the previous section (i.e. section 3.4.1).

Table 3.7 Based on the values obtained for the Hydrogen demand, all impact categories showed values higher than 2%. In particular, 12 out of 13 categories present values between 2% and 3%. In addition, values of mean and median are 0.025 and 0.021 respectively, which show a centred distribution slightly shifted to the lower limit. Also, a variation of $9 \cdot 10^{-3}$ was obtained, and, thus, representing a slight dispersion from values such as OD (upper limit) and WD (lower limit). Then, OD shows high dependency with almost 5%, due to the Radon 10-emissions. Also, it is important to highlight that this hydrogen demand is also affected by the electricity production, due to the hydrogen production route. Therefore, it is not possible in this model to decouple the hydrogen production from the electricity production, and, thus, evaluate the independency of the impact categories from the hydrogen demand independently.

Regarding the electricity demand, 12 out of 13 categories vary between 1% and 2.6% except OD, which is an impact category dependent from the Radon 10 emissions during the hydrogen production process. More into detail, a median and a mean of 0.017 were obtained. Moreover, the variation resulted in 0.004. Based on these metrics, the data distribution is centred close to the lower limit with a slight dispersion and therefore it has been demonstrated the high influence of the electricity production process over the model. This reason is based on the high electricity demand in comparison to other inputs as aluminium concentrates or Hydrogen.

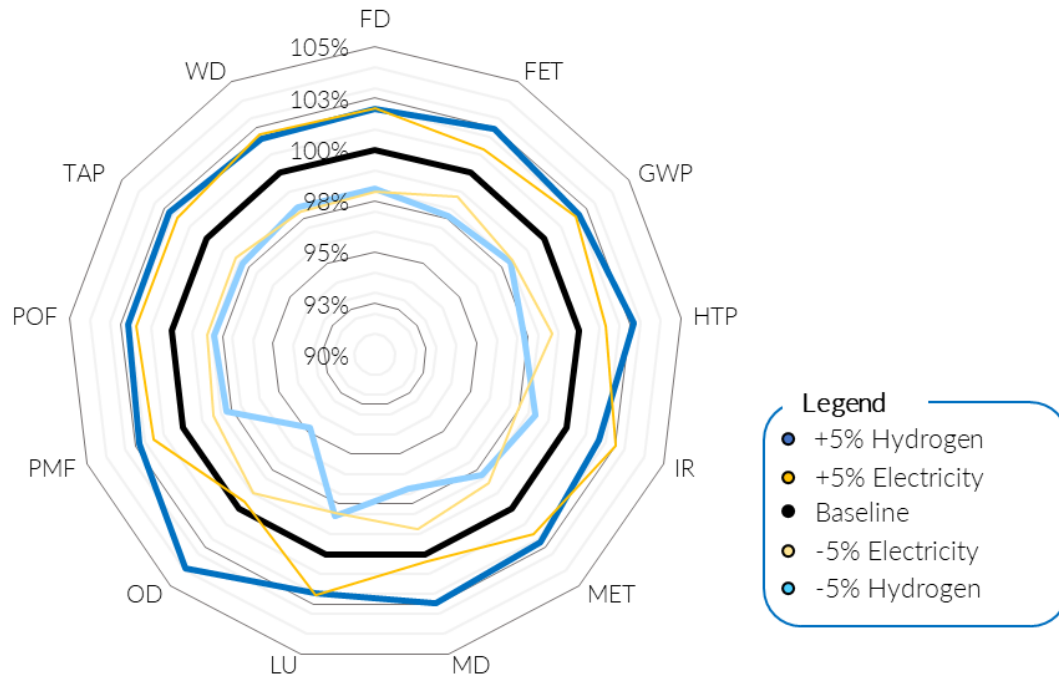


Figure 3.8: Sensitivity analysis for the H₂ and electricity demand for scenario 1 from case 2

Table 3.7. Results on the sensitivity analysis for the H₂ and electricity demand for scenario 1 from case 2

Impact category	Baseline	+5% H ₂ demand	-5% H ₂ demand	+5% Electricity demand	-5% Electricity demand
FD	100%	102%	98%	102%	98%
FET	100%	102%	98%	101%	99%
GWP	100%	102%	98%	102%	98%
HTP	100%	103%	97%	101%	99%
IR	100%	102%	98%	103%	97%
MET	100%	102%	98%	102%	98%
MD	100%	103%	97%	101%	99%
LU	100%	102%	98%	102%	98%
OD	100%	105%	95%	100%	100%
PMF	100%	102%	98%	102%	98%
POF	100%	102%	98%	102%	98%
TAP	100%	102%	98%	102%	98%
WD	100%	102%	98%	102%	98%

3.4.3 Overall interpretation

In this case, the implementation of hydrogen showed a worse environmental impact in comparison with the use of NG presented in section 3.3.2. Nevertheless, the reasons for the worse environmental results are not based on the use of hydrogen, rather to the electricity production and consumption. Therefore, if only the environmental impact of the furnace is being analysed, then, this impact is eliminated, since CO₂ emissions are not generated.

As shown in section 3.1, the electrical Spanish grid depends on production process that highly affects the impact categories of GWP and IR (nuclear and NG). In particular, both models showed an influence of 62% and 68% on the impact categories average values for electricity production. Then, based on the results from the SA in sections 3.4.1 and 3.4.2, it was proven that 12 out of 13 categories showed variations between 1% and 3%, except OD which is purely dependent on the Hydrogen production process. Based on these results, it can be stated the high influence of the electricity production process over the model. This influence is also

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

increased due to the high value for electricity demand in both cases. As result, this model is not only high dependent on electricity, but it has also high electricity demand in comparison to the hydrogen or NG demand. Therefore, in order to properly analyse this case, the hydrogen/NG demand should be decoupled from the electricity demand. Finally, the oxygen production process it is possible to neglect it, as the implication on the impact categories is insignificant.

4 Case 3: LCA on the trials of the reverberatory furnace from CTEC

4.1 Scope and goal

Based on the goal and scope from report D1.2 in section A.2.2.4 in the following will be explained the modifications applied in this analysis. First, in this analysis there was not considered in the product system the refractories and argon/chlorine treatment. Then, the system boundary for this analysis is “cradle-to-gate” instead of a “gate-to-gate”. These elements were not considered in the trials. Furthermore, the LCIA methodology is the same as presented, but the following impact categories were considered: FD, FET, HTP, MD, NLT, POFP and WD. Finally, the considerations presented in the aforementioned report remains the same in this analysis.

4.2 Life cycle inventory

Table 4.1 presents the base data considered for modelling the system for the baseline case. As mentioned in the deliverable 1.2, the system boundary chosen is “cradle-to-gate”, thus this data only represents the inputs and outputs in the furnace occurred during the trials. The description of these trials is explained in report D5.3.

Regarding to energy, it is important to mention the origin of both energy sources. Firstly, electricity source comes from the electricity mix from France, presented in Figure 4.1: Electricity mix for electricity production in France in 2024. Data taken from [5]. Then, NG production is considered directly extracted from petroleum. As the interest of this study lies on environmental influence of hydrogen in the combustion processes, the upstream and downstream environmental impacts from the rest of materials of the table below, which do not affect the process in this furnace, have not been taken into account.

Finally, since not all the emissions were measured (except NO_x), the mass of CO₂, H₂O and O₂ have been calculated through combustion assuming over stoichiometric conditions. These calculations were performed by the demonstrator.

Table 4.1. Input and output parameters for modelling the baseline case from case 3 provided by CTEC

	Parameter	Unit	Value
Input	NG Volume	kWh _{LHV} /t _{al}	730
	Electricity consumption	kWh	10
	Primary aluminium	t	10
	Aluminium scrap	t	2
	Pressurized air	m ³ /t _{al}	800
Output	Dross	t _{dross} /t _{al}	0.168
	Aluminium	t	11.832
	CO ₂	Nm ³ /t _{al}	75
	CO	Nm ³ /t _{al}	0
	H ₂ O	Nm ³ /t _{al}	150
	O ₂	Nm ³ /t _{al}	17
	NO _x	kg _{NOx} /t _{al}	0.1

Table 4.2 shows the input and output data for modeling the retrofitted case. Similarly to Table 4.1, this case presents an analogous mass balance with the difference that the fuel has been changed to hydrogen and oxygen. Furthermore, in order to model these materials, hydrogen was considered from SMR. Then, the oxygen production is considered from a cryogenic air separation process. Finally, similarly as before, only NO_x has been measured. Therefore, the rest of the emission values have been calculated by the demonstrator.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 4.2. Input and output parameters for modeling the retrofitted case from case 1 provided by CTEC

	Parameter	Unit	Value
Input	Hydrogen	kWh _{LHV} /t _{al}	460
	Electricity consumption	kWh	10
	Primary aluminium	t	10
	Aluminium scrap	t	2
	Oxygen	Nm ³ /t _{al}	81
Output	Dross	t _{dross} /t _{al}	0.168
	Aluminium	t	11.832
	CO ₂	Nm ³ /t _{al}	0
	CO	Nm ³ /t _{al}	0
	H ₂ O	Nm ³ /t _{al}	160
	O ₂	Nm ³ /t _{al}	3
	NOx	kg _{NOx} /t _{al}	0.06

represents the electricity mix applied in the model. This model was taken from the source [5] for representing the electricity production in France. Finally, the part “other sources” are represented by geothermal and tidal power.

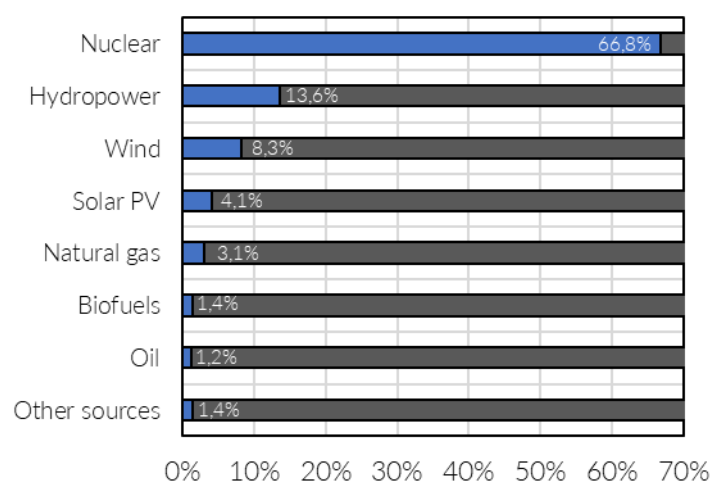


Figure 4.1: Electricity mix for electricity production in France in 2024. Data taken from [5]

4.3 Impact assessment

4.3.1 Baseline case

Table 4.3 presents the results on the IA for the baseline scenario. Based on the input data presented in Table 4.1, this process resulted on providing around 0.4 t_{CO2}/tal, from which a 60% is generated in the combustion process. This value was obtained from the sum of all CO₂ emissions implemented in this process and other products with their CO₂ equivalent. Furthermore, in this process has been considered the electricity mix presented in Figure 4.1: Electricity mix for electricity production in France in 2024. Data taken from [5] and the production of raw materials such as NG and compressed air. The model used for this calculation is presented in Figure 12.5 in [Annex E](#).

Table 4.3: Values on the IA for the baseline of case 3 (ReCiPe 2016 Midpoint-H)

Impact category	Acronym	Unit	Value
Fossil depletion Potential	FD	kg oil-eq/tal	677.3
Freshwater Eutrophication	FET	kg P eq/tal	19.3·10 ⁻³
Global Warming Potential	GWP	kg CO2 eq/tal	397.5
Human Toxicity Potential	HTP	kg 1.4 DB/tal	210.35
Ionizing radiation	IR	kBq Co-60 eq./tal	5.75
Land Use	LU	Annual crop eq./tal	57·10 ⁻³
Metal Depletion	MD	kg Cu-eq/tal	9.7
Marine Eutrophication	MET	kg N eq/tal	1
Stratospheric Ozone Depletion	OD	kg CFC-11-eq/tal	0.1·10 ⁻³
Particulate matter formation	PMF	kg PM25-eq/tall	0.17
Photochemical oxidant formation potential	POF	kg NOx eq./tal	0.71
Terrestrial Acidification	TAP	kg SO2-eq/tal	0.43
Water depletion	WD	m3 water -eq/tal	151.4

Figure 4.2 shows the influence of each process individually with respect to the analysed impact categories. This figure is built up on the corresponding part of each process obtained from the IA. Furthermore; this figure demonstrates the high influence of the NG production process, with special interest on FD and HTP. Furthermore, the effect of the combustion process on the furnace is also important due to the emissions generated. This effect is demonstrated in the categories GWP and WD.

Figure 4.3 is a summary of the values presented in Figure 4.2. This figure represents the mean values of the percentage of all the impact categories per process. Therefore, it summarizes the environmental influence of each process in all of the impact categories. As result, it is possible to preliminary assume that the NG production process dominates the environmental impact the system. Nevertheless, the influence and robustness on each impact category will be discussed in section 4.4 as result of the SA.

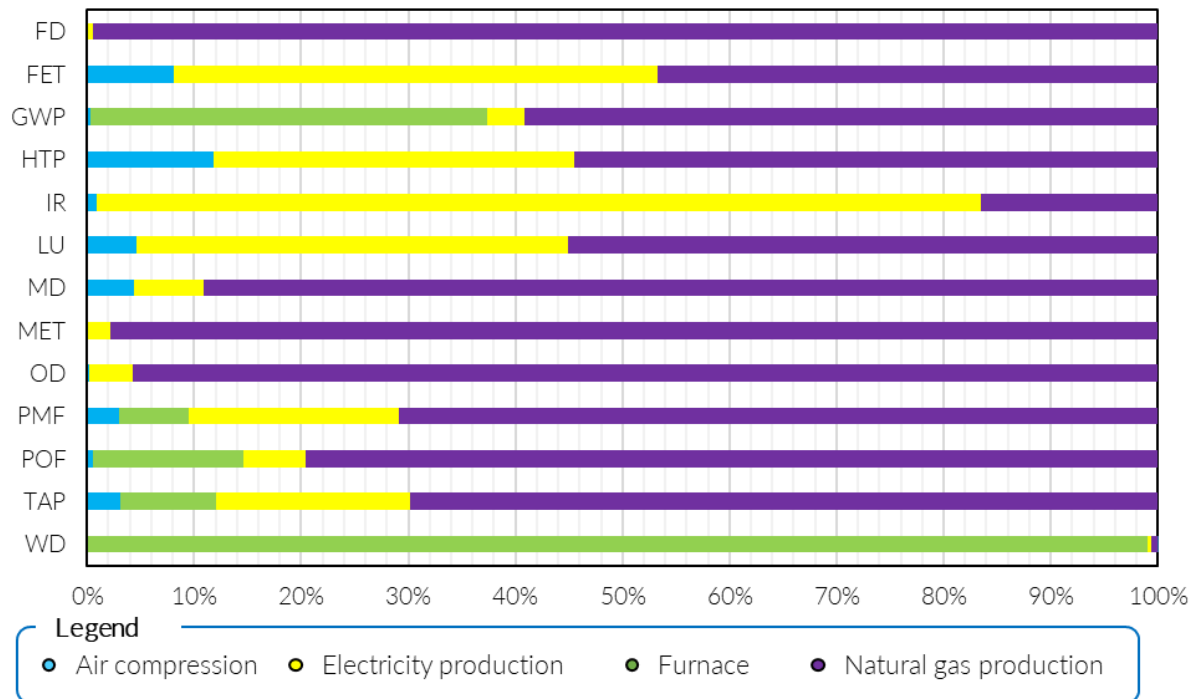


Figure 4.2: Percentage of IA of each process from the case 3 baseline (ReCiPe 2016 Midpoint-H)

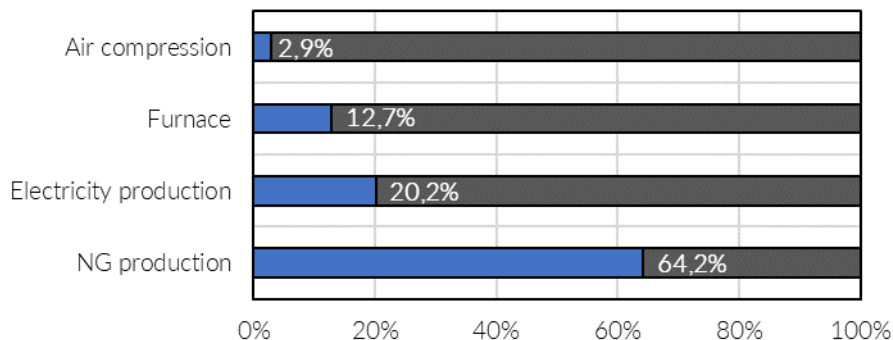


Figure 4.3: Distribution of the mean value among the processes for all the environmental impacts under the baseline scenario

4.3.2 Scenario 1: Hydrogen oxycombustion

Table 4.4 shows the values of each impact category of retrofitted case on the reverberatory furnace. In this case, this melting process provides 0.2 t_{CO2}/t_{al} from which 93.6% comes from the SMR process. Nevertheless, the CO₂ emissions in the furnace as part of the combustion process have been removed. The model used for this calculation is presented in Figure 12.6 in [Annex F](#).

Similar as before, this case considers the production of the electricity mix from France, production of hydrogen (SMR) and oxygen. This modification in the process considerations is based on the application of the oxycombustion technology. More into detail, the production of oxygen is considered by cryogenic air separation.

Table 4.4: Values on the IA for the hydrogen oxycombustion scenario of case 3 (ReCiPe 2016 Midpoint-H)

Impact category	Acronym	Unit	Value
Fossil depletion Potential	FD	kg oil-eq/t _{al}	76.5
Freshwater Eutrophication	FET	kg P eq/t _{al}	6.5·10 ⁻³

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Global Warming Potential	GWP	kg CO ₂ eq./t _{al}	204.6
Human Toxicity Potential	HTP	kg 1.4 DB/t _{al}	14.1
Ionizing radiation	IR	kBq Co-60 eq./t _{al}	88.9
Marine Eutrophication	MET	kg N eq./t _{al}	0.46
Metal Depletion	MD	kg Cu-eq./t _{al}	2.27
Land use	LU	Annual cropeq./t _{al}	5.1•10 ⁻³
Stratospheric Ozone Depletion	OD	kg CFC-11-eq./t _{al}	3.08•10 ⁻⁵
Particulate Matter Formation	PMF	kg PM25-eq./t _{al}	9.4•10 ⁻³
Photochemical Ozone Formation	POF	kg NOx eq./t _{al}	0.47
Terrestrial Acidification	TAP	kg SO ₂ -eq./t _{al}	0.16
Water depletion	WD	m ³ water -eq./t _{al}	163.6

Figure 4.4 shows the percentage of each impact category for each process considered in this scenario. Similar to the baseline case, the hydrogen production process demonstrates the high influence on the overall of the analysed impacts categories and, thus, its environmental impact in comparison to the rest of the processes. This fact emphasizes especially in the categories FD, GWP and MD. Although with a lower implication, the production of electricity also plays an important role, especially in the category IR. For that purpose, Figure 4.5 presents the distribution based on mean values, which evidences the higher influence of the hydrogen over the electricity production, except on the IR and WD impact categories.

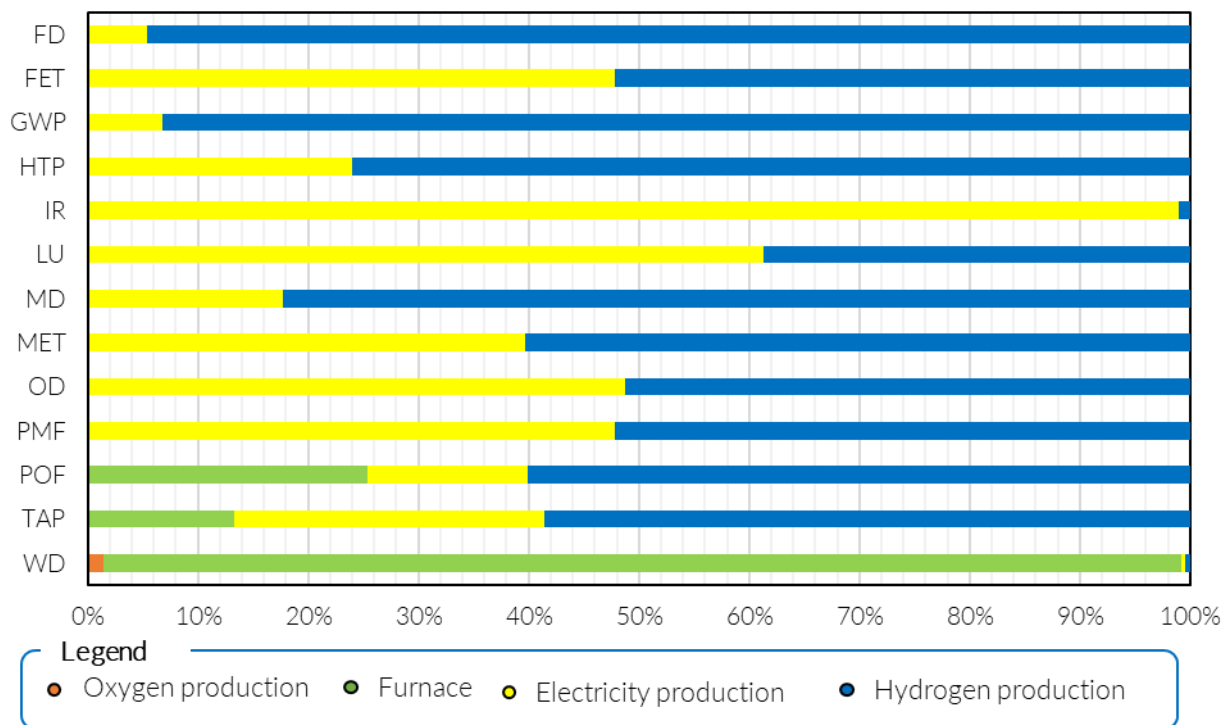


Figure 4.4: Percentage of IA of each process from the case 3 scenario 1 (ReCiPe 2016 Midpoint-H)

As aforementioned in Figure 4.5 the distribution of the mean values among processes is explained. Besides the higher environmental influence of the hydrogen production, this figure provides an overview of the environmental impact from all the processes. More into detail, the influence of the combustion of Hydrogen and the oxygen production has lower influence in comparison to the rest of the processes. Nevertheless, the environmental impact is still dominated by the hydrogen production process.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

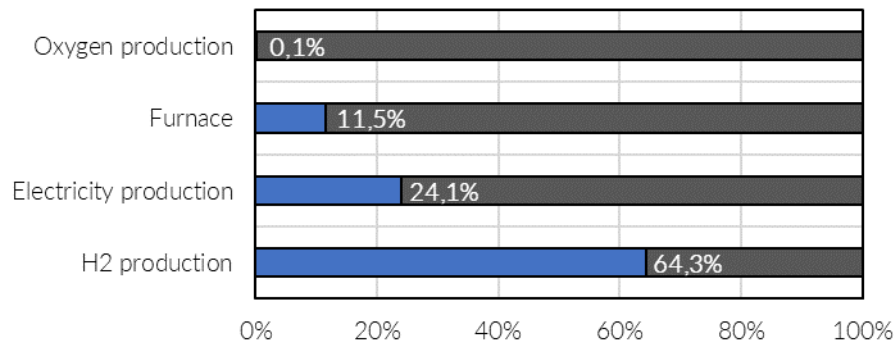


Figure 4.5: Distribution of the mean value among the processes for all the environmental impacts under the scenario 1

4.3.3 Results comparison

Table 4.5 shows the deviation on the results presented in Table 4.3 and Table 4.4. For that purpose, a comparison between the impact categories from the baseline and the hydrogen oxycombustion scenario case is presented. Furthermore, these values are illustrated in Figure 4.6 with the baseline presented as a red-dotted line. In particular, 11 impact categories improved, especially GWP which is one of the main objectives of this project. Only IR and WD are the impact categories which obtained higher values in comparison to the baseline. On one side, the IR is higher, due to the higher electricity demand generated by the oxygen production. Since as the great part of the electricity production of France is generated by nuclear energy (66.8%, as in Figure 4.1: Electricity mix for electricity production in France in 2024. Data taken from [5]), higher IR is generated. Then, the result of higher WD is based on the Hydrogen combustion, that generates more water in comparison to NG.

Table 4.5: Percentage deviation of all impact categories from the scenario 1 from case 3 (ReCiPe 2016 Midpoint-H)

Impact category	Baseline	Scenario	Unit
Fossil depletion Potential	100%	11.3%	kg oil-eq/tal
Freshwater Eutrophication	100%	54.0%	kg P eq/tal
Global Warming Potential	100%	52.0%	kg CO2 eq/tal
Human Toxicity Potential	100%	8.6%	kg 1.4 DB/tal
Ionizing radiation	100%	102.1%	kBq Co-60 eq./tal
Land Use	100%	64.0%	Annual crop eq./tal
Metal Depletion	100%	24.1%	kg Cu-eq/tal
Marine Eutrophication	100%	8.8%	kg N eq/tal
Stratospheric Ozone Depletion	100%	13.4%	kg CFC-11-eq/tal
Particulate matter formation	100%	38.8%	kg PM25-eq/tall
Photochemical oxidant formation potential	100%	33.1%	kg NOx eq./tal
Terrestrial Acidification	100%	41.4%	kg SO2-eq/tal
Water depletion	100%	108.0%	m3 water -eq/tal

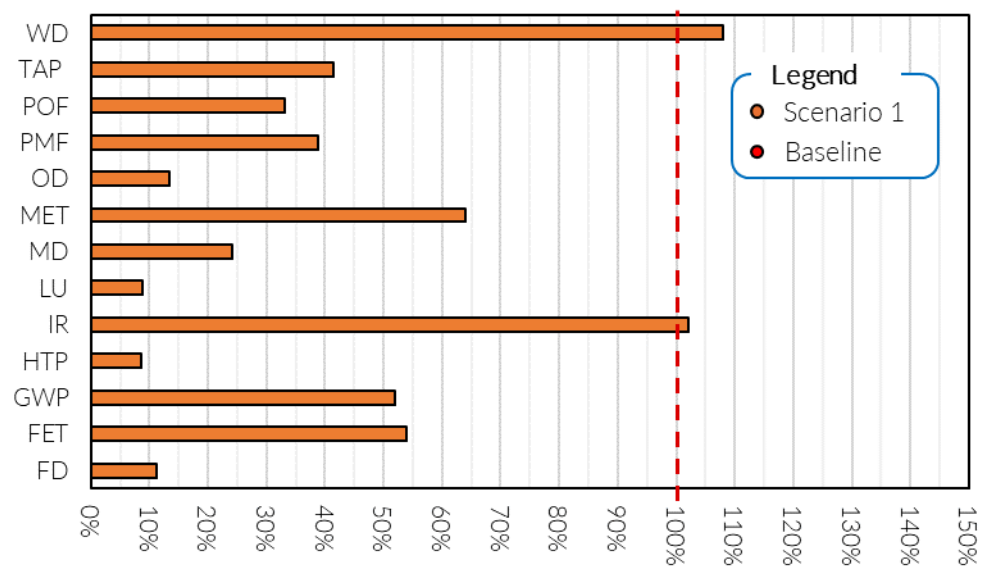


Figure 4.6: Relative change for all impact categories between baseline (reference) and scenario 1 for case 3

4.4 Interpretation

In order to improve the results on the IA, a SA is performed on the most dominant variables from each case. These variables belong to the process with highest influence on the environmental impact presented in sections 4.3.1 and 4.3.2 respectively. As result, the influence of individual parameters over their respective product systems are shown. For that purpose, in the baseline case the NG and electricity demand will be increased $\pm 5\%$. Similar procedure will be done in the scenario 1 for the respective variables for the processes of hydrogen and electricity demand.

4.4.1 Sensitivity analysis on the baseline

Table 4.6 presents the results on the SA for the baseline from case 3. These values are presented as relative percentage from the baseline case. This data is as well presented in Figure 4.7. In particular, the results obtained for the modification of the electricity demand show barely an influence on the impact categories. In particular, the values obtained for mean and median are 0.018 and 0.017 respectively. These metrics represent that the dataset is centred and shifted towards the lower limit of the data range. Additionally, a standard variation value of 0.014 was obtained, which defines a high dispersion generated from the FD and HTP from the upper limit and WD and IR from the lower limit. Therefore, based on aforementioned values, this model has low sensitivity on the NG demand, except for FD and HTP which highly depend on this variable. In contrast, the SA on the NG demand shows the higher influence of this process on all impact categories except WD, MD and IR, thus, the influence of NG production on these three impact categories is independent and robust from the aforementioned process.

As aforementioned, the single category affected is IR due to the part of electricity generated by nuclear power. The rest of the impact categories are not influenced by this application. More into detail, the analysis on the SA results led to the same mean and median of 0.001 and a standard variation of $1.5 \cdot 10^{-3}$. As result of these metrics, it is possible to infer that the electricity demand has a low influence on the model.

Therefore, based on the data from Table 4.6, Figure 4.7 and as aforementioned in paragraph 4.3.1, the process of NG production has huge influence in the process, especially in all impact categories except WD and IR. Finally, as aforementioned, the electricity production for this case has minimal influence.

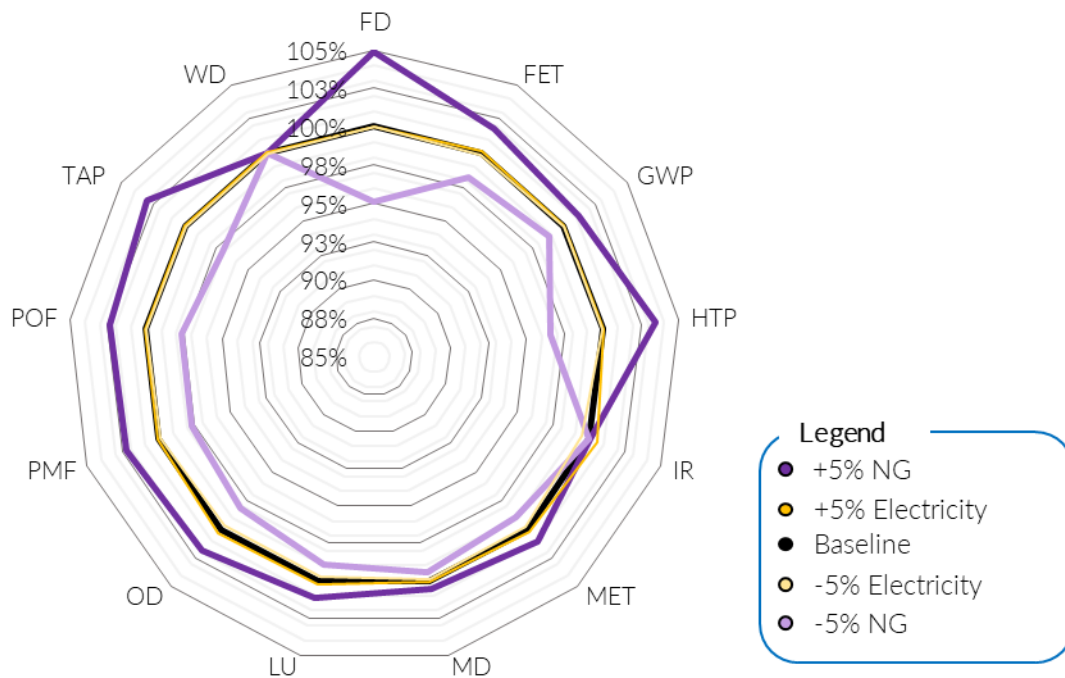


Figure 4.7: Results on the sensitivity analysis for the NG and electricity demand for baseline from case 3

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 4.6: Results on the sensitivity analysis for the NG and electricity demand for baseline from case 3

Impact category	Baseline	+5% NG demand	-5% NG demand	+5% Electricity demand	-5% Electricity demand
FD	100%	104.9%	95.1%	100.01%	100%
FET	100%	101.7%	98.3%	100.10%	100%
GWP	100%	101.1%	98.9%	100.01%	100%
HTP	100%	103.5%	96.5%	100.07%	100%
IR	100%	100.0%	100.0%	100.55%	99%
MET	100%	101.1%	98.9%	100.19%	100%
MD	100%	100.6%	99.4%	100.11%	100%
LU	100%	101.1%	98.9%	100.23%	100%
OD	100%	101.9%	98.1%	100.31%	100%
PMF	100%	102.2%	97.8%	100.06%	100%
POF	100%	102.4%	97.6%	100.03%	100%
TAP	100%	103.0%	97.0%	100.04%	100%
WD	100%	100.0%	100.0%	100.00%	100%

4.4.2 Sensitivity analysis on the Scenario 1

Table 4.7 shows the results on the SA for the hydrogen oxycombustion scenario on case 3. These data have been illustrated in Figure 4.8 to provide a clearer overview on the influence of H₂ and robustness and independency of electricity over this model. Similar to the baseline, the electricity modification does not influence the environmental impact of this process as there are not many variations on the impact categories.

In contrast, the modification on hydrogen consumption in the furnace leads to high variations in the results, except the impact categories WD and IR which are mostly defined by the water produced in the combustion process and the nuclear power from the French electricity mix. On the other side, the rest of the impact categories vary differently. On one side, MET, MD, NLT and FET change up to 2.5% showing a moderate dependence from hydrogen. On the other side, the rest of the categories (FD, GWP, ODE, PMPF, POFP and TAP) show variations between 2.5% up to 5%. More into detail, the impact categories of FD and ODE show the highest dependency from hydrogen. This reason is based on the direct correlation between FD and ODE, i.e. the higher the quantity of hydrogen, the higher the emissions related to these two impact categories.

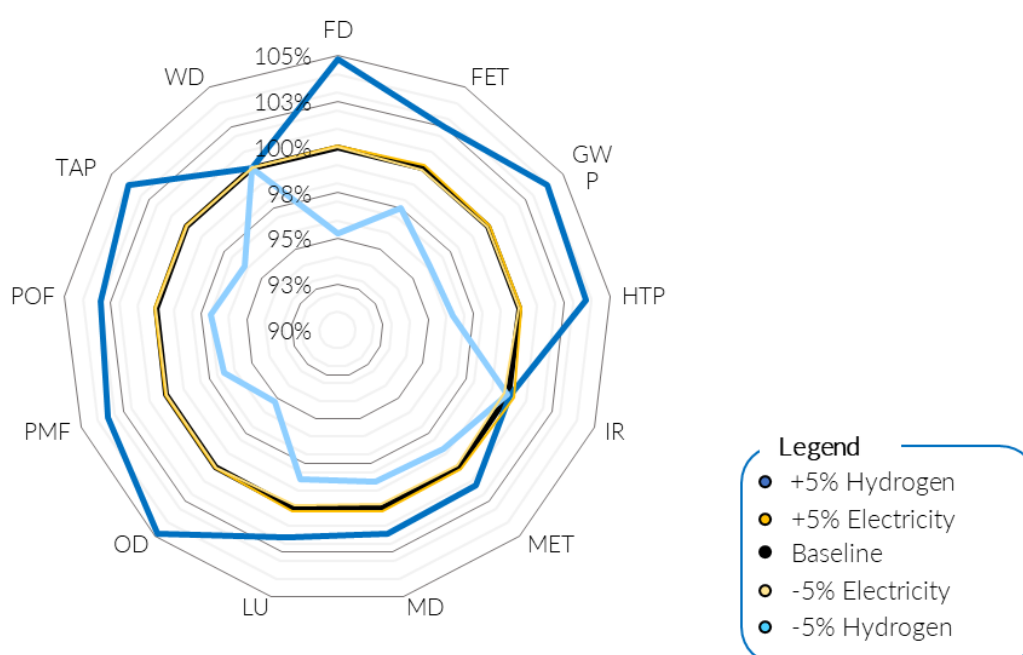


Figure 4.8: Results on the sensitivity analysis for hydrogen and electricity demand on the scenario 1 from case 3

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 4.7: Results on the sensitivity analysis for hydrogen and electricity demand on the scenario 1 from case 3

Impact category	Baseline	+5% H ₂ demand	-5% H ₂ demand	+5% Electricity demand	-5% Electricity demand
FD	100%	104.8%	95.3%	100.04%	99.99%
FET	100%	102.5%	97.5%	100.15%	99.90%
GWP	100%	103.9%	96.1%	100.09%	99.99%
HTP	100%	103.7%	96.3%	100.10%	99.93%
IR	100%	100.1%	99.9%	100.29%	99.45%
MET	100%	101.4%	98.7%	100.17%	99.81%
MD	100%	101.5%	98.5%	100.21%	99.89%
LU	100%	101.6%	98.4%	100.18%	99.77%
OD	100%	104.9%	95.2%	100.04%	99.69%
PMF	100%	103.4%	96.6%	100.07%	99.94%
POF	100%	103.0%	97.0%	100.05%	99.97%
TAP	100%	103.9%	96.1%	100.06%	99.96%
WD	100%	100.0%	100.0%	100.00%	100.00%

4.4.3 Overall interpretation

As demonstrated in section 4.3.3, the environmental impact of the hydrogen retrofit improves in some impact categories in comparison with the NG case, except for WD and IR. Based on these results, the use of Hydrogen from SMR provides almost a better environmental impact as the NG case.

First of all, based on the SA performed in sections 4.4.1 and 4.4.2, the impact categories WD and IR are independent from the NG and H₂ production, thus, the influence of the fuel change is minimal. This reason is based on that these two impact categories rely mainly on the combustion process in the furnace and the French electricity production respectively.

Regarding the fuel production process comparison, 11 impact categories have notable improvement, especially GWP, FD and MD. Nevertheless, 2 of impact categories got worse, due to the Hydrogen production process. In particular, WD and IR.

5 Case 4: LCA on the study of the reverberatory furnace from METL

5.1 Scope and goal

Similar as previous cases, the scope and goal applied for this case is described in section A.2.2.4 from report D1.2. However, some modifications which have been applied, need to be clarified. In this case a “cradle-to-gate” LCA for one year timeline is going to be conducted in a 65t reverberatory furnace. More into detail, the H₂ source is a SMR process. Furthermore, in this case the refractories and filters from the furnace are not going to be considered. Also, as a clarification the FU is going to be the aluminium held in the furnace and the oxidant during the combustion process is oxygen and air, as 2 scenarios are going to be considered. Finally, the emissions to air of Nitrogen and CO will not be considered.

5.2 Life cycle inventory

The data represented in Table 5.1, Table 5.2 and Table 5.3 show the parameters used in the modelling of the 65t reverberatory furnace used for melting and holding operations in the same facility as case 1 (chapter 2). However, in this case there were not trials conducted, thus the data was taken from other similar cases or manually calculated, as shown in each table respectively. In particular, the emission composition and total values were calculated by the application of the similar methodology explained in section 2.2. Then, the NO_x values were taken from deliverable 7.1. Furthermore, based on recommendations from GHI, in order to calculate the total values, a production time of 310 days and a 1% of dross were considered as well [6]. Finally, the production mix applied in this model is the same as the one presented in Figure 2.1: Electricity mix for electricity production in Greece in 2025. Data taken from [3], as this case belongs to the same industrial partner (METL).

Table 5.1: Input and output parameters for the baseline case from case 4

	Parameter	Unit	Value	Reference
Input	Volume flow NG	Nm ³ /h	567	Deliverable D.5.1
	Electricity consumption	kWh/t	14.79	ISO 13579-3 [7]
	Pressurized air	Nm ³ /h	5731	Calculated
	Aluminium	t/year	22220	Calculated
Output	Aluminium	t/year	22000	Given by METL
	Dross	t/year	220	Given by GHI
	NO _x *	mg/MJ	40	Deliverable D.7.1
	CO ₂	kg/h	1096.4	Calculated
	H ₂ O	m ³ /h	217.02	Calculated

*Benchmark

Table 5.2: Input and output parameters for the Hydrogen/air combustion from case 4

	Parameter	Unit	Value	Reference
Input	Volume Hydrogen	Nm ³ /h	1950	Deliverable D.5.2
	Electricity consumption	kWh/t	14.79	ISO 13579-3
	Pressurized air	Nm ³ /h	4642.86	Calculated
	Aluminium	t/year	22220	Calculated
Output	Aluminium	t/year	22000	Given by METL
	Dross	t/year	220	Given by GHI
	NO _x *	mg/MJ	116	Deliverable D.7.1
	CO ₂	kg/h	0	Calculated
	H ₂ O	m ³ /h	676.84	Calculated

*Benchmark

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 5.3: Input and output parameters for the Hydrogen oxycombustion case from case 4

	Parameter	Unit	Value	Reference
Input	Volume Hydrogen	Nm ³ /h	1060	Deliverable D.5.2
	Electricity consumption	kWh/t	14.79	ISO 13579-3 [8]
	Oxygen	Nm ³ /h	530	Calculated
	Aluminium	t/year	22220	Calculated
Output	Aluminium	t/year	22000	Given by METL
	Dross	t/year	220	Given by GHI
	NO _x *	mg/MJ	3.5	Deliverable D.7.1
	CO ₂	kg/h	0	Calculated
	H ₂ O	m ³ /h	1060	Calculated

*Flameless mode 180 kW burner

5.3 Impact assessment

5.3.1 Baseline case

Table 5.4 presents the values for the IA for the NG combustion case for this case. More into detail, in this process has been considered the NG, compressed air and electricity production processes and the combustion process. As result, this model led to 0.63 tCO₂/t_{al}, from which only a 58% of the total amount is emitted in the furnace. The model applied in the software Umberto 11[®] to obtain this value is presented in Figure 12.7 in [Annex G](#).

Table 5.4: Values on the IA for the NG combustion case of case 4 (ReCiPe 2016 Midpoint-H)

Impact category	Acronym	Unit	Value
Fossil depletion Potential	FD	kg oil-eq/t _{al}	244.35
Freshwater Eutrophication	FET	kg P eq/t _{al}	0.12
Global Warming Potential	GWP	kg CO ₂ eq/t _{al}	631.34
Human Toxicity Potential	HTP	kg 1.4 DB/t _{al}	270.48
Ionizing radiation	IR	kBq Co-60 eq./t _{al}	1.67
Land use	LU	Annual crop eq./t _{al}	24.25·10 ⁻³
Marine Eutrophication	MET	kg N eq/t _{al}	0.78
Metal Depletion	MD	kg Cu-eq/t _{al}	4.885
Stratospheric Ozone Depletion	OD	kg CFC-11-eq/t _{al}	0.12·10 ⁻³
Particulate Matter Formation	PMF	kg PM25-eq/t _{al}	0.26
Photochemical Ozone Formation	POF	kg NO _x eq./t _{al}	1.37
Terrestrial Acidification	TAP	kg SO ₂ -eq/t _{al}	0.7
Water depletion	WD	m ³ water -eq/t _{al}	397.68

Figure 5.1 shows percentage of each process on each impact category for case 4. In particular, the influence of the electricity production process is significant, since 7 out of 13 categories have values over 50%. However, also the NG production affects this model in a lower degree as 4 out of 13 categories have values over 30%. Therefore, these 2 processes are the most influential in this model. Nevertheless, this dependency needs to be demonstrated in the SA. Then, the combustion process affects GWP, PMF, POF, TAP and WD, but it mostly influences the WD impact category. Finally, the air production process is present in 11 categories in which only 2 is over 20%, and, thus, its influence does not affect the model.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Figure 5.2 represents the distribution of the impact categories mean value among the processes under the baseline scenario. Similar as previously described, the electricity production process has the highest value in comparison to the rest of the processes. This reason is based on the fossil-fuel routes on the Greek electricity production mix, as presented in Figure 2.1: Electricity mix for electricity production in Greece in 2025. Data taken from [3]. Furthermore, although the electricity consumption is lower as the NG consumption, this process still has more than double the mean value in comparison to the NG production process over the model. Then, the combustion process and the air production process are also present with less influence with values of 13% and 6.3% respectively

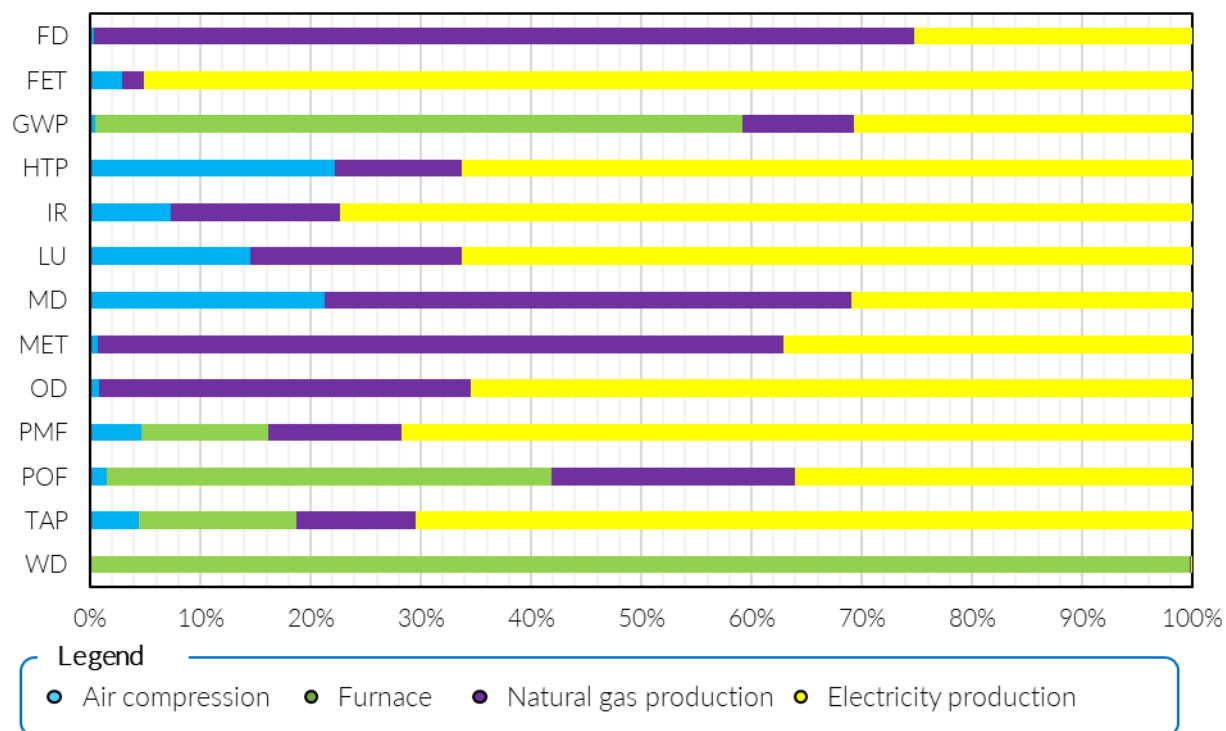


Figure 5.1: Percentage of IA of each process from the case 4 baseline (ReCiPe 2016 Midpoint-H)

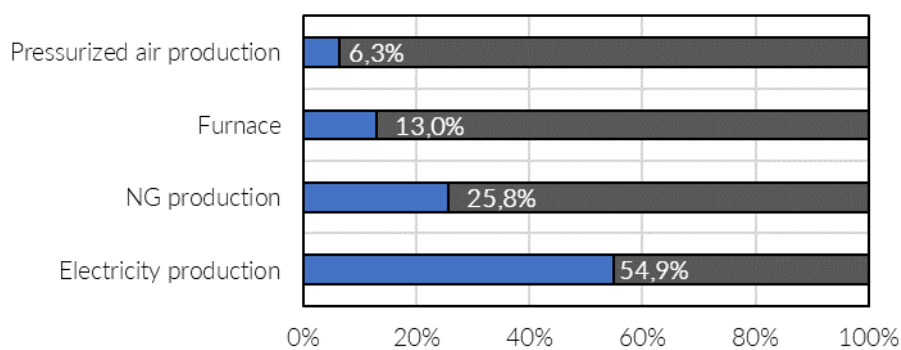


Figure 5.2: Distribution of the mean value among the processes for all the environmental impacts under the baseline scenario for case 4

5.3.2 Scenario 1: Hydrogen/air combustion

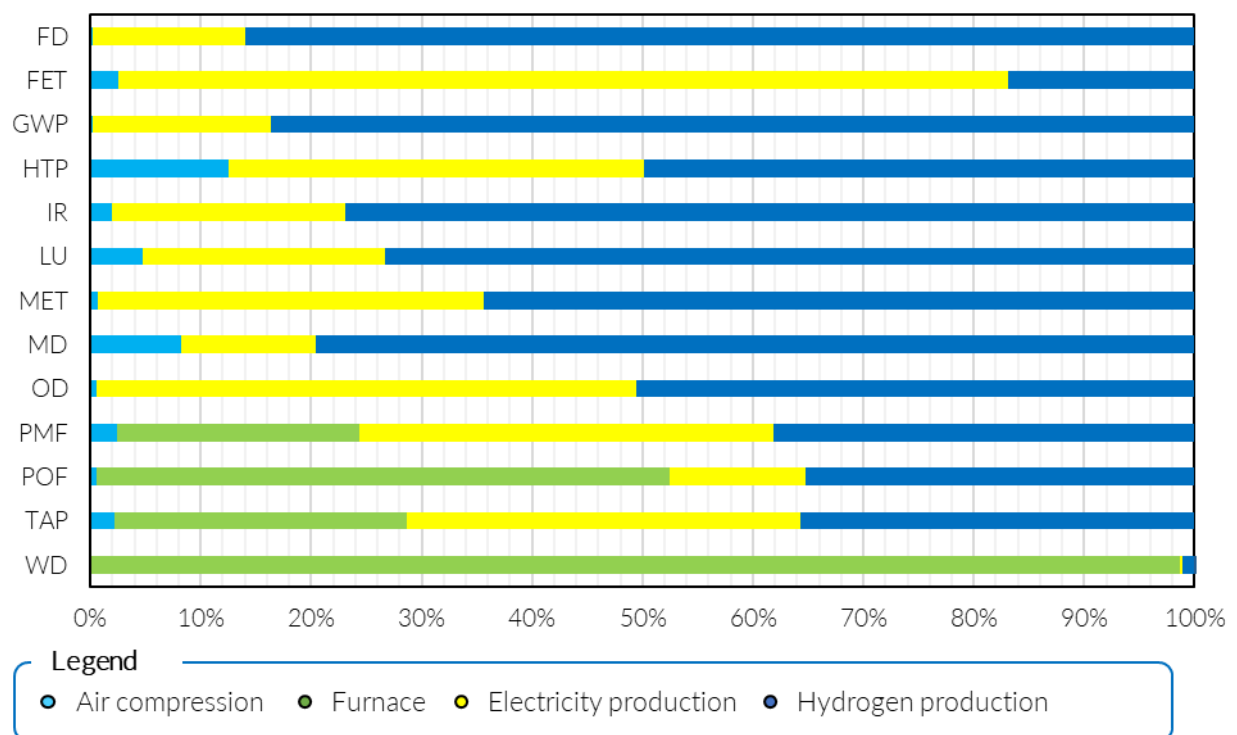
Table 5.5 presents the values for the IA for the H₂/air combustion case. In particular, this process has been considered the H₂ (SMR), compressed air and electricity production processes and the combustion process. As result, this model led to 0.982 t_{CO2}/t_{al}, from which only an 83.6% of the total amount is generated on the SMR process. As result, no CO₂ were emitted in the furnace. The model applied in the software Umberto 11[®] to obtain this value and the following results is presented in Figure 12.8 in [Annex J](#). This model was created applying the values presented in Table 5.2.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 5.5: Values on the IA for the H₂/air combustion of case 4 (ReCiPe 2016 Midpoint-H)

Impact category	Acronym	Unit	Value
Fossil depletion Potential	FD	kg oil-eq/t _{al}	362
Freshwater Eutrophication	FET	kg P eq/t _{al}	0.12
Global Warming Potential	GWP	kg CO ₂ eq/t _{al}	982.85
Human Toxicity Potential	HTP	kg 1.4 DB/t _{al}	389.46
Ionizing radiation	IR	kBq Co-60 eq./t _{al}	5
Land use	LU	Annual crop eq./t _{al}	21·10 ⁻³
Marine Eutrophication	MET	kg N eq/t _{al}	1.93
Metal Depletion	MD	kg Cu-eq/t _{al}	10.17
Stratospheric Ozone Depletion	OD	kg CFC-11-eq/t _{al}	0.13·10 ⁻³
Fine Particulate Matter Formation	PMF	kg PM25-eq/t _{al}	0.41
Photochemical Ozone Formation	POF	kg NOx eq./t _{al}	3.2
Terrestrial Acidification	TAP	kg SO ₂ -eq/t _{al}	1.12
Water depletion	WD	m ³ water -eq/t _{al}	255.72

Figure 5.3 shows the percentage of each process on each impact category for case 4 under the Hydrogen/air combustion case. Similar to other cases, the SMR process dominates on 8 out of 13 categories with values over 50%. Also, the electricity production process has an important impact over the model, especially in FET. Then, the combustion process affects only 4 impact categories in which WD is totally dominant. Finally, the pressurized air production has the lowest influence in the model, only being remarkable in the HTP impact category.



D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Figure 5.3: Percentage of IA of each process from the case 4 scenario 1 (ReCiPe 2016 Midpoint-H)

Figure 5.4 represents the distribution of the mean values corresponding to all the impact categories divided by process for case 4 under the hydrogen/air combustion. In this case, the SMR process has the highest influence over the model with 53.2 % of the mean values followed by the electricity production process with a 28.7%. Similar as previously performed, these two variables will be modified in order to analyse their influence over the model. Finally, the influence of the combustion process and the pressurized air led to a 15.3% and 2.8% respectively on the mean values of the impact categories. Based on this value, it is possible to assume that the pressurized air production process has an insignificant influence and, thus, could be neglected.

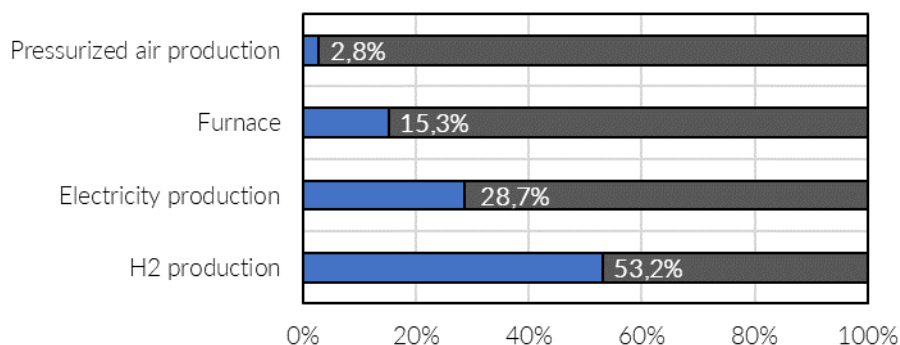


Figure 5.4: Distribution of the mean value among the processes for all the environmental impacts under the scenario 1 for case 4

5.3.3 Scenario 2: Hydrogen oxycombustion

Table 5.6 presents the values for the IA for the H₂/oxygen combustion case. In this process has been considered the H₂ (SMR), oxygen and electricity production and the combustion processes. Consequently, this model led to 0.6 tCO₂/t_{al}, from which only a 53.7% of the total amount is emitted on the hydrogen production process. The model applied in the software Umberto 11® to obtain this value is presented in Figure 12.9 in [Annex K](#).

Table 5.6: Values on the IA for the NG combustion case from case 4 (ReCiPe 2016 Midpoint-H)

Impact category	Acronym	Unit	Value
Fossil depletion Potential	FD	kg oil-eq/t _{al}	219.87
Freshwater Eutrophication	FET	kg P eq/t _{al}	0.11
Global Warming Potential	GWP	kg CO ₂ eq/t _{al}	605.8
Human Toxicity Potential	HTP	kg 1.4 DB/t _{al}	236.14
Ionizing radiation	IR	kBq Co-60 eq./t _{al}	2.9
Land use	LU	Annual crop eq./t _{al}	0.014
Metal Depletion	MD	kg Cu-eq/t _{al}	5.49
Marine Eutrophication	MET	kg N eq/t _{al}	1.1
Stratospheric Ozone Depletion	OD	kg CFC-11-eq/t _{al}	0.1·10 ⁻³
Particulate Matter Formation	PMF	kg PM25-eq/t _{al}	0.23
Photochemical Ozone Formation	POF	kg NOx eq./t _{al}	1.07
Terrestrial Acidification	TAP	kg SO ₂ -eq/t _{al}	0.61
Water depletion	WD	m ³ water -eq/t _{al}	142.9

Figure 5.5 presents the percentage of the IA of each process from case 4 under the Hydrogen oxycombustion conditions. Similar as scenario 1 (section 5.3.2), the SMR process dominates the environmental impact of this model. In particular, 8 out 13 impact categories remain over 50% of its total value. This fact is based on the NG, Methane and CO₂ emissions. Then, the electricity production process is present in 12 impact categories, from which in 4 of them values exceeded 50% of the total values (HTP, OD, PMPF and TAP). The reason for these results is the dependency of the Greek electricity mix from coal and oil (Figure 2.1: Electricity mix for

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

electricity production in Greece in 2025. Data taken from [3]). In addition, the combustion and oxygen production process are less present in the environmental impacts. In particular, the combustion process has a significant impact on the WD impact category, due to the water generated on the combustion process, which is the most influential in the aforementioned impact category. Finally, regarding the oxygen production process is barely present in these results.

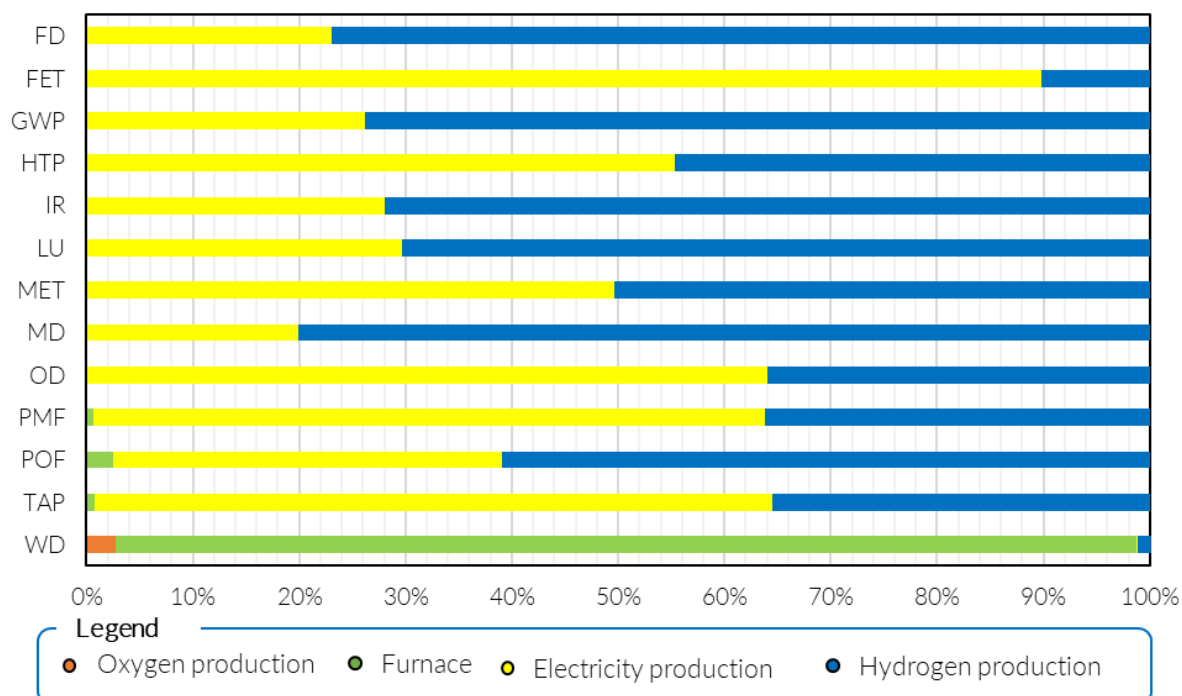


Figure 5.5: Percentage of IA of each process from the case 4 scenario 2 (ReCiPe 2016 Midpoint-H)

Figure 5.6 shows the distribution of the mean value among the processes for all the environmental impacts under the Hydrogen oxycombustion case. Similar as previously mentioned, the hydrogen and electricity production are the most influential processes with both a 91.2% on the mean values. Then, the rest of the processes have values below 10%, which demonstrates the low influence of this inputs, except for the combustion process in the WD category, which is the most dominant.

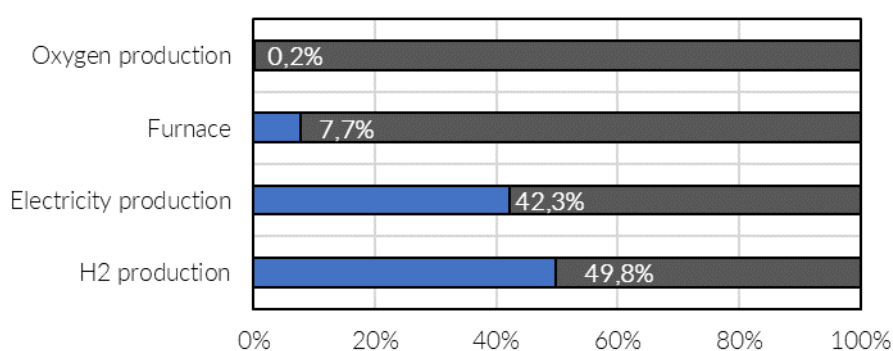


Figure 5.6: Distribution of the mean value among the processes for all the environmental impacts under the scenario 2

5.3.4 Results comparison

Table 5.7 presents the values obtained for the deviation of all the impact categories for scenario 1 and 2 in comparison to the reference, which is represented by a red-dotted line in Figure 5.7. More into detail, the data used for this figure is represented in Table 5.4, Table 5.5, Table 5.6 for the baseline, scenario 1 and 2 respectively. In the case of scenario 1, only 2 out of 13 categories improved, while the rest got worse. In

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

contrast, scenario 2 showed an improvement on 10 out of 13 categories which obtained values below 10% and 20% with respect to the baseline, except LU which reached a 40% less.

With respect to the hydrogen air combustion scenario shows the worst environmental performance in comparison to the aforementioned scenarios. More into detail, from the 9 impact categories in which a worse value has been obtained, their result varies between 0.5 and 2.5 times. This impact is especially remarkable in categories such as GWP, IR or WD. However, the impacts which a lower value has been obtained are only FET and LU. The rest of the categories obtained a reduced value with respect to the baseline.

Regarding to scenario 2, the 10 impact categories which obtained lower values in comparison to the baseline case are FD, FET, GWP, HTP, LU, OD, PMF, POF and TAP. In particular, these results are in the range between 10% and 40% less. The reason for these values is based on the lower hydrogen consumption. This fact is also representative when comparing with scenario 1 and 2. As result, less hydrogen is produced and, thus, less emissions generated during the SMR process. In contrast, from the rest of the impact categories, which got worse values, MET and IR are to highlight.

Table 5.7: Percentage deviation of all impact categories in reference to baseline for case 4 under scenario 1 and 2

Impact category	Baseline	Scenario 1	Scenario 2	Unit
Fossil depletion Potential	100%	148%	90%	kg oil-eq/tal
Freshwater Eutrophication	100%	96%	87%	kg P eq/tal
Global Warming Potential	100%	156%	96%	kg CO2 eq/tal
Human Toxicity Potential	100%	144%	87%	kg 1.4 DB/tal
Ionizing radiation	100%	299%	174%	kBq Co-60 eq./tal
Land use	100%	87%	60%	Annual crop eq./tal
Marine Eutrophication	100%	208%	112%	kg Cu-eq/tal
Metal Depletion	100%	248%	140%	kg N eq/tal
Stratospheric Ozone Depletion	100%	110%	84%	kg CFC-11-eq/tal
Particulate matter formation	100%	156%	90%	kg PM25-eq/tall
Photochemical oxidant Formation	100%	239%	78%	kg NOx eq./tal
Terrestrial Acidification	100%	161%	88%	kg SO2-eq/tal
Water depletion	100%	64%	92%	m3 water -eq/tal

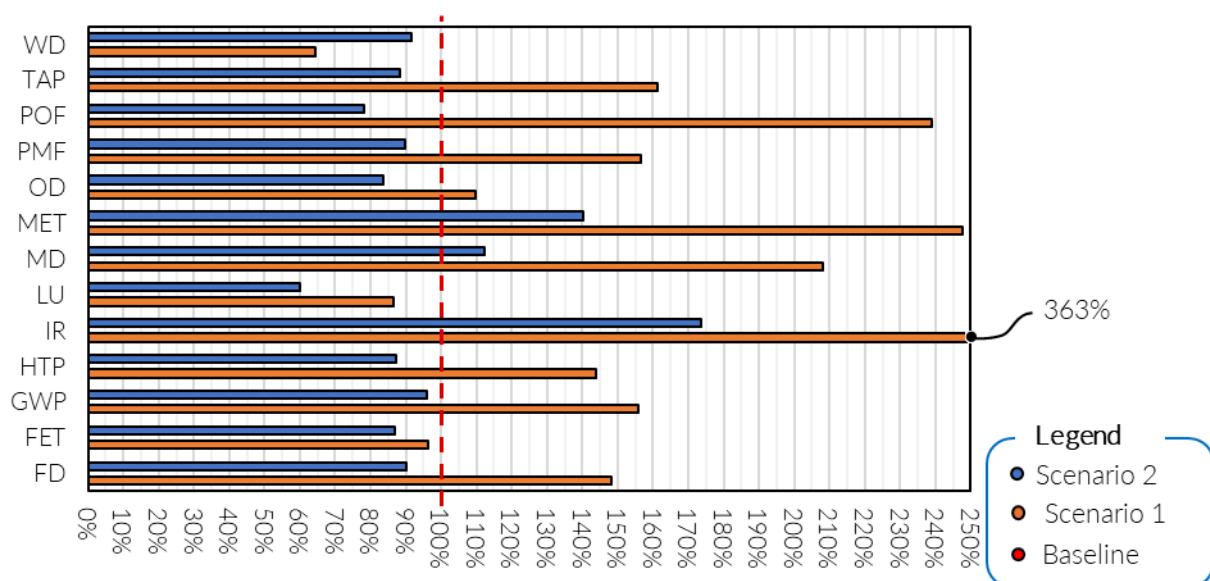


Figure 5.7: Relative change for all impact categories among baseline (reference), scenario 1 and scenario 2

5.4 Interpretation

5.4.1 Sensitivity analysis on the baseline

Table 5.8 shows the numerical results of the SA for the NG and electricity demand for baseline from case. 4. In this case, the variables of NG and electricity demand have been modified. As mentioned in section 5.3.1, these are the variables with higher influence over the model. Throughout this section it will be examined the robustness and independency of the model from the aforementioned variables.

Regarding the NG demand, this case is represented by a dark and light purple line in Figure 5.8. In particular, the values obtained have a mean and median value of 0.013 and 0.01 respectively. These metrics represent that the data distribution is closer to the zero. Therefore, based on the aforementioned, the NG demand has low influence as an overall over the model. Nevertheless, there are impact categories such as FD and MET, which varied more than a 3%, leading to a higher dependence on NG demand. Also, the SA shows a standard variation of 0.01, which demonstrates that the data is dispersed. This reason is based on the values of FD and MET that shift the data distribution closer to the upper limit.

The results on the SA for the electricity demand are represented in light and dark yellow in Figure 5.8. In this case, the results show a mean and median value of 0.01. These values demonstrates that the data distribution is concentrated on the lower limit. Furthermore, as the standard variation is $0.4 \cdot 10^{-3}$, from this metric is possible to infer that the distribution is not disperse. Therefore, based on the metrics described previously, these values demonstrated that for this model the electricity demand has low influence, and, thus, is robust and independent in relation to this parameter.

Based on the aforementioned, NG demand has lower influence on the model and the electricity demand has insignificant influence over the model. As result, this model is robust and independent from the electricity demand and slightly dependent on NG demand, especially in FD and MET impact categories.

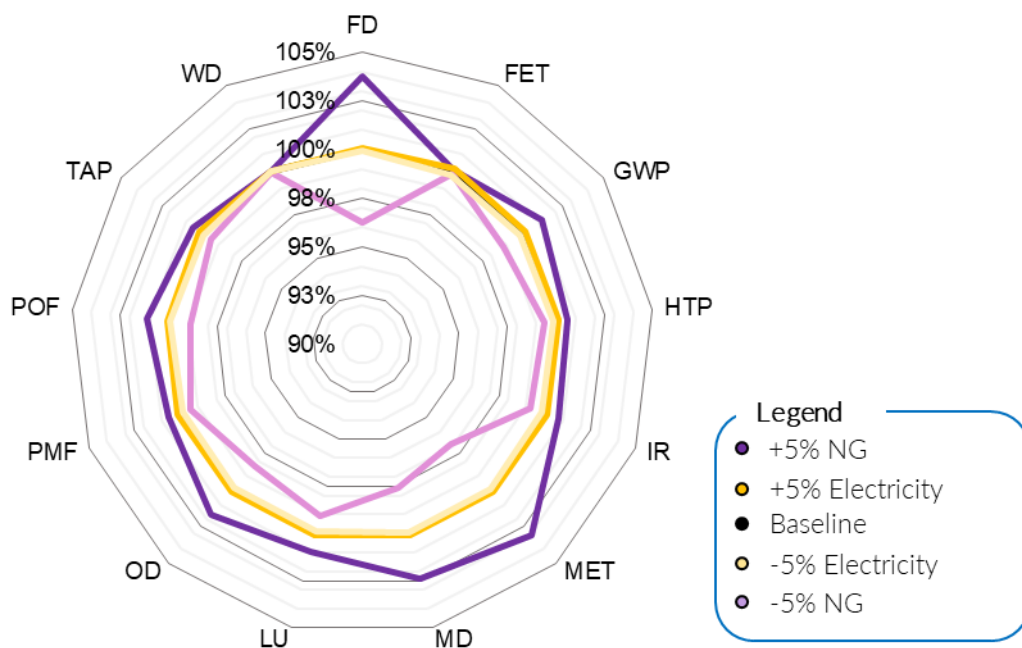


Figure 5.8: Sensitivity analysis on the NG and electricity demand for the baseline from case 4

Table 5.8: Results on the sensitivity analysis for the NG and electricity demand for baseline from case 4

Impact category	Baseline	+5% NG demand	-5% NG demand	+5% Electricity demand	-5% Electricity demand
FD	100%	103.7%	96.3%	100.0%	100.0%
FET	100%	100.1%	99.9%	100.2%	99.8%
GWP	100%	101.2%	98.8%	100.1%	99.9%
HTP	100%	100.6%	99.4%	100.1%	99.9%
IR	100%	100.8%	99.2%	100.1%	99.9%
MET	100%	103.1%	96.9%	100.1%	99.9%

MD	100%	102.4%	97.6%	100.1%	99.9%
LU	100%	101.0%	99.0%	100.1%	99.9%
OD	100%	101.7%	98.3%	100.1%	99.9%
PMF	100%	100.6%	99.4%	100.1%	99.9%
POF	100%	101.1%	98.9%	100.1%	99.9%
TAP	100%	100.5%	99.5%	100.1%	99.9%
WD	100%	100.0%	100.0%	100.0%	100.0%

5.4.2 Sensitivity analysis on the scenario 1: Hydrogen/air combustion

Table 5.9 shows the numerical results of the SA for the Hydrogen and electricity demand for the scenario 1 model from case. 4. In this case, the variables of Hydrogen and electricity demand have been modified. As commented in section 5.3.2, these are the variables with higher influence over the model, especially the hydrogen demand as result of the SMR process. These results are graphically represented in Figure 5.9. In the following, the robustness and independency of the model in relation to the previously mentioned variables will be analysed.

With respect to the results on the SA from the Hydrogen demand, Figure 5.9 presents these values in dark and light blue. More into detail, this data shows a mean of 0.027 and a median value of 0.025. From these values is possible to infer that the data distribution is centred in the middle of the data range. However, as a standard variation of 0.01 was obtained, this value shows a high dispersion, which is generated by high sensitivity impact categories such as FD, GWP, IR, MD and LU, and low sensitivity impact categories as WD or FET. Therefore, although the data is centred in the middle, the dispersion is high. This fact led to a medium sensitivity of the model from the Hydrogen demand, especially for FD, GWP, IR, MD and LU.

Regarding the SA on the electricity demand for this model, the values obtained are represented in dark and light yellow in Figure 5.9. In this case, the same occurs as the baseline, in which a low standard variation ($0.4 \cdot 10^{-3}$) and the same mean and median (0.01) are obtained. These values demonstrate that the data distribution is centred close to the lower limit of the data range. Consequently, similar as aforementioned, the electricity demand has low influence in the model, and, thus, the model is robust and independent over the electricity demand.

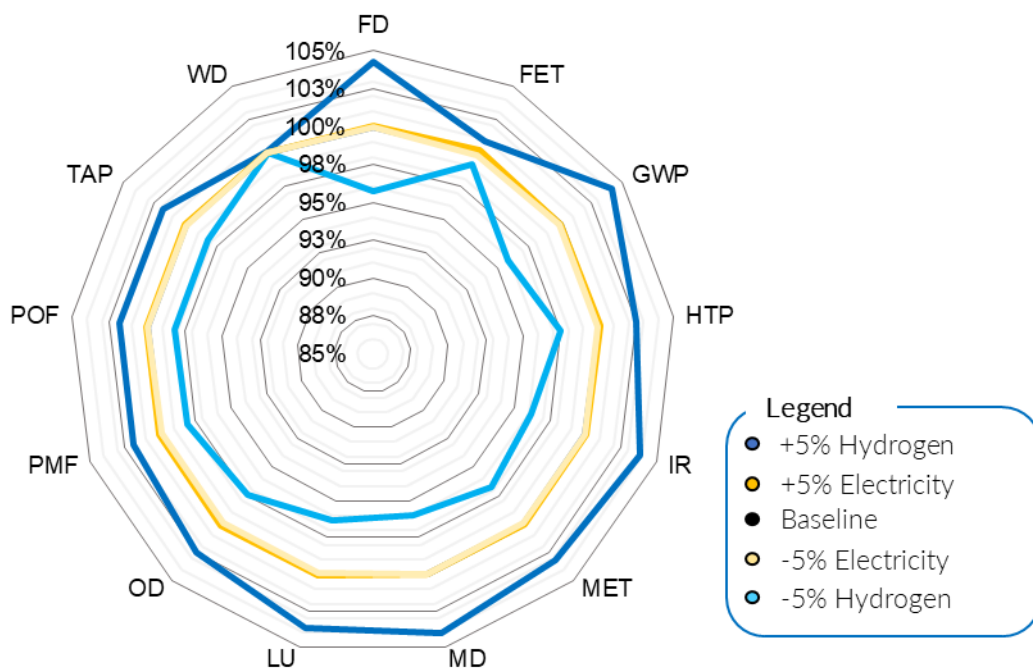


Figure 5.9: Sensitivity analysis on the Hydrogen and electricity demand for the scenario 1 from case 4

Table 5.9: Results on the sensitivity analysis for the H_2 and electricity demand for scenario 1 from case 4

Impact category	Baseline	+5% NG demand	-5% NG demand	+5% Electricity demand	-5% Electricity demand
FD	100%	104.3%	95.7%	100.0%	100.0%
FET	100%	100.8%	99.2%	100.2%	99.8%
GWP	100%	104.2%	95.8%	100.0%	100.0%
HTP	100%	102.5%	97.5%	100.1%	99.9%
IR	100%	103.8%	96.2%	100.0%	100.0%
LU	100%	103.2%	96.8%	100.1%	99.9%
MD	100%	104.0%	96.0%	100.0%	100.0%
MET	100%	103.7%	96.3%	100.1%	100.0%
OD	100%	102.5%	97.5%	100.1%	99.9%
PMF	100%	101.9%	98.1%	100.1%	99.9%
POF	100%	101.8%	98.2%	100.0%	100.0%
TAP	100%	101.8%	98.2%	100.1%	99.9%
WD	100%	100.1%	99.9%	100.0%	100.0%

5.4.3 Sensitivity analysis on the scenario 2: Hydrogen/oxygen combustion

Table 5.10 presents the results of the SA for the Hydrogen and electricity demand for scenario2 from case. 4. Throughout this analysis the variables of Hydrogen and electricity demand have been modified on their $\pm 5\%$ value. As commented in section 5.3.3, these are the variables with higher influence over the model.

Firstly, with regard to the Hydrogen demand, Figure 5.10 presents the results of the SA in a dark and light blue line. Furthermore, the analysis of these values is represented by a mean and a median of 0.025. These values indicate that the data distribution is centred with respect to the data range. More into detail, the standard variation is 0.012, which demonstrates a high dispersion of the data distribution. Therefore, based on the aforementioned data, it is possible to conclude that, although the data distribution is centred in the middle of the data range, it has a high dispersion, thus, there are some impact categories which are highly influenced such as FD, GWP, IR, MD or LU and other impact categories which are not affected such as WD or FET. Consequently, this model is middle sensitive to hydrogen demand.

Regarding to the electricity demand, the same values for mean, median and standard variation are obtained in comparison to the baseline (NG combustion, section 5.4.1) and scenario 1 (Hydrogen/air combustion, section 5.4.2). Therefore, these facts lead to the same conclusion as previously described, and, thus, the model is robust and independent over the electricity demand. Finally, the impact category of WD was not affected by any of the aforementioned energy demands.

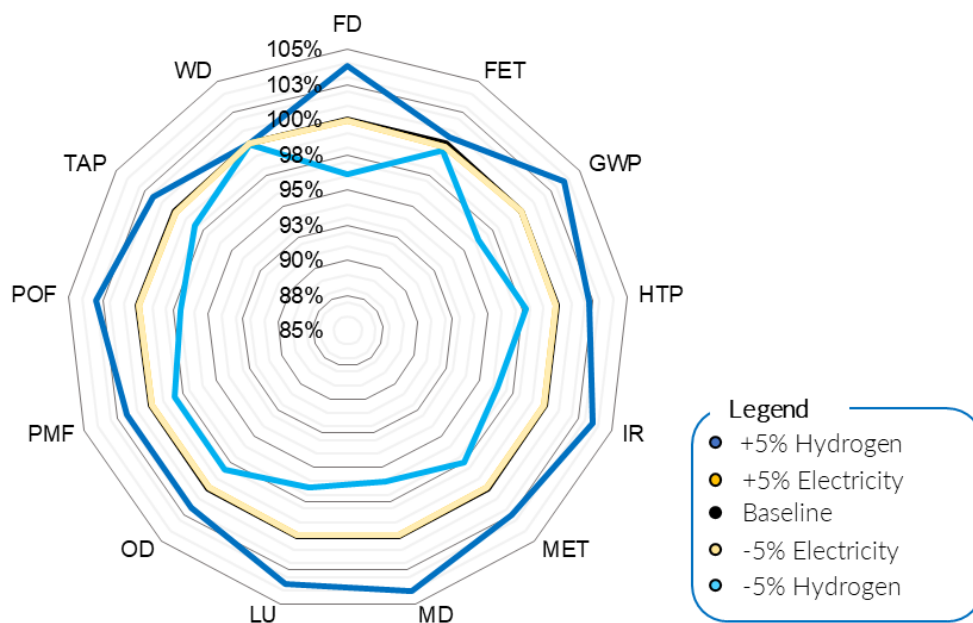


Figure 5.10: Sensitivity analysis on the Hydrogen and electricity demand for the scenario 2 from case 4

Table 5.10: Results on the sensitivity analysis for the H₂ and electricity demand for scenario 2 from case 4

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Impact category	Baseline	+5% H2 demand	-5% H2 demand	+5% Electricity demand	-5% Electricity demand
FD	100%	103.8%	96.2%	100.1%	99.9%
FET	100%	100.5%	99.5%	100.2%	99.8%
GWP	100%	103.7%	96.3%	100.1%	99.9%
HTP	100%	102.2%	97.8%	100.1%	99.9%
IR	100%	103.6%	96.4%	100.1%	99.9%
MET	100%	102.5%	97.5%	100.1%	99.9%
MD	100%	104.0%	96.0%	100.1%	99.9%
LU	100%	103.5%	96.5%	100.1%	99.9%
OD	100%	101.8%	98.2%	100.1%	99.9%
PMF	100%	101.8%	98.2%	100.1%	99.9%
POF	100%	103.0%	97.0%	100.1%	99.9%
TAP	100%	101.8%	98.2%	100.1%	99.9%
WD	100%	100.1%	99.9%	100.0%	100.0%

5.4.4 Overall interpretation

As described throughout this chapter, the implementation of hydrogen combustion with air led to a worse environmental impact in comparison to the NG baseline, due to the use of hydrogen from SMR. More into detail, as result of the use of Hydrogen, the environmental impact generated in the furnace is reduced. In particular, this reduction eliminated 365.4 kgCO₂/t_{al}

In contrast, the hydrogen oxycombustion provided a better environmental performance in comparison to the hydrogen/air scenario, but not for all the impact categories. This fact is based on the SMR production process and their corresponding emissions generated. Furthermore, the use of this process leads to a dependency over the model, especially in impact categories such as FD, GWP, IR, MD or LU.

Despite of the dependency of the Greek electricity production mix on some fossil fuel sources (e.g. oil, NG...), their effect and influence on the model is low. Also, based on the results shown in sections 5.3.1, 5.3.2 and 5.3.3, the models for each scenario are robust and independent over the electricity demand, since they indicate low sensitivity.

Regarding the combustion process, it is main influenced in the WD impact category, as is the main source of the water emissions and the pressurized air/oxygen production process have less influence on the process, as mentioned in sections 5.3.1, 5.3.2 and 5.3.3

6 Case 5: LCA on the study of the pusher furnace from SPE

6.1 Scope and goal

The scope and goal applied for this case is described in section A.2.2.4 from report D1.2. Nevertheless, some modifications need to be clarified. In this case a “cradle-to-gate” LCA is going to be performed in which the H₂ source is a Steam Methane Reforming (SMR) process. Also, the timeline stated for this study is fixed as 1 year. Finally, the emissions to air of Nitrogen and CO will not be considered.

6.2 Life cycle inventory

This model represents the Ebner pusher furnace in the factory in Hamburg, which is modelled for a one-year timeline. Since no measurements performed, all the emissions which were not available, were calculated. For that purpose, based on the information provided in deliverable D2.6 and specific data provided by SPE, the following has been created. For that purpose, taking from D2.6, the furnace production rate of 192 kt_{al} for the 2 preheating furnaces, and the 234 kWh_{th}/t_{al} and 31 kWh_{el}/t_{al}, these values lead to 12.9 t_{al}/h, 117.5 kWh_{th}/t_{al} and 15.5 kWh_{el}/t_{al} consumed by the furnace. As result, considering a low heating value of natural gas 10 kWh/Nm³ taken from [9], the flow rate for this furnace leads to 151.63 Nm³/h. Based on this data, combustion calculations were applied in order to calculate the flow rate of air and the emissions for CO, H₂O and O₂. For that purpose, the air-fuel ratio was considered equal to 1.15. Finally, the emissions from CO₂ and NO_x have been calculated based on the emission factor and NO_x emissions proposed in D2.6. The model applied with these values is presented in [Annex J](#).

Table 6.1: Input and output parameters for modelling the NG combustion with air for case 5

	Parameter	Unit	Value
Input	NG Volume	Nm ³	1128000
	Electricity consumption	kWh	1488000
	Aluminium slabs	t	96000
	Pressurized air	m ³	1315912.8
Output	Aluminium slabs	t	96000
	CO ₂	t	2181.34
	CO	t	0
	H ₂ O	m ³	2334960
	O ₂	t	387.077
	NO _x	mg/m ³	190

Table 6.2 shows the parameters used in the model for the Hydrogen combustion. Similar to the case before, no measurements were performed for this case. Therefore, all the data was manually calculated based on the previous assumptions. Furthermore, hydrogen was considered also produced by Steam Methane Reforming (SMR). Finally, NO_x values were obtained from research conducted by Busson et al. [10]. The model applied for these values is presented in [Annex K](#).

Table 6.2: Input and output parameters for modelling the H₂ combustion with air for case 5

	Parameter	Unit	Value
Input	Hydrogen	m ³	3760000
	Electricity consumption	kWh	1488000
	Aluminium slabs	t	96000
	Pressurized air	m ³	10295100

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Output	Aluminium slabs	t	96000
	CO ₂	t	0
	CO	t	0
	H ₂ O	m ³	4340214.9
	O ₂	t	282.243
	NO _x	mg/m ³ _{dry}	326

Figure 6.1: Electricity mix for electricity production in Germany for 2025. Data taken from [11] presents the electricity mix for the electricity production in Germany for the year 2025 obtained from [11]. This mix was taken to represent the environmental effect of the electricity production in this country, especially in the processes of air compression, SMR and the electricity used in the furnace.

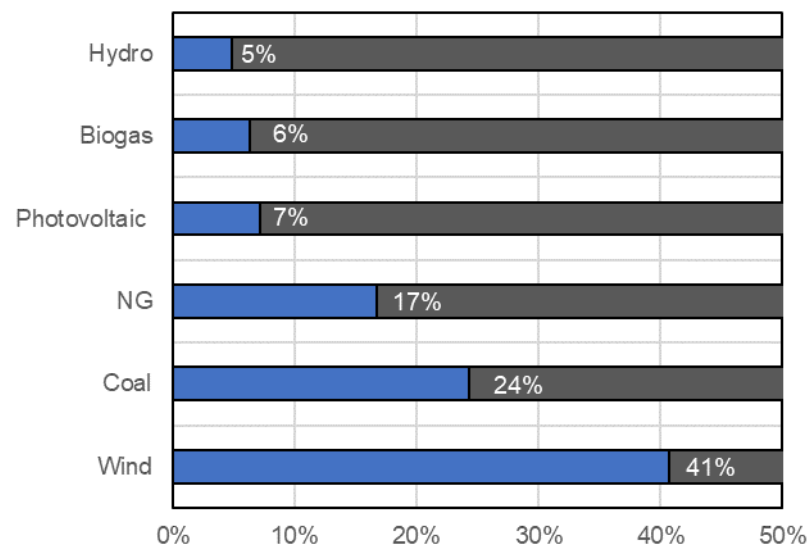


Figure 6.1: Electricity mix for electricity production in Germany for 2025. Data taken from [11]

6.3 Impact assessment

6.3.1 Baseline case

Table 6.3 presents the values obtained for each impact category for the baseline case 5. The aforementioned numerical data is presented in Figure 6.2. In particular, this case resulted in 0.03 tCO_{2eq}/t_{al}, from this part a 69.1 % is generated in the combustion process. These values were calculated with the value of GWP from the software Umberto. The model used for this calculation is presented in Figure 12.5 in [Annex L](#).

Table 6.3: Values on the IA for the baseline scenario of case 5 (ReCiPe 2016 Midpoint-H)

Impact category	Acronym	Unit	Value
Fossil depletion Potential	FD	kg oil-eq/t _{al}	11.96
Freshwater Eutrophication	FET	kg P eq/t _{al}	0.2·10 ⁻³
Global Warming Potential	GWP	kg CO ₂ eq/t _{al}	32.9
Human Toxicity Potential	HTP	kg 1.4 DB/t _{al}	3.28
Ionizing radiation	IR	kBq Co-60 eq./t _{al}	27.6·10 ⁻³
Land use	LU	Annual crop eq./t _{al}	21.7·10 ⁻³
Metal Depletion	MD	kg Cu-eq/t _{al}	0.18
Marine Eutrophication	MET	kg N eq/t _{al}	0.9·10 ⁻³

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Stratospheric Ozone Depletion	OD	kg CFC-11-eq/t _{al}	$4.87 \cdot 10^{-6}$
Particulate Matter Formation	PMF	kg PM25-eq/t _{al}	$4.5 \cdot 10^{-3}$
Photochemical Ozone Formation	POF	kg NOx eq./t _{al}	$38.9 \cdot 10^{-3}$
Terrestrial Acidification	TAP	kg SO ₂ -eq/t _{al}	$11.8 \cdot 10^{-3}$
Water depletion	WD	m ³ water -eq/t _{al}	24.34

Figure 6.2 presents the percentage of each process on each impact category for the case 5 with NG combustion. For that purpose, the combustion process in the furnace and the production processes of NG, compressed air and electricity were considered. As result, NG production plays a more dominant role over the rest of the processes, especially in 3 out of the 13 analysed categories (FD, MD and MET). Nevertheless, this dominance needs to be confirmed after the SA, which will be performed on section 6.4.1.

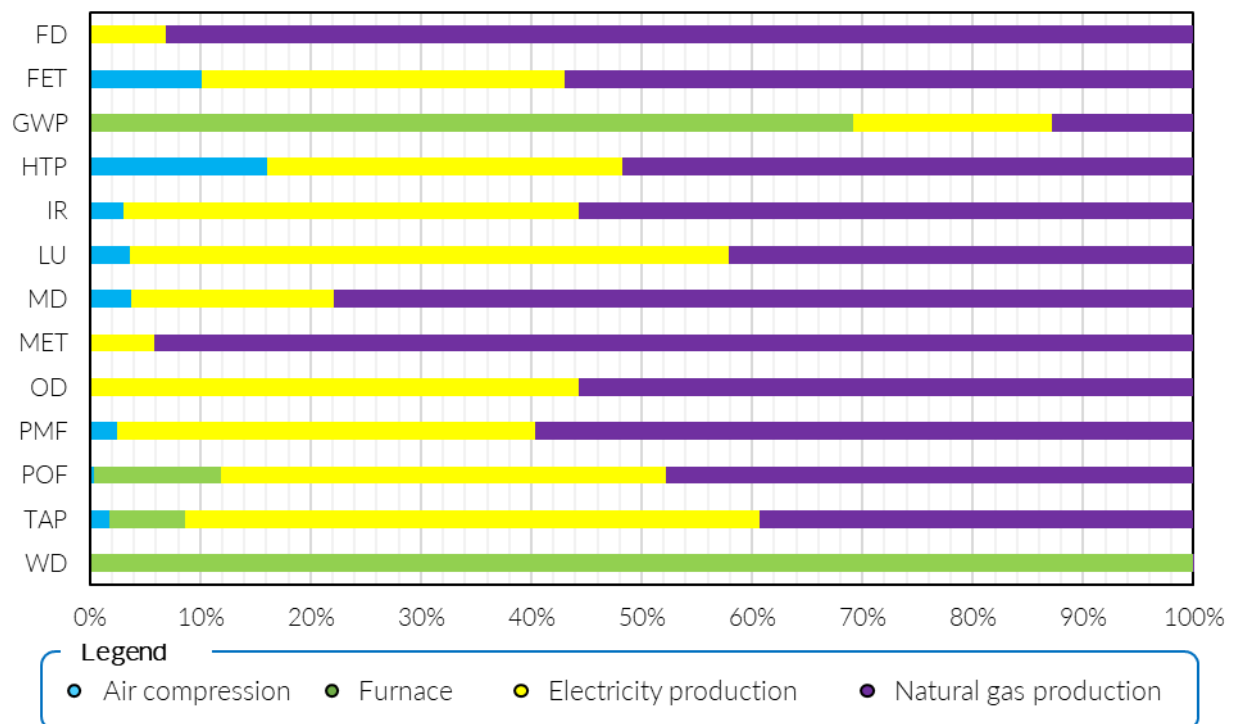


Figure 6.2: Percentage of IA of each process from the case 5 baseline (ReCiPe 2016 Midpoint-H)

Figure 6.3 presents the mean values of the percentages corresponding to all the impact categories for each process on case 5 for the baseline scenario. This figure is built up based on mean values from Figure 6.2. As result, this figure shows that the process which has higher environmental influence in average on the whole process is the NG production process. This process has been modelled based on direct extraction from petroleum refinery. Based on these results and similar as aforementioned, this process dominates a priori the environmental impact of this process.

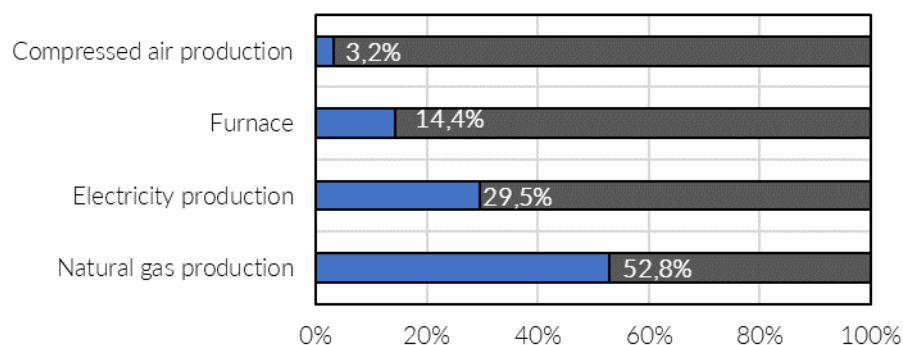


Figure 6.3: Distribution of the mean value among the processes for all the environmental impacts under the baseline scenario for case 5

6.3.2 Scenario 1: Hydrogen/air combustion

Table 6.4 presents the values on the IA for the hydrogen implementation for case 5. For that purpose, the production process of electricity, hydrogen via SMR and air compression and the combustion process have been considered. Although this process is CO₂-free from the combustion perspective, this case resulted in 0.054 tCO_{2eq}/t_{al}, from this part 89.5

% is generated in the SMR process and the rest from the electricity production process. Therefore, although in this model CO₂ is emitted, the process which occurs in the furnace is decarbonized. Then, the model used for the calculation of these values is presented in Figure 12.11 in [Annex K](#).

Table 6.4: Values on the IA for the scenario 1 of case 5

Impact category	Acronym	Unit	Value
Fossil depletion	FD	kg oil-eq/t _{al}	19.28
Freshwater Eutrophication	FET	kg P eq/t _{al}	1.3·10 ⁻³
Global Warming Potential	GWP	kg CO ₂ eq/t _{al}	54.54
Human Toxicity Potential	HTP	kg 1.4 DB/t _{al}	12.91
Ionizing radiation	IR	kBq Co-60 eq./t _{al}	0.24
Marine Eutrophication	MET	kg N eq/t _{al}	0.8·10 ⁻³
Metal Depletion	MD	kg Cu-eq/t _{al}	0.52
Land use	LU	Annual crop eq./t _{al}	96.9·10 ⁻³
Stratospheric Ozone Depletion	OD	kg CFC-11-eq/t _{al}	6.34·10 ⁻⁶
Fine Particulate Matter Formation	PMF	kg PM25-eq/t _{al}	13·10 ⁻³
Photochemical Ozone Formation	POF	kg NOx eq./t _{al}	0.11
Terrestrial Acidification	TAP	kg SO ₂ -eq/t _{al}	34.9·10 ⁻³
Water depletion	WD	m ³ water -eq/t _{al}	39.34

Figure 6.5 presents the percentage values for the IA of each process on each impact category for the case 5 with H₂ combustion. In this case the effect of the SMR process is dominant on the environmental impact as on all the impact categories has values over 60%, except in WD. In particular, FD, GWP, MD and LU are influenced by the quantity of NG used ($\approx 3 \text{ kg}_{\text{NG}}/\text{kg}_{\text{H}_2}$) [12] and the subsequent effects of its production and subproducts such as CO₂, Methane or NO_x. Furthermore, the influence of the air compression process is less than 1%. Thus, for this case could be neglected.

Figure 6.4 represents the mean values of the percentages corresponding to all impact categories analysed for the H₂ combustion applied to case 5. This figure is generated based on the data from Figure 6.5. This figure also presents a summary on what was mentioned before, regarding the dominance of the SMR process with

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

a 71.5%. Nevertheless, the dependency of the model over this process, and thus the dominance, will be proved on section 6.4.2.

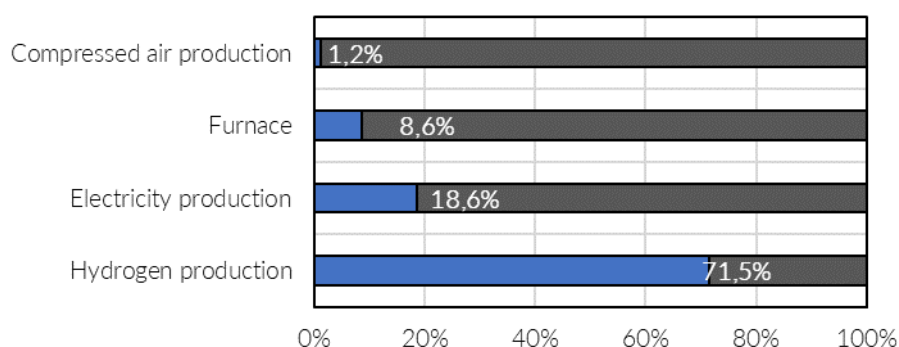


Figure 6.4: Distribution of the mean value among the processes for all the impact categories under scenario 1 for case 5

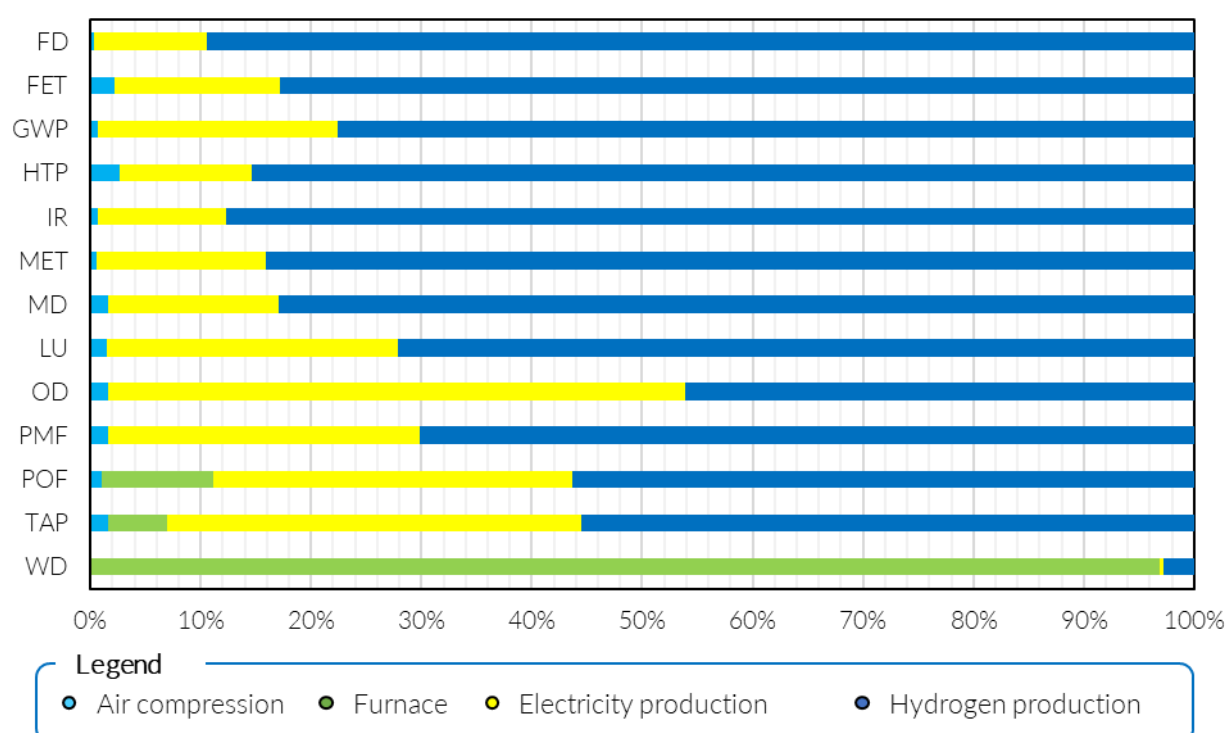


Figure 6.5: Percentage of IA of each process from the case 5 scenario 1 (ReCiPe 2016 Midpoint-H)

6.3.3 Results comparison

Table 6.5 presents the deviations of the impact categories from scenario 1 with respect to the baseline case. These values are presented in Table 6.3 and Table 6.4 for the NG and Hydrogen case respectively. Furthermore, this information is represented in Figure 6.6, in which 12 out of 13 categories showed worse environmental impact. In particular, the categories FD, GWP, OD and WD remain in a difference between up to 70%. Nevertheless, HTP, MD, PMF, POF and TAP obtained values between 100% and 350% higher as the baseline. Finally, the categories FET and IR obtained higher values of 5.2 and 8.5 times higher as the reference. These results are based on different reasons. Firstly, the increase on water on the combustion process, led to a higher value on WD. Then, the phosphate, nitrates, and the use of land for the infrastructure on the SMR process, increase the remaining impact categories.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 6.5: Percentage deviation of all impact categories from the scenario 1 from case 5 (ReCiPe 2016 Midpoint-H)

Impact category	Acronym	Baseline	Scenario	Unit
Fossil depletion Potential	FD	100%	161.2%	kg oil-eq/t _{al}
Freshwater Eutrophication	FET	100%	516.0%	kg P eq/t _{al}
Global Warming Potential	GWP	100%	168.6%	kg CO ₂ eq/t _{al}
Human Toxicity Potential	HTP	100%	393.3%	kg 1.4 DB/t _{al}
Ionizing radiation	IR	100%	853.3%	kBq Co-60 eq./t _{al}
Marine Eutrophication	MET	100%	87.6%	kg N eq/t _{al}
Metal Depletion	MD	100%	281.6%	kg Cu-eq/t _{al}
Land use	LU	100%	445.5%	Annual crop eq./t _{al}
Stratospheric Ozone Depletion	OD	100%	130.2%	kg CFC-11-eq/t _{al}
Fine Particulate Matter formation	PMF	100%	290.0%	kg PM25-eq/t _{all}
Photochemical Ozone Formation	POF	100%	289.4%	kg NOx eq./t _{al}
Terrestrial Acidification	TAP	100%	293.8%	kg SO ₂ -eq/t _{al}
Water depletion	WD	100%	161.6%	m ³ water -eq/t _{al}

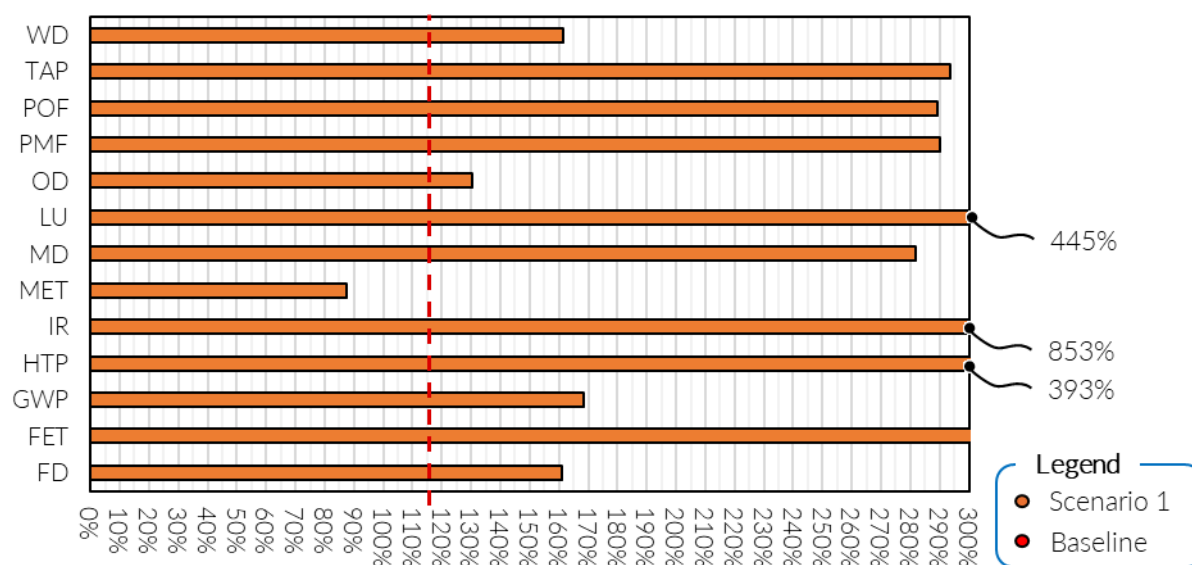


Figure 6.6: Relative change for all impact categories between baseline (reference) and scenario 1 for case 5

6.4 Interpretation

6.4.1 Sensitivity analysis in the baseline case

Table 6.6 presents the results for the SA performed in the model for case 5. In this case, the variables NG and electricity demand were modified. These values are presented in Figure 6.7. As result, this analysis shows the dependence of the model from the aforementioned variables in specific impact categories.

As result of the analysis on the modification of NG demand, a mean and a median of 0.029 and 0.028 were obtained. These metrics indicates that the data distribution is centred in the middle of the data range. Furthermore, a standard variation of 0.011 was obtained. Consequently, this figure indicates the high dispersion of the distribution. This data is shifted to the sides, because of high variation on FD and WD. this category does not modify its value. Then, the categories FET, GWP, HTP, IR, LU, OD, FPMF, POF and TAP maintained values between 1.5% and 3%. Finally, the categories FD, MD and MET showed most variability. These results were also mentioned in section 6.3.1, in which NG production was the main influential process in these aforementioned categories in more than a 50%. Consequently, based on the previously described facts, the model has a significant dependence on the NG production process.

Regarding the electricity production process, Figure 6.8 presents in dark and light yellow the results on the SA for the electricity demand in the baseline case. In this case, the electricity demand was modified ± 74400 kWh for each case individually. This fact led to a mean and median values of 0.014 and 0.016, from which is possible to infer that the data distribution is focus in the middle of the data range. Furthermore, the standard variation resulted in $7.6 \cdot 10^{-3}$, which indicates low dispersion. Therefore, this analysis shows a light sensitivity of the model over the impact categories. Although 32.5% of the impact categories mean values fall into the electricity production process, based on the aforementioned, this dependency among the impact categories over the model remains low.

Therefore, based on the prior described results, the NG production process has a remarkable influence over the impact categories. In contrast, the electricity production process has a lower influence over the model as a priori expected, based on the results from section 6.3.1. Finally, as shown in Figure 6.2, the effect on WD is purely based on the combustion process, since neither the NG production process nor the electricity production process has influence on it.

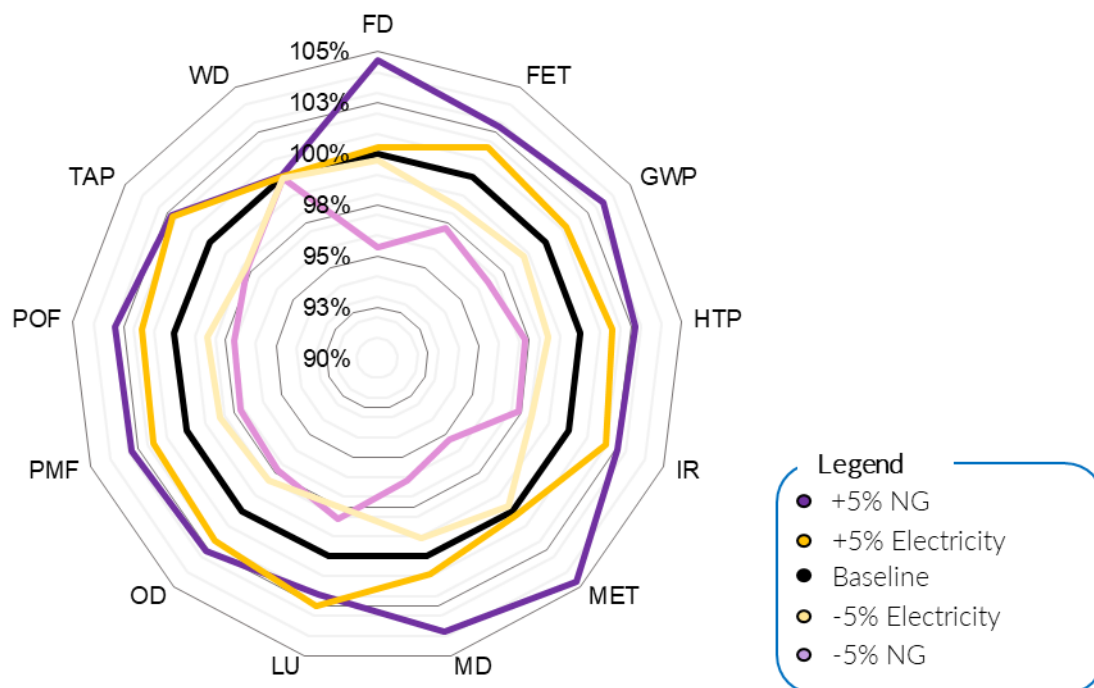


Figure 6.7: Results on the sensitivity analysis for NG and electricity demand on the baseline from case 5

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 6.6: Results on the sensitivity analysis for the NG and electricity demand for baseline from case 5

Impact category	Baseline	+5% NG demand	-5% NG demand	+5% Electricity demand	-5% Electricity demand
FD	100%	105%	95%	100%	100%
FET	100%	103%	97%	102%	98%
GWP	100%	103%	97%	101%	99%
HTP	100%	103%	97%	102%	98%
IR	100%	103%	97%	102%	98%
MET	100%	105%	95%	100%	100%
MD	100%	104%	96%	101%	99%
LU	100%	102%	98%	102%	98%
OD	100%	103%	97%	102%	98%
PMF	100%	103%	97%	102%	98%
POF	100%	103%	97%	102%	98%
TAP	100%	102%	98%	102%	98%
WD	100%	100%	100%	100%	100%

6.4.2 Sensitivity analysis in the hydrogen case

Similar as the previous section, Table 6.7 presents the results in the SA for case 5. In this analysis the model inputs H₂ and electricity demand were modified. The variables were chosen based on the results obtained in section 6.3, in which the processes of Hydrogen and electricity production had the highest environmental impact. Especially Hydrogen production with a 71.5% of the impact categories mean values.

The results on the SA for the H₂ production process are represented in Figure 6.8 with light and dark blue lines. As result, 7 out of 13 impact categories show high sensitivity. Consequently, the data distribution is shifted to the upper limit, since the values obtained for the mean and median are 0.034 and 0.039 respectively. More into detail, the standard variation led to 0.012. This fact reflects the high dispersion of the dataset. More into detail, FD, FET, GWP, HTP, IR, MET, MD and LU varied between 4% and 4.5%. The high variation of these values can be attributed to the amount of emissions and raw materials derived from the SMR process as mentioned in section 6.3.2. In particular, the impact categories FD, GWP, MD and LU are especially influenced from the products NG, NO_x or CO₂. Nevertheless, HTP, IR, FET and MET are influenced by other subproducts from the SMR process like nitrates or phosphates. Then, the rest of the categories remain between 2% and 3.5%, except WD which is independent from this process. Therefore and, as mentioned in subchapter 6.3.2., based on the results obtained for this process, the model is dependent of the hydrogen demand, based on the environmental impact of SMR process. Therefore, the model shows high sensitivity on H₂ demand.

Similarly, Figure 6.8 also shows the results for the SA for the electricity production with light and dark yellow lines. The influence of this process over the model is lower in comparison to the SMR process. This fact is based on the mean and median values of 0.009 and 0.007 respectively. Additionally, the value for the standard variation of $5 \cdot 10^{-3}$. As result, based on the previous values, the data distribution is focused on the lower limit of the data range with low dispersion. More into detail, the SA showed that all categories obtained values below 2%. In particular, FD, FET, GWP, HTP, IR, MET and MD remain below 1%. Similar as before, WD does not vary, as this impact category mostly depends on the water generated on the combustion process on the furnace. Finally, the rest of the categories remain between 1.2% and 2.2%.

These results lead to three conclusions. On one hand, the dependency of WD from the combustion process. On the other hand, the dominance of the SMR process on the whole environmental impact of the model (7 out 13 categories). Then, the low sensitivity on this model from the electricity demand. Finally, the rest of the categories exhibit low sensitivity with a variation between 1.5% and 3% from both aforementioned processes without being completely dominant.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 6.7: Results on the sensitivity analysis for H₂ and electricity demand on the baseline from case 5

Impact category	Baseline	+5% H ₂ demand	-5% H ₂ demand	+5% Electricity demand	-5% Electricity demand
FD	100%	104%	96%	100%	100%
FET	100%	104%	96%	101%	99%
GWP	100%	104%	96%	101%	99%
HTP	100%	104%	96%	101%	99%
IR	100%	104%	96%	100%	100%
MET	100%	104%	96%	101%	99%
MD	100%	104%	96%	101%	99%
LU	100%	104%	96%	101%	99%
OD	100%	102%	98%	102%	98%
PMF	100%	104%	96%	101%	99%
POF	100%	103%	97%	101%	99%
TAP	100%	103%	97%	102%	98%
WD	100%	100%	100%	100%	100%

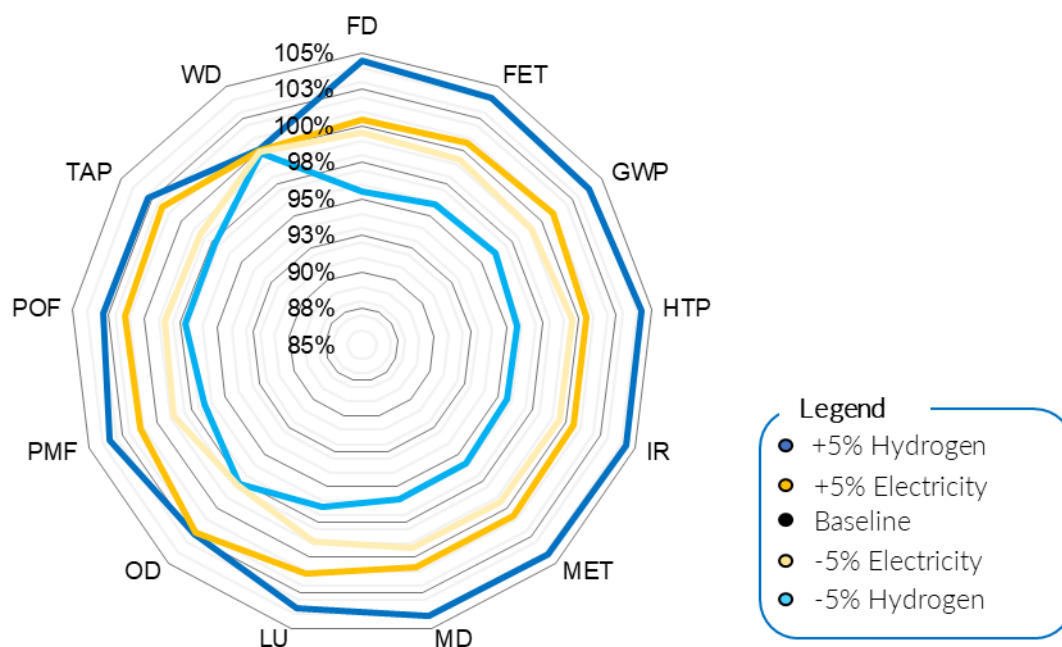


Figure 6.8: Results on the sensitivity analysis for H₂ and electricity demand on the baseline from case 5

6.4.3 Overall interpretation

As presented in section 6.3.3, the use of H₂ from SMR leads to worse environmental impact in comparison to the baseline case, as 8 out of 13 categories obtained higher values respective to their baseline equivalent. This reason is based on the SMR process for H₂ production as demonstrated throughout section 2.4.2, in which 71.5% of the impact categories mean values fall into this process. In particular, the SA performed for both cases (NG and H₂, Figure 6.7 and Figure 6.8) revealed the influence of the NG and H₂ production (SMR) process on the environmental impact of this furnace. Especially in the impact categories FD, MD, GWP and LU. Nevertheless, the environmental impact generated on the furnace is reduced in comparison to the NG combustion.

Regarding the electricity production process, its environmental influence is reduced based on the results obtained from the SA, as the sensitivity remains low. Furthermore, as presented in paragraphs 6.3.1 and 6.3.2, the mean values obtained for this process in each impact category remain below 0.009. Finally, the category WD is an impact category purely dependent on the combustion process happening in the process. More into detail, the air-compression process does not have much influence in both cases as demonstrated in sections 6.3.1 and 6.3.2 for the NG and H₂ combustion process respectively.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Therefore, although the CO₂ emissions in the furnace were eliminated, other emissions to air and soil such as CO₂, NO_x, Methane, Nitrates and Phosphates originated from the H₂ production process led to worse environmental performance in this case.

7 Case 6: LCA on the trials of the annealing furnace from TME

7.1 Scope and goal

This case evaluates the environmental performance of the annealing furnace operated by TME for the heat treatment of aluminium engine blocks. The process considered in this assessment is the T-5 artificial ageing / annealing step, where the furnace operates at approximately 230 °C. The functional unit selected for this analysis is one engine block treated in the annealing furnace.

The baseline corresponds to the current natural gas combustion case, while the hydrogen scenarios evaluate partial and full substitution of natural gas by hydrogen in air combustion. The assessment compares 100% natural gas, 50% hydrogen substitution, and 100% hydrogen substitution, considering both grey hydrogen and green hydrogen pathways. Two electricity supply assumptions are considered: EU grid mix electricity and renewable electricity.

The system boundary applied in this case is cradle-to-gate, following the same approach as the other LCA case studies in this deliverable. The model includes the production of fuels, electricity demand, and the furnace combustion process. The impact assessment was performed using the ReCiPe 2016 v1.1 Midpoint (H) methodology implemented in Sphera LCA for Experts 2026 (version content 2026.1). A sensitivity analysis was subsequently performed to evaluate the influence of electricity supply assumptions on the environmental performance of the investigated scenarios.

7.2 Life cycle inventory

This model represents the TME annealing furnace used for the heat treatment of aluminium engine blocks. The process is operated with a production rate of 2 parts every 94 seconds, corresponding to a part weight of 13 kg per part. The furnace temperature considered for the process is 230 °C. The natural gas consumption in the baseline case is 9.36 Nm³/h, corresponding to a gross furnace power demand of approximately 98 kWh.

The natural gas demand per engine block is 1.56 kWh/block, while the electricity demand is 0.20 kWh/block. These values were used as the main input parameters for modelling the baseline heat treatment process. For the hydrogen cases, a conversion factor of 3.33 Nm³ H₂ per Nm³ natural gas was considered.

Table 7.1: Input and output parameters for modelling the baseline case from TME

	Parameter	Unit	Value	Comment
Input	Natural gas consumption	Nm ³ /h	9.36	Calculated / provided
Input	Natural gas demand	kWh/block	1.56	Calculated
Input	Electricity demand	kWh/block	0.20	Provided
Input	Furnace temperature	°C	230	Provided
Output	Treated engine block	pcs	1	Functional unit
Output	CO ₂ factor for NG energy	kg/kWh	0.203	Used for calculation
Output	NO ₂ emission	kg/h	0.0165	Provided
Output	CO ₂ measured	kg/h	0.0217	Provided

The hydrogen scenario was modelled by replacing part or all of the natural gas demand by hydrogen. The assessment includes both grey hydrogen and green hydrogen pathways, as well as electricity supplied by the EU grid mix or renewable electricity. For the green hydrogen scenarios, hydrogen production is modelled as an upstream supply chain based on electrolysis, while the furnace electricity demand is assessed separately under either EU grid mix or renewable electricity assumptions. This distinction is important because the environmental benefit of hydrogen depends strongly on both the hydrogen production route and the electricity source used within the system boundary.

Table 7.2: Input parameters for modelling the hydrogen scenarios from TME

Scenario	Hydrogen share	Hydrogen type	Electricity demand
Baseline	0% H ₂	Not applicable	EU grid mix / renewable electricity
Scenario 1a	50% H ₂	Grey hydrogen	EU grid mix / renewable electricity
Scenario 1b	50% H ₂	Green hydrogen	EU grid mix / renewable electricity
Scenario 2a	100% H ₂	Grey hydrogen	EU grid mix / renewable electricity
Scenario 2b	100% H ₂	Green hydrogen	EU grid mix / renewable electricity

7.3 Impact assessment

7.3.1 Baseline case

The baseline scenario represents the current operation of the TME annealing furnace using 100% natural gas combustion. Two electricity supply assumptions were considered for the annealing process: the EU grid electricity mix and 100% renewable electricity (from wind). The objective of this comparison is to evaluate the influence of the electricity source on the overall environmental performance of the annealing process, while maintaining identical furnace operating conditions and natural gas consumption.

Regarding climate change (Global Warming Potential, GWP), the updated baseline configuration generates 0.469 kg CO₂-eq per engine block when supplied with the EU electricity mix. Replacing grid electricity with renewable electricity reduces the impact to 0.404 kg CO₂-eq per engine block, representing an improvement of approximately 14%. This shows that the electricity source has a measurable influence on the baseline result, although natural gas combustion remains the dominant contributor to the remaining greenhouse gas emissions.

A similar trend is observed for most environmental impact categories, although natural gas combustion remains the dominant driver of the baseline climate change impact. This means that changing the electricity source alone improves the baseline, but it does not fully decarbonise the heat treatment process.

Table 7.3 Baseline results

Impact category	Unit	Baseline EU electricity mix	Baseline renewable electricity
Climate change, default, excl. biogenic carbon	kg CO ₂ eq.	0.469	0.404
Fine particulate matter formation	kg PM _{2.5} eq.	5.110E-05	2.430E-05
Fossil depletion	kg oil eq.	0.189	0.161
Freshwater consumption	m ³	6.242E-04	4.250E-05
Human toxicity, non-cancer	kg 1,4-DB eq.	0.005	8.401E-04
Ionizing radiation	kBq Co-60 eq. to air	0.004	6.390E-05
Land use	Annual crop eq.y	0.006	2.367E-04
Marine eutrophication	kg N eq.	2.210E-05	1.960E-05
Metal depletion	kg Cu eq.	1.553E-04	1.539E-04
Photochemical ozone formation, ecosystems	kg NO _x eq.	2.042E-04	1.320E-04
Stratospheric ozone depletion	kg CFC-11 eq.	3.770E-08	9.560E-09
Terrestrial acidification	kg SO ₂ eq.	1.621E-04	6.630E-05
Freshwater eutrophication	kg P eq.	8.560E-08	1.950E-08

7.3.2 Hydrogen/air combustion scenarios

The environmental performance of the hydrogen-based annealing furnace scenarios was evaluated for both partial and complete substitution of natural gas by hydrogen. The analysis considered hydrogen produced via two different pathways: grey hydrogen produced through steam methane reforming (SMR) and green hydrogen produced through water electrolysis. Scenario S1a represents 50% grey hydrogen, S1b represents 50% green hydrogen, S2a represents 100% grey hydrogen, and S2b represents 100% green hydrogen. The assessment was performed using the ReCiPe 2016 Midpoint (H) methodology and subsequently repeated assuming renewable electricity supply. for annealing process Renewable electricity is always used to produce green hydrogen.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

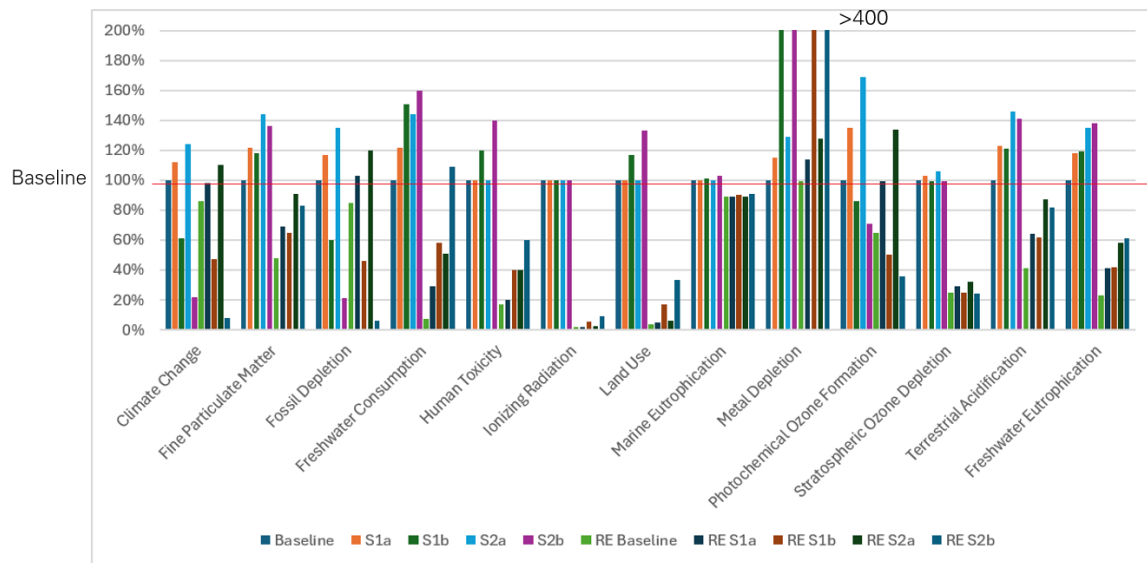


Figure 7.1 Impact categories for all cases

Table 7.4 EU electricity mix results

Impact category	Unit	Baseline EU electricity mix	S1a 50% grey H2	S1b 50% green H2	S2a 100% grey H2	S2b 100% green H2
Climate change, default, excl. biogenic carbon	kg CO2 eq.	0.469	0.526	0.287	0.583	0.104
Fine particulate matter formation	kg PM2.5 eq.	5.110E-05	6.220E-05	6.020E-05	7.334E-05	6.931E-05
Fossil depletion	kg oil eq.	0.189	0.222	0.114	0.255	0.040
Freshwater consumption	m3	6.242E-04	7.630E-04	9.440E-04	9.015E-04	0.001
Human toxicity, non-cancer	kg 1,4-DB eq.	0.005	0.005	0.006	0.005	0.007
Ionizing radiation	kBq Co-60 eq. to air	0.004	0.004	0.004	0.004	0.004
Land use	Annual crop eq.y	0.006	0.006	0.007	0.006	0.008
Marine eutrophication	kg N eq.	2.210E-05	2.220E-05	2.240E-05	2.220E-05	2.273E-05
Metal depletion	kg Cu eq.	1.553E-04	1.781E-04	7.250E-04	2.009E-04	0.001
Photochemical ozone formation, ecosystems	kg NOx eq.	2.042E-04	2.747E-04	1.749E-04	3.451E-04	1.456E-04
Stratospheric ozone depletion	kg CFC-11 eq.	3.770E-08	3.890E-08	3.740E-08	4.014E-08	3.716E-08
Terrestrial acidification	kg SO2 eq.	1.621E-04	2.000E-04	1.957E-04	2.370E-04	2.293E-04
Freshwater eutrophication	kg P eq.	8.560E-08	1.010E-07	1.020E-07	1.159E-07	1.184E-07

GWP follows a clear decarbonisation trend only for the green hydrogen pathways. The EU electricity mix baseline generates 0.469 kg CO₂-eq per engine block. The 50% green hydrogen scenario reduces this to 0.287 kg CO₂-eq, while the 100% green hydrogen scenario reaches 0.104 kg CO₂-eq. In contrast, grey hydrogen increases the climate-change burden compared with the updated baseline, reaching 0.526 kg CO₂-eq for S1a and 0.583 kg CO₂-eq for S2a. Relative to the updated EU electricity baseline, complete substitution with green hydrogen reduces greenhouse gas emissions by approximately 78%.

Several impact categories increase when hydrogen is introduced into the system, particularly for full hydrogen substitution. Freshwater consumption increases from 6.242E-04 m³ in the EU baseline case to approximately 0.001 m³ in S2b. Human toxicity increases from 0.005 kg 1,4-DB-eq to 0.007 kg 1,4-DB-eq, while land-use impacts increase from 0.006 to 0.008 annual crop eq.y. Metal depletion exhibits the largest increase, rising from 1.553E-04 kg Cu-eq in the baseline scenario to approximately 0.001 kg Cu-eq in S2b. This burden shifting is mainly associated with the production of green hydrogen and the renewable electricity and electrolysis infrastructure required, including wind turbines, photovoltaic systems, transformers, transmission networks and electrolyzers.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 7.5 Renewable electricity scenario

Impact category	Unit	RE baseline	RE S1a 50% grey H ₂	RE S1b 50% green H ₂	RE S2a 100% grey H ₂	RE S2b 100% green H ₂
Climate change, default, excl. biogenic carbon	kg CO ₂ eq.	0.404	0.460	0.221	0.517	0.039
Fine particulate matter formation	kg PM _{2.5} eq.	2.430E-05	3.540E-05	3.340E-05	4.649E-05	4.245E-05
Fossil depletion	kg oil eq.	0.161	0.194	0.086	0.227	0.012
Freshwater consumption	m ³	4.250E-05	1.812E-04	3.623E-04	3.199E-04	6.822E-04
Human toxicity, non-cancer	kg 1.4-DB eq.	8.401E-04	0.001	0.002	0.002	0.003
Ionizing radiation	kBq Co-60 eq. to air	6.390E-05	8.550E-05	2.080E-04	1.070E-04	3.517E-04
Land use	Annual crop eq.-y	2.367E-04	2.981E-04	0.001	3.596E-04	0.002
Marine eutrophication	kg N eq.	1.960E-05	1.960E-05	1.990E-05	1.964E-05	2.016E-05
Metal depletion	kg Cu eq.	1.539E-04	1.767E-04	7.236E-04	1.995E-04	0.001
Photochemical ozone formation, ecosystems	kg NO _x eq.	1.320E-04	2.025E-04	1.027E-04	2.729E-04	7.335E-05
Stratospheric ozone depletion	kg CFC-11 eq.	9.560E-09	1.080E-08	9.310E-09	1.204E-08	9.060E-09
Terrestrial acidification	kg SO ₂ eq.	6.630E-05	1.037E-04	9.990E-05	1.412E-04	1.335E-04
Freshwater eutrophication	kg P eq.	1.950E-08	3.470E-08	3.600E-08	4.984E-08	5.239E-08

When renewable electricity is introduced throughout the system boundary, the results show a more differentiated trend. Green hydrogen scenarios deliver strong environmental impacts reductions, while grey hydrogen scenarios become less favourable than the renewable baseline because the upstream production of grey hydrogen still carries a fossil-based burden.

The most significant improvement is observed for GWP impacts when green hydrogen is combined with renewable electricity for annealing process. The renewable baseline case generates 0.404 kg CO₂-eq per engine block. This decreases to 0.221 kg CO₂-eq for RE S1b and to only 0.039 kg CO₂-eq for RE S2b. Compared with the updated EU electricity baseline of 0.469 kg CO₂-eq per engine block, RE S2b represents an overall greenhouse gas reduction of approximately 92%.

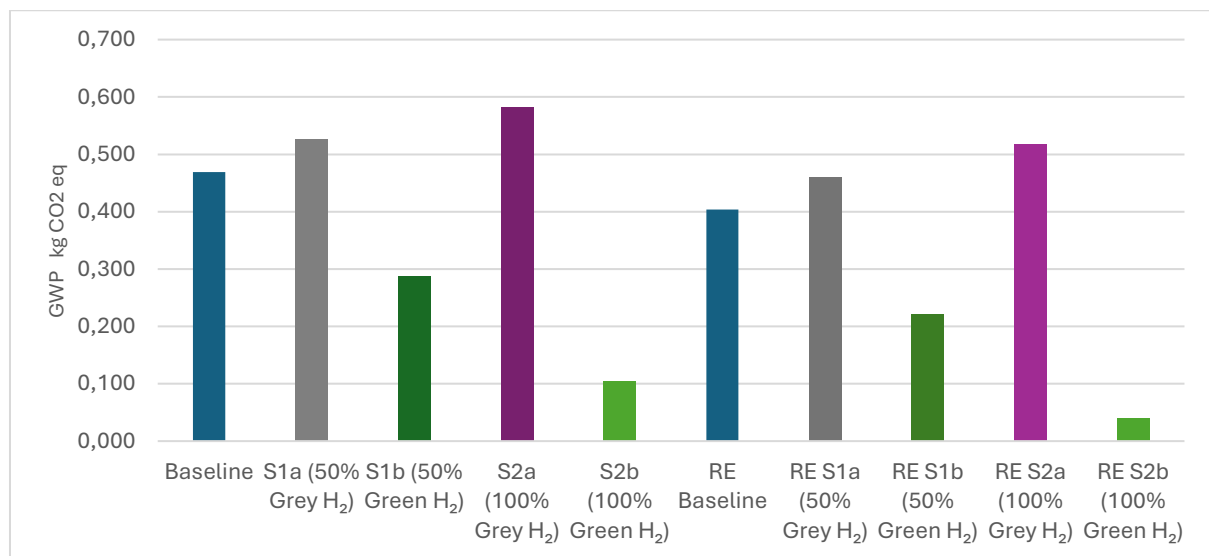


Figure 7.2 Global Warming Potential analysis

Fossil resource depletion is reduced from 0.161 kg oil-eq in the renewable-electricity baseline case to only 0.012 kg oil-eq in RE S2b. Photochemical ozone formation decreases from 1.320E-04 kg NO_x-eq to 7.335E-05 kg NO_x-eq, corresponding to a reduction of approximately 44%. However, RE S1a and RE S2a show higher fossil depletion than the renewable baseline because grey hydrogen production remains linked to fossil resource use.

Despite these improvements, burden-shifting effects remain visible. Water consumption, land use, ionizing radiation, human toxicity and metal depletion increase in the hydrogen scenarios, especially for green

hydrogen. This is linked to electrolysis and renewable-electricity infrastructure, which require additional water, electricity-generation assets and metal-intensive components such as wind turbines, photovoltaic systems, transformers, transmission networks and electrolyzers.

7.4 Interpretation

The updated LCA results show that hydrogen substitution only delivers a climate benefit when the hydrogen is produced through a low-carbon route. Under the EU electricity mix, grey hydrogen increases the climate-change impact from 0.469 kg CO₂-eq/block to 0.526 kg CO₂-eq/block for 50% substitution and to 0.583 kg CO₂-eq/block for 100% substitution. These correspond to increases of approximately 12% and 24%, respectively. In contrast, green hydrogen reduces the result to 0.287 kg CO₂-eq/block for 50% substitution and to 0.104 kg CO₂-eq/block for 100% substitution, equivalent to reductions of approximately 39% and 78%. This confirms that the hydrogen production pathway is more critical than the burner conversion itself for achieving a net GWP reduction.

The renewable electricity sensitivity case further clarifies the decarbonisation hierarchy. Switching only the furnace electricity supply from the EU mix to renewable electricity reduces the baseline from 0.469 to 0.404 kg CO₂-eq/block, which is a reduction of approximately 14%. This improvement is useful but limited because the furnace still consumes natural gas. The strongest reduction is obtained when renewable electricity is combined with green hydrogen: RE S1b reaches 0.221 kg CO₂-eq/block, while RE S2b reaches 0.039 kg CO₂-eq/block. RE S2b therefore reduces GWP by approximately 92% compared with the EU electricity baseline and by approximately 90% compared with the renewable electricity baseline.

However, the climate-optimal scenarios create measurable burden shifting in several midpoint categories. For the EU electricity mix case, freshwater consumption increases from 6.242E-04 m³/block in the baseline to approximately 0.001 m³/block in S2b, while metal depletion rises from 1.553E-04 kg Cu-eq/block to approximately 0.001 kg Cu-eq/block. Terrestrial acidification also increases from 1.621E-04 to 2.293E-04 kg SO₂-eq/block, and freshwater eutrophication increases from 8.560E-08 to 1.184E-07 kg P-eq/block. These increases indicate that green hydrogen reduces direct and upstream carbon emissions but transfers part of the environmental load to electricity generation, electrolysis and supporting infrastructure.

The same trade-off is visible in the renewable electricity case. RE S2b gives the lowest climate-change result at 0.039 kg CO₂-eq/block, but it also increases freshwater consumption from 4.250E-05 to 6.822E-04 m³/block, metal depletion from 1.539E-04 to approximately 0.001 kg Cu-eq/block, and freshwater eutrophication from 1.950E-08 to 5.239E-08 kg P-eq/block. Therefore, RE S2b should be considered the preferred decarbonisation pathway, but not a zero-burden solution. The implementation strategy should prioritise green hydrogen supplied by renewable electricity while reducing secondary impacts through efficient electrolyzers, low-water hydrogen production routes, careful selection of renewable electricity infrastructure, optimised hydrogen logistics and material-efficient equipment design.

8 Case 7: LCA on the trials of the walking beam furnace from SWE & SSAB

8.1 Scope and goal

The goal of the case study is to evaluate the environmental performance of alternative reheating strategies for steel slabs in a walking beam furnace, with particular emphasis on the transition from fossil-based combustion to hydrogen-based systems. In this LCA case study, the focus is on quantifying the environmental implications of substituting light fuel oil (LFO) with hydrogen, including the influence of different oxidant configurations, namely air, oxygen-enriched air, and pure oxygen. Eight pilots were conducted at Swerim, in collaboration with SSAB. From an industrial perspective, the result of the pilot campaign can serve as a technical basis for the development of future industrial systems linked to SSAB's planned greenfield steel production facilities.

The FU of the study was defined as the heating of one ton of steel slab from an initial temperature ($\sim 20^{\circ}\text{C}$) to the target temperature of approximately 1200°C in a continuous walking beam furnace, ready for hot rolling in steelmaking.

The system boundary was defined as “cradle-to-gate”. The foreground system of the walking beam furnace includes furnace operation, comprising fuel combustion under different oxidant conditions, direct atmospheric emissions (e.g., CO_2 and NO_x), and auxiliary electricity consumption associated with furnace operation, such as burners, fans, and other mechanical systems. Background/upstream processes include the production of LFO, hydrogen production via water electrolysis, oxygen production via cryogenic air separation, electricity production (country or regional mix), etc. Hydrogen production is assumed to be based on alkaline water electrolysis using an Alkaline Electrolysis Cell (AEC). The excluded processes include slab production and downstream steelmaking processes such as hot rolling. In addition, capital goods, including the construction and maintenance of furnaces, electrolysis units (for H_2 production), and air separation units (ASU, for O_2 production), are not considered, assuming that their contribution is minor relative to furnace operational impacts for the purposes of this comparative LCA. Similarly, infrastructure associated with hydrogen and oxygen transport and distribution was excluded.

Economic allocation was employed to address multifunctionality associated with hydrogen and oxygen production, respectively. For hydrogen production by electrolysis, environmental burdens were distributed between hydrogen and the co-produced oxygen according to their relative market value. For ASU-based oxygen production, environmental burdens were allocated among oxygen, nitrogen, and argon, based on their economic values. Detailed allocation factors and calculation basis are presented in Section 8.2.

The life cycle IA was performed using the method ReCiPe 2016 Midpoint (H) v1.12 in SimaPro v10.3.0.1. All the eighteen ReCiPe midpoint impact categories were included in this study.

8.2 Life cycle inventory

The LCI was based on a combination of primary data obtained from the campaign conducted in Swerim's pilot-scale walking beam furnace and secondary data on airborne emissions from LFO combustion, transportation, etc. All inputs and output flows are normalized to the defined FU. Table 8.1 present the experimental design of the eight pilots at Swerim.

Table 8.1: Experimental design of the eight pilots

Experiment	Fuel	Oxidant	Excess O_2
1	LFO	Air (21% O_2)	1%
2	LFO	Air	2.5%
3	H_2	Air	1%
4	H_2	Air	2.5%
5	H_2	40% O_2	1%
6	H_2	40% O_2	2.5%
7	H_2	100% O_2	1%
8	H_2	100% O_2	2.5%

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 8.2 presents the foreground LCI results. For the reference cases (Exp. 1 & 2), LFO consumption ranged from 27.3 to 33.0 kg per ton of slab. Associated truck transportation of LFO was assumed to be 20 km from the supplier to the user. Air consumption ranged from 473 to 557 kg per ton of slab.

Table 8.2: Foreground LCI data for the walking beam furnace trials

	Parameter	Unit	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8
Input	Slab	ton	1	1	1	1	1	1	1	1
	LFO ¹	kg	27.5	32.98	–	–	–	–	–	–
	Hydrogen ¹	kg	–	–	11.2	11.3	8.7	8.8	8.6	8.5
	O ₂ , pure ¹	kg	–	–	–	–	38.3	34.4	61.1	61.9
	Air ¹	kg	473	557	361	393	107	130	15	13
	Electricity, auxiliary ²	kWh	0.825	0.989	0.112	0.113	0.087	0.088	0.086	0.085
Output	Slab, incl. scale	ton	1	1	1	1	1	1	1	1
	CO ₂	kg	86.89 ²	104.21 ²	0 ³	0 ³	0 ³	0 ³	0 ³	0 ³
	CO ⁴	kg	0.005	0.006	0.04	0.04	0.1	0	0	0
	NO _x ⁴	kg	0.06	0.07	2.9	3.2	0.04	0.1	0.002	0.002
	N ₂ O ⁴	kg	0.0007	0.0008	–	–	–	–	–	–
	O ₂ ⁴	kg	38.37	162.54	51.87	104.96	77.66	115.63	78.08	103.47

¹ Measured data from Swerim.

² Estimated data based on the generic dataset “Heat, district or industrial, other than natural gas {Europe without Switzerland}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, U” from ecoinvent v3.11.

³ Assumption, since no carbon sources associated with fuels were introduced to the furnace.

⁴ Measured data from Endress+Hauser AG, reported at standard conditions (273.15 K, 101.3 kPa), dry basis.

The generic background LCI data used in the study were primarily from the ecoinvent v3.11 within SimaPro v10.3.0.1. In specific, the production of LFO was represented by the ecoinvent dataset “Light fuel oil {Europe without Switzerland}| market for light fuel oil | Cut-off, U”. Electricity production was based on the dataset “Electricity, medium voltage {SE}| market for electricity, medium voltage | Cut-off, U”, representing the Swedish market mix supplied to consumer in 2021. As illustrated in Figure 8.1, the Swedish electricity market mix was dominated by hydropower (44.7%), nuclear power (30.4%), and wind power (16.5%).

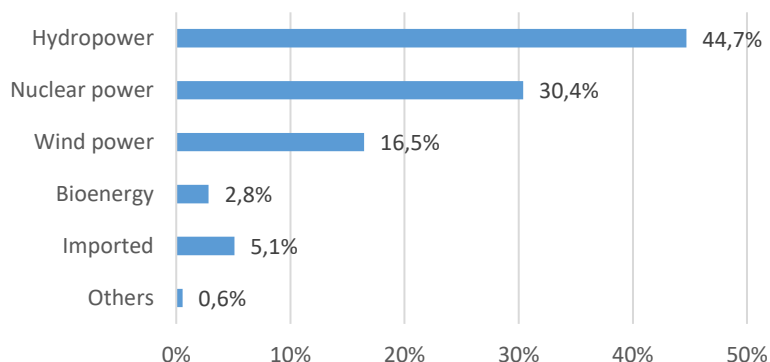


Figure 8.1: Share of energy sources in the Swedish electricity mix in 2021, based on ecoinvent v3.11. “Others” includes the Swedish electricity generation technologies that each contribute less than 1%, while imported electricity from other EU countries mainly originates from Norway (3.56%) and Denmark (1.08%).

The background LCI datasets were created for electrolysis-based hydrogen production (for Exp. 3-8) and the ASU-based oxygen production (for Exp. 5-8), respectively. For AEC-based hydrogen production, hydrogen and oxygen are generated according to a fixed stoichiometric ratio of approximately 1 kg hydrogen and 8 kg oxygen. The electricity use was assumed to be 52.3 kWh to produce 1 kg H₂ [13]. The electricity demand for on-site compression of H₂ was assumed to be 2 kWh per kg H₂ [14]. Market prices representative of the European market were applied, corresponding to 6.71 EUR/kg renewable H₂ in 2024 [15] and 0.15 EUR/kg O₂ on average in 2025 [16]. Therefore, 85.1% of the total burdens associated with electrolysis were allocated to hydrogen and 14.9% to oxygen.

For ASU-based oxygen supply for the oxygen-enhanced combustion (Exp. 5-6) and oxy-fuel combustion (Exp. 7-8), it was modelled using cryogenic air separation. Economic allocation was performed using European market prices of 0.15 EUR/kg O₂ (IMARC, 2026a), 0.22 EUR/kg N₂ [17], and 0.45 EUR/kg Ar [18]. In this study, it was assumed that 20% of produced nitrogen is sold at normal market price, since nitrogen is produced in large excess from large on-site ASU systems and has relatively low market value. The resulting allocation factor were 46.3% for oxygen, 45.8% for nitrogen, and 7.9% for argon. The total electricity demand of ASU was assumed to be 0.55 kWh/Nm³ O₂ [19] prior allocation. After the economic allocation, the electricity demand attributed to oxygen production was 0.178 kWh/kg O₂, equivalent to around 0.255 kWh/Nm³ O₂. Moreover, pipeline transport of pure oxygen was assumed, since Linde Gas AB is very close to Swerim and SSAB in Luleå, Sweden.

8.3 Impact assessment

The life cycle environmental impacts of the reheating process in the eight pilot experiments are presented in Table 8.3. To facilitate comparison across impact categories, the results were also normalized relative to the worst-performing experiment within each category (Figure 8.2) and to Experiment 1 (Table 8.4).

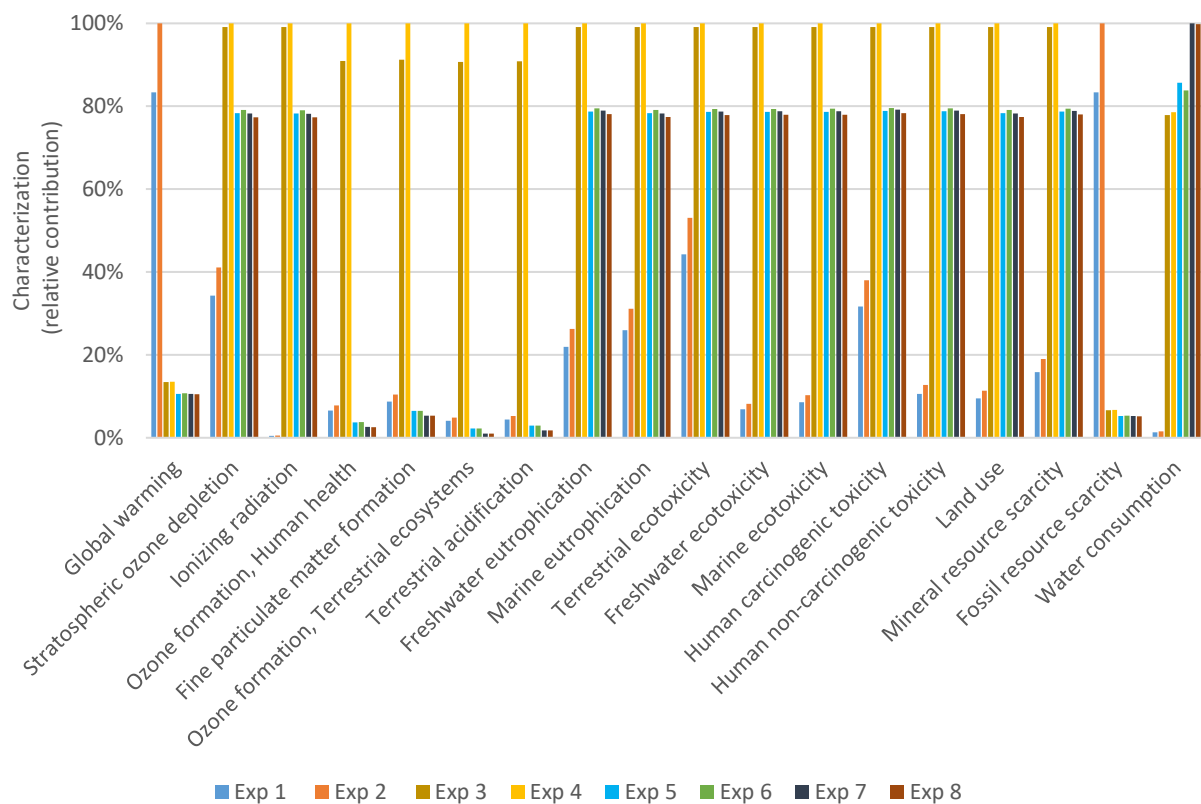


Figure 8.2: Comparison between the life cycle environmental impacts of the eight pilot experiments, normalized to the highest value within each impact category.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 8.3: LCIA (characterization) results of the eight pilots, reported per ton of slab

Impact category	Unit	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8
Global warming	kg CO ₂ eq	113.25	135.82	18.22	18.38	14.42	14.55	14.42	14.26
Stratospheric ozone depletion	kg CFC11 eq	1.43×10 ⁻⁵	1.72×10 ⁻⁵	4.15×10 ⁻⁵	4.18×10 ⁻⁵	3.28×10 ⁻⁵	3.31×10 ⁻⁵	3.27×10 ⁻⁵	3.24×10 ⁻⁵
Ionizing radiation	kBq Co-60 eq	0.57	0.68	122.82	123.92	97.02	97.95	96.88	95.82
Ozone formation, Human health	kg NOx eq	0.10	0.12	1.41	1.55	0.06	0.06	0.04	0.04
Fine particulate matter formation	kg PM _{2.5} eq	0.03	0.04	0.34	0.37	0.02	0.02	0.02	0.02
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.17	0.20	3.76	4.15	0.09	0.09	0.04	0.04
Terrestrial acidification	kg SO ₂ eq	0.12	0.14	2.50	2.75	0.08	0.08	0.05	0.05
Freshwater eutrophication	kg P eq	1.55×10 ⁻³	1.86×10 ⁻³	7.01×10 ⁻³	7.07×10 ⁻³	5.57×10 ⁻³	5.62×10 ⁻³	5.58×10 ⁻³	5.52×10 ⁻³
Marine eutrophication	kg N eq	6.55×10 ⁻⁴	7.86×10 ⁻⁴	2.50×10 ⁻³	2.53×10 ⁻³	1.98×10 ⁻³	2.00×10 ⁻³	1.98×10 ⁻³	1.96×10 ⁻³
Terrestrial ecotoxicity	kg 1,4-DCB	48.84	58.58	109.36	110.34	86.74	87.53	86.83	85.89
Freshwater ecotoxicity	kg 1,4-DCB	0.24	0.29	3.55	3.58	2.82	2.84	2.82	2.79
Marine ecotoxicity	kg 1,4-DCB	0.39	0.46	4.47	4.51	3.55	3.58	3.55	3.51
Human carcinogenic toxicity	kg 1,4-DCB	3.00	3.60	9.40	9.48	7.48	7.55	7.51	7.43
Human non-carcinogenic toxicity	kg 1,4-DCB	6.33	7.59	59.08	59.60	46.95	47.37	47.05	46.54
Land use	m ² a crop eq	0.58	0.69	6.05	6.10	4.78	4.83	4.77	4.72
Mineral resource scarcity	kg Cu eq	0.04	0.05	0.26	0.26	0.21	0.21	0.21	0.21
Fossil resource scarcity	kg oil eq	33.15	39.76	2.63	2.66	2.09	2.11	2.09	2.07
Water consumption	m ³	0.04	0.05	2.57	2.60	2.83	2.77	3.30	3.30

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 8.4: Life cycle environmental impacts per ton of slab in the eight pilots, normalized relative to Experiment 1

Impact category	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8
Global warming	100%	120%	16%	16%	13%	13%	13%	13%
Stratospheric ozone depletion	100%	120%	289%	292%	229%	231%	228%	226%
Ionizing radiation	100%	120%	21611%	21804%	17071%	17235%	17047%	16860%
Ozone formation, Human health	100%	119%	1385%	1524%	57%	57%	39%	39%
Fine particulate matter formation	100%	119%	1043%	1144%	74%	75%	61%	61%
Ozone formation, Terrestrial ecosystems	100%	118%	2220%	2447%	54%	54%	25%	25%
Terrestrial acidification	100%	119%	2050%	2258%	67%	67%	40%	40%
Freshwater eutrophication	100%	120%	452%	456%	359%	362%	360%	356%
Marine eutrophication	100%	120%	382%	386%	302%	305%	302%	298%
Terrestrial ecotoxicity	100%	120%	224%	226%	178%	179%	178%	176%
Freshwater ecotoxicity	100%	120%	1449%	1462%	1150%	1161%	1152%	1139%
Marine ecotoxicity	100%	120%	1159%	1169%	920%	928%	921%	911%
Human carcinogenic toxicity	100%	120%	313%	316%	249%	251%	250%	247%
Human non-carcinogenic toxicity	100%	120%	933%	942%	742%	748%	743%	735%
Land use	100%	120%	1043%	1053%	825%	833%	824%	815%
Mineral resource scarcity	100%	120%	625%	631%	496%	501%	497%	492%
Fossil resource scarcity	100%	120%	8%	8%	6%	6%	6%	6%
Water consumption	100%	120%	6098%	6152%	6710%	6564%	7830%	7817%

Compared to the LFO-based reference cases (Exp. 1 & 2), Exp. 3-8 achieves a lower impact in two environmental categories, namely GWP and “fossil resource scarcity”. Regarding GWP, it decreases from 113.25 and 135.82 kg CO₂-eq per ton of reheated slab in Experiments 1-2, respectively, to only 14.22-18.38 kg CO₂-eq in Experiments 3-8. Relative to Experiment 2, the GWP of Experiments 3-8 correspond to only 10-14%, representing life cycle carbon emission reductions of approximately 86-90%. With respect to “fossil resource scarcity”, the impacts decrease from 33.15-39.76 kg oil-eq in Experiments 1 and 2 to only 2.07-2.66 kg oil-eq in Experiments 3-8, corresponding to around 6-8% of Experiment 2. Moreover, Exp. 5-8 have a lower impact in other four environmental categories, namely “Ozone formation, Human health”, “Fine particulate matter formation”, “Ozone formation, Terrestrial ecosystems”, and “Terrestrial acidification”, while Exp 3-4 have a higher impact in the four categories, compared to Exp. 1-2.

In the other 12 environmental categories, Exp. 3-8 have higher environmental impacts than Exp 1-2. For example, the impact category “ionizing radiation” increases from less than 1 kBq Co-60-eq in Experiments 1-2 to approximately 123 kBq Co-60-eq in Experiments 3-4 and to 95.8-97.95 kBq Co-60-eq in Experiments 5-8. Regarding “water consumption”, Exp. 1 and 2 require only 0.04-0.05 m³ of water per tonne of reheated slab, water consumption varies from 2.57 (Exp. 3) to 3.30 (Exp. 7) m³ per tonne of slab in Exp. 3-8, representing increases of approximately 6100-7800% relative to Experiment 1. Experiments 7 and 8 show the highest water demand and consequently reach nearly 100% of the maximum normalized impact for this category.

8.4 Interpretation

8.4.1 Hotspot analysis

Figure 8.3 presents the contribution analysis for each impact category across the eight pilot-scale experiments. For Experiments 1 and 2, the environmental impacts are mainly driven by a combination of direct process emissions and upstream production of LFO. On-site emissions are the dominant contributor to GWP, accounting for around 77% of the total impacts. The direct emissions also make substantial contributions to OD (ozone depletion), OFh (ozone formation, human health), PMF (fine particulate matter formation), OFt (ozone formation, terrestrial ecosystems), and TA (terrestrial acidification), varying between 20% and 54%. LFO production dominates 16 of the 18 environmental categories, except GWP and OD, primarily associated with upstream extraction, processing, and refining activities required for fossil fuel production. Electricity consumption of the auxiliary system contributes noticeably only to IR (ionising radiation), where the Swedish electricity mix accounts for 34.2%. Transport of LFO contributes negligibly across all impact categories.

Regarding Experiments 3 and 4, hydrogen production becomes the dominant contributor for 14 of 18 environmental impact categories, contributing approximately 99.9% of the impact categories. The environmental profile is largely determined by the life cycle impacts associated with hydrogen production via electrolysis using the Swedish electricity country mix. The on-site NO_x emissions contribute to 92.7% - 98.8% of the remaining four impact categories, namely OFh, PMF, OFt, and TA. This indicates that atmospheric pollutant emissions generated during the H₂ combustion process can drive air-quality-related impacts despite the substitution of fossil fuel with hydrogen. Hydrogen transport and direct electricity use outside the electrolysis system contribute negligibly to the overall environmental impacts.

With respect to Experiments 5 and 6, hydrogen production is the main contributor to 17 impact categories, ranging from 57% to 98.5%. The exception is the category OFt, where the on-site NO_x emissions contribute around 56% of the total impact. Moreover, the direct NO_x emissions are the second contributor in three impact categories, i.e., 41% in TA, 32% in OFh, and 18% in PMF. For oxygen production in the ASU using Swedish electricity mix, it contributes 27%-29% to water consumption and 1.1%-2.2% to the other 17 impact categories. Same to Experiments 1-4, auxiliary electricity use and hydrogen transport remain negligible contributions in all impact categories.

Experiments 7 and 8 show the strongest dominance of upstream processes among all studied systems. Hydrogen production contributes around 59% of the impact in the category “water consumption” and around 91%-97% in the other 17 impact categories. Oxygen production is the second largest contributor to “water consumption”, accounting for around 40% of the total impact. Similar to the other experiments, hydrogen transport and direct electricity consumption make negligible contributions across all environmental categories.

8.4.2 Sensitivity analysis

Since hydrogen production was identified as the dominant environmental hotspots in the hydrogen-based pilots (Experiments 3-8), a SA was conducted to evaluate the influence of electricity supply assumptions on the overall environmental performance. The baseline assessment was based on the Swedish electricity country mix (2021) available in ecoinvent v3.11. Sweden’s electricity system is characterized by a high share of low-carbon electricity sources, such as hydropower and wind power, resulting in relatively low greenhouse gas emissions compared with the European average electricity system.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment



Figure 8.3. Life cycle contribution analysis of the eight pilot experiments. The “on-site emissions” category includes only direct emissions of CO₂, CO, N₂O, and NO_x from combustion of LFO (Exp 1 & 2) and H₂ (Exp 3-8). GWP = global warming; OD = stratospheric ozone depletion; IR = ionizing radiation; OFh = ozone formation, human health; PMF = fine particulate matter formation; OFt = Ozone formation, Terrestrial ecosystems; TA = terrestrial acidification; FE = freshwater eutrophication; ME =

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

marine eutrophication; TET = terrestrial ecotoxicity; FET = freshwater ecotoxicity; MET = marine ecotoxicity; HTC = human carcinogenic toxicity; HTnc = human non-carcinogenic toxicity; LU = land use; MRS = mineral resource scarcity; FRS = fossil resource scarcity; WC = water consumption.

To investigate the robustness of the comparative LCA results, two alternative electricity supply scenarios were assessed. The analysis focused on the global warming potential since scope 1 carbon emission reduction is the primary environmental benefit expected from replacing fossil fuels with hydrogen.

- Swedish hydropower in 2021, representing a renewable and low-carbon electricity supply (“green electricity”), the ecoinvent dataset “Electricity, high voltage {SE}| electricity production, hydro, run-of-river | Cut-off, U”.
- European electricity mix in 2021, represented by the ecoinvent dataset “Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U”. According to the Eurostat statistics [20], the European electricity system in 2021 consisted of approximately 37.4% renewables and biofuels, 25.4% nuclear power, 20.2% natural gas, 14.5% solid fossil fuels, 1.6% oil products, and 1.1% other energy sources. This scenario was selected to evaluate the influence of a relatively more carbon-intensive electricity system for hydrogen production outside Sweden.

The calculated carbon footprint is 0.004 kg CO₂-eq/kWh for Swedish hydropower, 0.334 kg CO₂-eq/kWh for European electricity mix, and 0.035 kg CO₂-eq/kWh for the Swedish electricity mix. Hydrogen produced using the Swedish hydropower scenario results in a GWP of 0.207 kg CO₂-eq per kg H₂, representing an 87% reduction compared with hydrogen produced using the Swedish electricity mix (1.63 kg CO₂-eq per kg H₂). Hydrogen produced using the European electricity mix reaches 15.6 kg CO₂-eq per kg H₂. Figure 8.4 presents the changes in GWP for the hydrogen-based experiments under alternative electricity supply scenarios, relative to the baseline LFO-based Experiment 1.

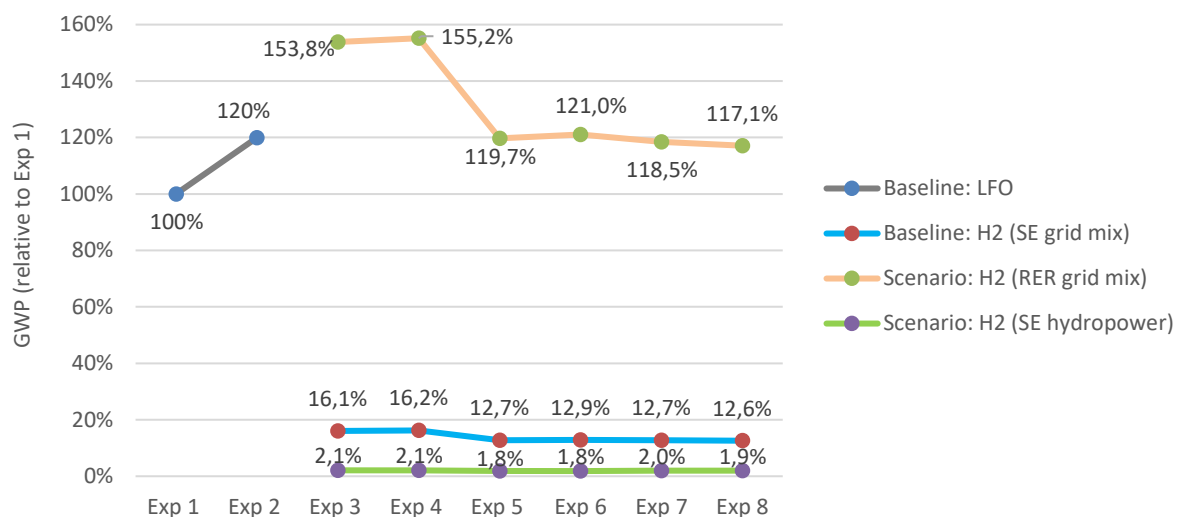


Figure 8.4: Sensitivity analysis of the global warming potential (GWP) of the eight pilot-scale experiments under alternative electricity supply scenarios for hydrogen production. Results are expressed relative to Experiment 1, which is set to 100%.

The SA results indicate that the GWP values of the experiments using H₂ production from Swedish hydropower electricity are reduced to 1.8% - 2.1% of the reference case, representing a reduction of approximately 98% compared with Experiment 1. These results confirm that the climate performance of hydrogen-based reheating operation can be substantially improved when hydrogen is produced using electrolysis powered by renewable hydropower.

A markedly different trend is observed for the European electricity scenario. When hydrogen is produced using the European electricity mix, the GWP of the H₂-based experiments increases substantially, reaching 117.1–155.2% of the reference case. The highest impacts are observed for Experiments 3 and 4, where the GWP reaches around 154% and 155%, relative to Experiment 1. For Experiments 5–8, the GWP decreases slightly but remains between 117% and 121% of the reference case, indicating that these hydrogen-based configurations still exhibit higher climate change impacts than the LFO-based system under European electricity supply conditions. This also implicates a potential risk of burden shifting between scope 1 and scope 2 greenhouse gas emissions.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

The results demonstrate that the climate performance of hydrogen-based reheating operation is highly sensitive to the electricity source used for electrolysis-based hydrogen production. While hydrogen produced with the Swedish electricity mix or Swedish hydropower yields substantial reductions in climate change impacts, hydrogen produced using the European electricity mix results in higher life cycle greenhouse gas emissions than the LFO reference system. This outcome is attributable to the significantly larger contribution of fossil-based electricity generation in the European electricity system. Consequently, the climate benefits of replacing LFO with hydrogen can only be fully realized when low-carbon electricity sources are available for hydrogen production.

9 Case 8: LCA on the trials of Ladle Preheater from 7Steel

9.1 Scope and goal

The goal of this case study was to evaluate the environmental performance of two alternative fuels for ladle preheating: a conventional baseline using CO-rich gas and oxygen (CO/O₂) and a hydrogen-based alternative using hydrogen and oxygen (H₂/O₂). The demonstrations were carried out at 7Steel in Norway.

The functional unit (FU) of the study was defined as the preheating of one 85-ton ladle from an initial temperature of approximately 0 °C to a target temperature of 1200°C over a 10-hour period. This FU represents the service provided by the studied system and enables a fair comparison between the CO/O₂ and H₂/O₂ combustion technologies.

The system boundary of the study was defined as “cradle-to-gate”, including (i) raw material supply such as for production of hydrogen and oxygen, (ii) transport of hydrogen from the supplier to the steelmaking site, and (iii) onsite combustion and operation. In the baseline CO/O₂ system, the CO-rich gas originates as a by-product of silicomanganese and/or ferromanganese alloy production at facilities located near 7Steel. Hydrogen production was assumed to be based on Alkaline Electrolysis Cell (AEC). Oxygen production was assumed to be based on air separation units (ASU). The CO-rich gas is supplied to 7Steel via pipeline. Compressed oxygen (15 bar) is delivered by Linde located adjacent to 7Steel, through a fixed piping system. Due to a lack of industry-specific data, the energy demand for transport of CO-rich gas and O₂ was excluded from the study. Compressed hydrogen (200 bar) was transported by a tube-trailer, and the transport distance was assumed to be 200 km. Several background processes associated with capital goods were excluded from the present study, including the manufacturing and maintenance of ladle preheating equipment, as well as the manufacture of AEC for H₂ production, and ASU for O₂ production.

Economic allocation was applied to address multifunctionality associated with hydrogen and oxygen production. The allocation approach and factors were identical to those used in the Swedish walking beam furnace case study and are described in Section 8.2.

The life cycle IA was performed using the method ReCiPe 2016 Midpoint (H) v1.12 in SimaPro v10.3.0.1. All the eighteen ReCiPe midpoint impact categories were included in this study.

9.2 Life cycle inventory

Table 9.1 presents the foreground LCI results. All input data were measured during the demonstration campaigns. Regarding the outputs, onsite NO_x emission in the H₂/O₂ demonstration was from the flue gas measurement system, whereas onsite CO₂ emission from the CO-rich gas combustion was estimated based on theoretical calculations, assuming complete conversion of the CO presented in the CO-rich gas to CO₂.

Table 9.1: Foreground LCI data for the demonstrations of ladle preheating

	Parameter	Unit	Preheating (CO/O ₂)	Preheating (H ₂ /O ₂)
Input	CO-rich gas ^{1,2}	Nm ³	3218	–
	O ₂ ¹	Nm ³	1607	1454.2
	Air ¹	Nm ³	1221	1414
	Hydrogen ¹	Nm ³	–	2869.3
	Electricity, auxiliary ¹	kWh	30	30
Output	CO ₂ (onsite, from fuel combustion)	kg	2554.5 ³	0 ⁴
	NO _x	kg	0 ⁵	8.83 ⁶

¹ Data provided by 7Steel.

² Composition of the CO-rich gas: 79.6 wt% CO, 8.6 wt% H₂, 7.7 wt% CO₂, 3.8 wt% N₂, and 0.3 wt% O₂.

³ Estimated data based on theoretical calculations, including 2406.4 kg CO₂ generated from CO combustion and 148.1 kg of CO₂ contained in the CO-rich gas.

⁴ Assumption, since no carbon-containing fuel sources were introduced into the ladle furnace.

⁵ Assumption, due to the lack of measured data from the demonstration.

⁶ Estimated based on the measured NO_x concentration of 3000 ppm in the flue gas.

The generic background LCI data used in the study were primarily from the ecoinvent v3.11 database within SimaPro v10.3.0.1. In specific, electricity production was modelled using the dataset “Electricity, medium voltage {NO} market for electricity, medium voltage | Cut-off, U”, representing the Norwegian market mix in

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

2021. As shown in Figure 9.1, the Norwegian electricity mix was dominated by hydropower (87.7%), followed by wind power (7.1%).

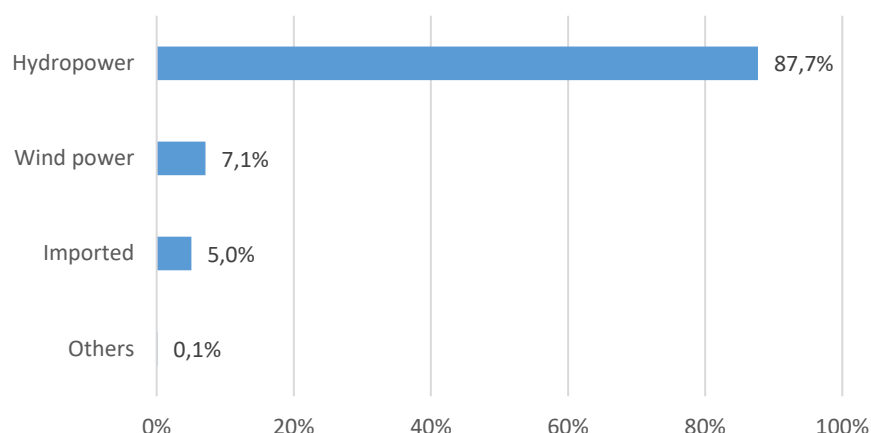


Figure 9.1: Share of energy sources in the Norwegian electricity mix in 2021, based on ecoinvent v3.11. "Others" includes the Norwegian electricity generation technologies that each contribute less than 0.1%, while imported electricity from other EU countries mainly originates from Sweden (3.07%) and Denmark (1.02%).

9.3 Impact assessment

The comparative LCIA results for the CO/O₂ and H₂/O₂ combustion systems are presented in Figure 9.2 and Table 9.2. Compared with the CO/O₂ baseline, the H₂/O₂ combustion reduced the GWP from 2566.8 to 303.2 kg CO₂eq, corresponding to a reduction of 88.2%. However, the H₂/O₂ combustion exhibited higher impacts across all other impact categories. These results indicate a trade-off between climate change mitigation and other environmental impacts when hydrogen produced by electrolysis using the Norwegian electricity mix is employed for ladle preheating.

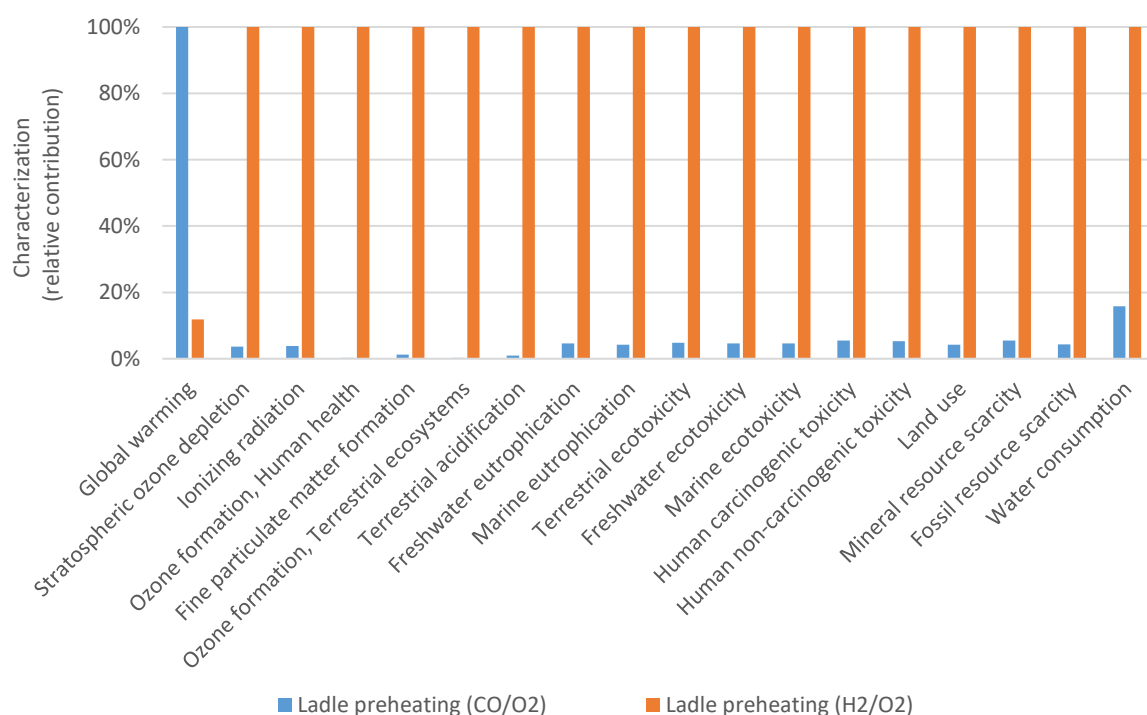


Figure 9.2. Comparative LCIA result for the ladle preheating with CO/O₂ and H₂/O₂ combustion, respectively. The H₂/O₂ combustion is based on H₂ produced from electrolysis using the Norwegian electricity country mix in 2021.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 9.2: LCIA characterization results for the ladle preheating demonstrations using CO/O₂ and H₂/O₂ combustion.

Impact category	Unit	Ladle preheating (CO/O ₂)	Ladle preheating (H ₂ /O ₂) ¹
Global warming	kg CO ₂ eq	2566.8	303.2
Stratospheric ozone depletion	kg CFC11 eq	3.1×10 ⁻⁵	8.6×10 ⁻⁴
Ionizing radiation	kBq Co-60 eq	4.6	120.7
Ozone formation, Human health	kg NO _x eq	0.02	9.4
Fine particulate matter formation	kg PM _{2.5} eq	0.02	1.3
Ozone formation, Terrestrial ecosystems	kg NO _x eq	0.02	9.4
Terrestrial acidification	kg SO ₂ eq	0.04	4.0
Freshwater eutrophication	kg P eq	0.01	0.2
Marine eutrophication	kg N eq	0.0005	0.01
Terrestrial ecotoxicity	kg 1,4-DCB	66.2	1381.5
Freshwater ecotoxicity	kg 1,4-DCB	3.3	72.1
Marine ecotoxicity	kg 1,4-DCB	4.2	90.4
Human carcinogenic toxicity	kg 1,4-DCB	9.4	172.3
Human non-carcinogenic toxicity	kg 1,4-DCB	49.4	939.1
Land use	m ² a crop eq	1.2	29.4
Mineral resource scarcity	kg Cu eq	0.2	3.4
Fossil resource scarcity	kg oil eq	2.1	49.3
Water consumption	m ³	59.8	379.1

¹ H₂ produced from electrolysis using the Norwegian electricity country mix in 2021.

9.4 Interpretation

9.4.1 Hotspot analysis

Figures 9.3 present the contribution analysis of the characterization results for each impact category of the preheating system with CO/O₂ combustion. On-site CO₂ emissions from the combustion of the CO-rich gas are the dominant contributor to GWP, accounting for around 99.5% of the total impact. The ASU-based oxygen production is the main contributor to all other impact categories, with contributions ranging from 93.3% (Stratospheric ozone depletion) to 98.7% (Water consumption). The contribution of electricity consumption of the auxiliary system varies between 0.03% (GWP) and 6.7% (Stratospheric ozone depletion).

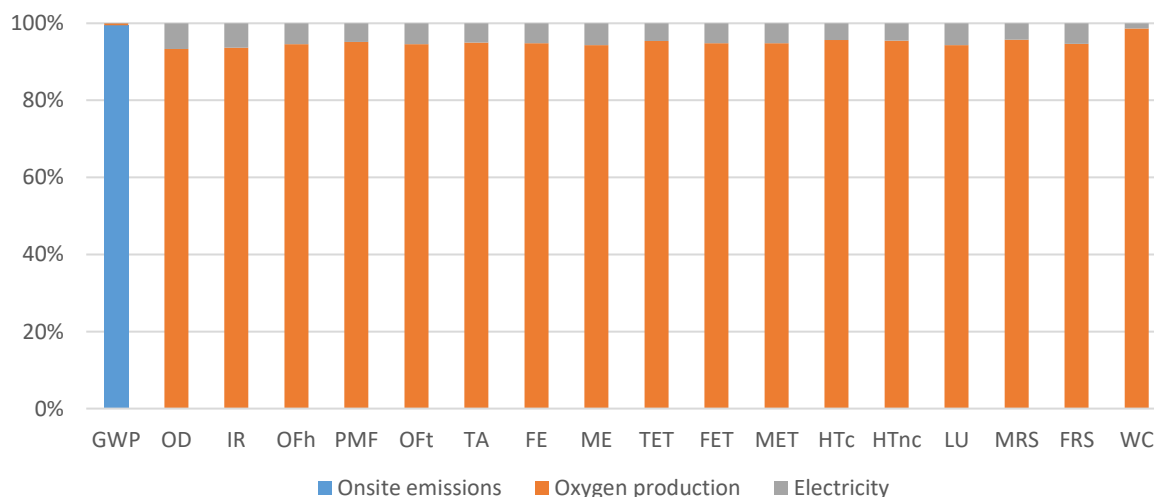


Figure 9.3: Life cycle contribution analysis of the ladle preheating with CO/O₂. The “on-site emissions” category includes only direct emissions of CO₂ from combustion of the CO-rich gas. GWP = global warming; OD = stratospheric ozone depletion; IR = ionizing radiation; OFh = ozone formation, human health; PMF = fine particulate matter formation; Oft = Ozone formation, Terrestrial ecosystems; TA = terrestrial acidification; FE = freshwater eutrophication; ME = marine eutrophication; TET = terrestrial ecotoxicity; FET = freshwater ecotoxicity; MET = marine ecotoxicity; HTc = human carcinogenic toxicity; HTnc = human non-carcinogenic toxicity; LU = land use; MRS = mineral resource scarcity; FRS = fossil resource scarcity; WC = water consumption.

Figure 9.4 presents the contribution analysis of the characterization results for each impact category of the preheating system with H₂/O₂ combustion. The on-site NO_x emissions from fuel combustion are the dominant contributor to four impact categories, accounting for 73.8% of “Fine particulate matter formation”,

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

79.4% of “Terrestrial acidification”, 93.9% of “Ozone formation, Terrestrial ecosystems”, and 94.1% of “Ozone formation, Human health”. The electrolysis-based hydrogen production is the main contributor for all other impact categories, with contributions ranging from 85.7% (Water consumption) to 96.5% (Ionizing radiation). The contribution of electricity consumption by the auxiliary system is negligible across all impact categories, accounting for less than 0.25%.

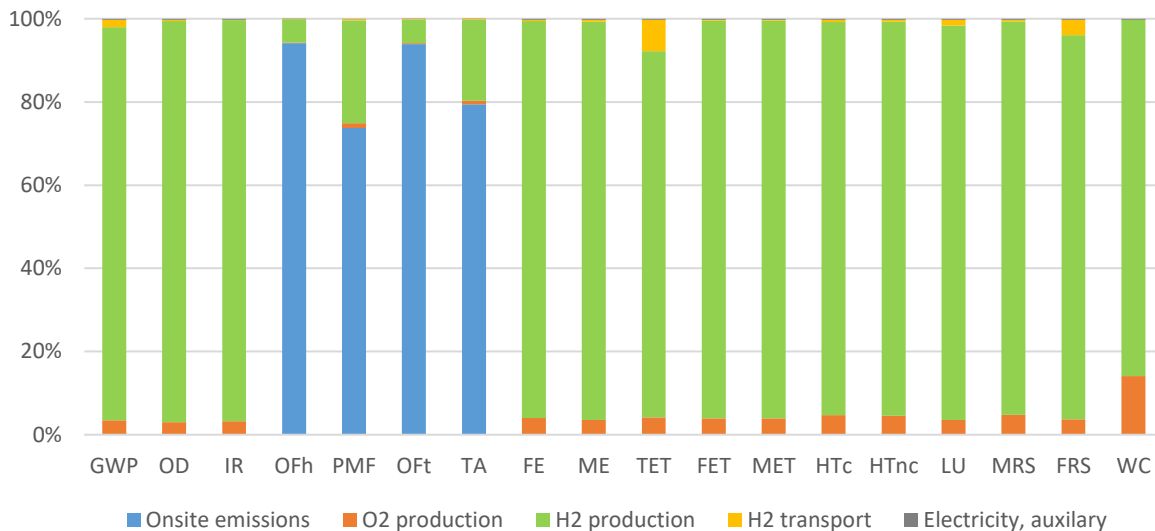


Figure 9.4. Life cycle contribution analysis of the ladle preheating with H₂/O₂. The “on-site emissions” category includes only direct emissions of NO_x from H₂ combustion.

9.4.2 Sensitivity analysis

Since hydrogen production was identified as the dominant environmental hotspots in the H₂/O₂ combustion system, a SA was conducted to evaluate the influence of electricity supply assumptions on the overall environmental performance of hydrogen production. The baseline assessment was based on the Norwegian electricity country mix (2021) available in ecoinvent v3.11.

To investigate the robustness of the comparative LCA results, two alternative electricity supply scenarios were assessed. The analysis focused on the global warming potential since scope 1 carbon emission reduction is one primary environmental benefit expected from replacing fossil fuels with hydrogen.

- Norwegian hydropower in 2021, representing a renewable and low-carbon electricity supply (i.e., 100% “green electricity”), the ecoinvent dataset “Electricity, high voltage {NO} electricity production, hydro, reservoir, alpine region | Cut-off, U”.
- European electricity mix in 2021, represented by the ecoinvent dataset “Electricity, medium voltage {RER} | market group for electricity, medium voltage | Cut-off, U”. For more information on the European electricity system, see Section 8.4.2.

The calculated carbon footprint is 0.007 kg CO₂eq/kWh for Norwegian hydropower, 0.334 kg CO₂eq/kWh for European electricity mix, and 0.024 kg CO₂eq/kWh for the Norwegian electricity mix. Hydrogen produced using the Norwegian hydropower scenario results in a GWP of 0.311 kg CO₂eq per kg H₂, representing a 72% reduction compared with hydrogen produced using the Norwegian electricity mix (1.11 kg CO₂eq per kg H₂). Hydrogen produced using the European electricity mix reaches 15.55 kg CO₂eq per kg H₂.

Figure 9.5 presents a comparison of the baseline results with scenarios using alternative electricity sources used for hydrogen production. Compared with the GWP of the baseline CO/O₂, the scenario H₂/O₂ (NO hydropower) results in a 96% reduction, while the scenario H₂/O₂ (RER grid mix) has a 57% increase.

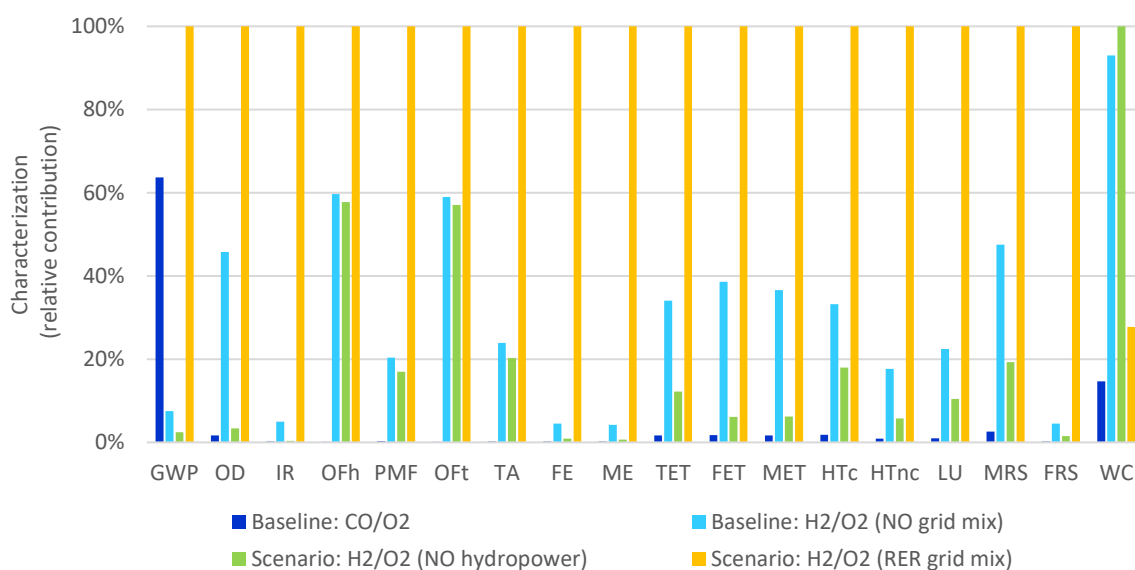


Figure 9.5: Comparison of the baseline results with scenarios using alternative electricity sources used for hydrogen production, normalized to the highest value within each impact category.

Overall, the results show that the environmental performance of the H₂/O₂ route can be strongly influenced by the electricity source used for hydrogen production. For example, the scenario based on the European (RER) grid mix exhibits the highest impacts in 17 of the 18 impact categories, except the category “water consumption”. In comparison, the H₂/O₂ system using the Norwegian grid mix and the hydropower-based scenario show substantially lower impacts across most categories.

10 Framework for future NO_x regulation in hydrogen-fired industrial furnaces

10.1 Introduction

The transition towards low-carbon and carbon-free fuels in industrial combustion systems introduces new challenges for the assessment and regulation of pollutant emissions. Existing nitrogen oxides (NO_x) emission limits and reporting procedures have largely been developed for conventional fossil fuel combustion with air as the oxidiser. However, future industrial furnaces are expected to operate with a broader range of fuel and oxidiser compositions, including natural gas-hydrogen mixtures, pure hydrogen, oxygen-enriched air and oxyfuel. These developments raise new questions regarding the applicability of current NO_x reporting methodologies and the comparability of emissions obtained from different fuel and oxidiser combinations.

Recent studies have highlighted potential limitations of existing reporting methodologies when applied to low-carbon and carbon-free fuels, particularly due to changes in off-gas composition and off-gas volume. At the same time, several hydrogen-based combustion systems have been demonstrated in steel and aluminium processes within the HyInHeat project. The resulting data provides an opportunity to evaluate NO_x emissions from different processes and combustion concepts under conditions close to industrial practice.

The overall objective of this deliverable is therefore to evaluate the suitability of current and alternative NO_x reporting approaches for future industrial combustion systems operating with hydrogen and hydrogen-containing fuels. The assessment covers air-fuel combustion as well as oxygen-enriched and oxyfuel concepts and combines a review of the current regulatory framework with an evaluation of current and alternative NO_x reporting approaches using available demonstrator results.

The specific objectives of this deliverable are:

- to evaluate the applicability of current NO_x reporting methodologies and emission metrics to hydrogen-based combustion systems,
- to review and discuss alternative approaches for NO_x emission reporting, and
- to apply and compare current and alternative reporting approaches to NO_x emission data obtained from the HyInHeat demonstrators (WP4–WP6) operating with hydrogen and hydrogen-containing fuels.

A detailed overview of NO_x formation mechanisms, existing emission regulations and standardised measurement procedures has already been presented in Deliverable D1.2 and is therefore only briefly summarised at the beginning of this report to provide the necessary context.

The outcomes of this deliverable will provide input to Deliverable D8.8 “Concepts for NO_x Limit Definitions, Standardisation and Certification”. While the present work focuses on identifying challenges associated with hydrogen-based combustion systems and evaluating different reporting approaches, Deliverable D8.8 will build upon these findings to develop concepts for future NO_x limit definitions, emission reporting methodologies and standardisation activities.

10.2 Current NO_x Reporting and Measurement Framework

Existing Regulatory Framework

NO_x emissions from industrial combustion processes are regulated within the European Union through the Industrial Emissions Directive (IED) 2010/75/EU [21] and its subsequent revisions. The directive establishes the use of Best Available Techniques (BAT) as the basis for setting permit conditions and emission limit values for industrial installations. BAT conclusions and associated emission levels are documented in sector-specific Best Available Techniques Reference Documents (BREFs). For the steel and aluminium sectors considered within the HyInHeat project, the most relevant reference documents are the BREF for the Ferrous Metals Processing Industry (FMP) [22] and the BREF for the Non-Ferrous Metals Industries (NFM) [23].

The BREF documents may define BAT-Associated Emission Levels (BAT-AELs) for specific pollutants, including NO_x. BAT-AELs represent the range of emission levels that can be achieved under normal operating conditions when applying the Best Available Techniques defined in the same documents. They are specified for defined averaging periods and under predefined reference conditions, such as a reference oxygen

concentration and a dry off-gas basis. BAT-AELs are subsequently used by permitting authorities when establishing emission limit values for industrial installations.

For thermal processing applications in the steel industry, the FMP BREF [22] defines BAT-AELs for NO_x emissions from processes such as reheating, intermediate heating and post-heating. Depending on the process and fuel type, NO_x emission levels are expressed as concentrations in the dry off-gas (mg/m³_{dry,ref}) corrected to a reference oxygen concentration of 3 vol%. As an example, the document specifies NO_x emissions of 80 to 200 mg/m³_{dry,ref} for new reheating installations and 100 to 350 mg/m³_{dry,ref} for existing reheating installations used in hot rolling. It should be noted that BAT-AELs defined in the BREF FMP [22] are primarily based on data from natural gas-fired plants. Although additional emission levels are provided for so-called “other fuels”, hydrogen and other alternative fuels are not explicitly addressed.

In contrast, the current NFM BREF [23] does not define BAT-AELs for NO_x emissions from aluminium processing applications. Instead, it reports emission data from existing industrial installations and highlights the need for further data collection and evaluation before sector-wide emission levels can be established. Consequently, a more harmonised framework for NO_x emission assessment currently exists within the steel sector than within the aluminium sector.

Table 10.1 provides an overview of the current NO_x emission framework for the steel and aluminium sectors relevant to the HyInHeat project. A more detailed review of the relevant legislation, BAT conclusions and BAT-AELs for both sectors can be found in Deliverable D1.2. For the purpose of the present deliverable, it is sufficient to note that current NO_x regulations are based on concentration-based emission values expressed in mg/m³_{dry,ref} under specific reference conditions.

Table 10.1: Overview of NO_x emission reporting frameworks in the steel and aluminium sectors

Sector	Reference Document	NO _x emission framework	Unit
Steel	FMP BREF [22]	BAT-AELs defined	mg/m ³ _{dry,ref}
Aluminium	NFM BREF[23]	No BAT-AELs defined	-

Current NO_x Reporting Methodology

As discussed in the previous section, current NO_x regulations and BAT-AELs are based on concentration-based emission values expressed in mg/m³_{dry,ref} under specified reference conditions. Before assessing the applicability of this approach to hydrogen-based combustion systems, the current NO_x reporting methodology is briefly described below.

In practice, NO_x concentrations are typically measured and reported by gas analysers in volumetric units (ppmv_{dry}). Regulatory emission limits and BAT-AELs, however, are generally expressed as mass concentrations in the dry off-gas (mg/m³_{dry,ref}) under specified reference conditions. Consequently, the measured NO_x concentration must first be converted from ppmv_{dry} to mg/m³_{dry} according to Eq. (1). The resulting value is then corrected to the applicable reference oxygen concentration using Eq. (2), where the measured NO_x concentration is adjusted based on the measured and reference oxygen concentrations in the dry off-gas. This correction enables the comparison of processes operating with different excess air ratios. For most thermal processing applications in the ferrous metals industry, a reference oxygen concentration of 3 vol% in the dry off-gas is used.

$$Q_{NO_x,dry} \left[\frac{mg}{m^3} \right] = Q_{NO_x,dry} [ppmv_{dry}] * \rho_{NO_2} \quad (1)$$

$$Q_{NO_x,dry,ref} \left[\frac{mg}{m^3_{dry,ref}} \right] = Q_{NO_x,dry} \left[\frac{mg}{m^3_{dry}} \right] * \left(\frac{x_{O_2,ox} - y_{O_2,dry,ref}}{x_{O_2,ox} - y_{O_2,dry,M}} \right) \quad (2)$$

Here, the density ρ_{NO_2} is used to convert the measured volumetric concentration from ppmv_{dry} into a mass concentration, as NO_x emissions are conventionally reported as NO₂ equivalents. Furthermore, $y_{O_2,dry,M}$ represents the measured oxygen concentration in the dry off-gas and $y_{O_2,dry,ref}$ is the corresponding reference oxygen concentration. The oxygen concentration in the oxidiser is given by $x_{O_2,ox}$. For combustion with air, $x_{O_2,ox} = 0.21$, whereas for oxyfuel combustion $x_{O_2,ox} = 1.00$.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

For combustion systems operating with oxygen-enriched air or pure oxygen, an alternative correction based on a reference carbon dioxide concentration may be applied, as shown in Eq. (3). In this case, the measured NO_x concentration is corrected using the ratio between the reference and measured CO₂ concentrations $y_{CO_2,dry,ref}$ and $y_{CO_2,dry,M}$ in the dry off-gas.

$$Q_{NO_x,dry,ref} \left[\frac{mg}{m^3_{dry,ref}} \right] = Q_{NO_x,dry} \left[\frac{mg}{m^3_{dry}} \right] * \frac{y_{CO_2,dry,ref}}{y_{CO_2,dry,M}} \quad (3)$$

The reporting methodologies described above were primarily developed for conventional combustion systems operating with fossil fuels and air as the oxidiser. While this framework has proven effective for conventional combustion processes, its applicability to future low-carbon and carbon-free combustion systems is increasingly being discussed in the scientific literature. The underlying assumptions are closely linked to the off-gas characteristics of fossil fuel combustion. However, hydrogen-based, oxygen-enriched and oxyfuel combustion can significantly alter the composition of the off-gas, particularly with respect to water vapour and carbon dioxide concentrations. As a result, the interpretation and comparability of reported NO_x emissions using this approach may be affected.

Current Measurement Practice

The reporting methodologies described in the previous section are based on the measurement of NO_x and O₂ concentrations in the off-gas. Therefore, a brief overview of current NO_x measurement practices is provided in the following.

The measurement of NO_x emissions from industrial combustion processes is governed by a series of European standards defining both the measurement methodology and the requirements for emission monitoring systems. In conventional analyser systems, NO_x emissions are typically determined using extractive measurement systems. A sample of the off-gas is extracted from the off-gas duct, transported through a sampling line and subsequently dried and filtered prior to analysis. Different techniques can then be used to determine NO and NO_x concentrations in dried the off-gas. For regulatory purposes, NO_x concentrations are commonly measured using chemiluminescence according to EN 14792 [24], which represents the standard reference method for the determination of NO and NO_x concentrations in off-gases. Continuous Emission Monitoring Systems (CEMS) are further regulated through standards such as EN 14181 [25] and the EN 15267-1 to 15267-4 [26–29] series, which define requirements for certification, calibration and quality assurance.

In addition to NO_x concentrations, the oxygen concentration is measured, as it is required for the correction of the emissions to the applicable reference conditions. Paramagnetic analysis is the standard reference method for O₂ measurement, as specified in DIN EN 14789 [30]. However, ZrO₂ probes are widely used in industrial combustion control and ISO 12039 [31] specifies their use in permanently installed measurement systems for continuous monitoring. Depending on the combustion process and reporting methodology, additional parameters such as CO₂ concentration and off-gas temperature may also be monitored.

More recently, analyser systems capable of measuring the off-gas composition on a moist basis have become available. In these systems, the sample gas is extracted through a heated probe, transported via a heated sampling line and analysed without prior drying. This allows the direct measurement of species such as NO_x, O₂ and H₂O in the moist off-gas.

Nevertheless, dry-basis measurements remain the predominant approach in industrial emission monitoring and form the basis of most current regulations and emission reporting procedures. Current measurement methodologies are generally applicable to both fossil fuel-based and hydrogen-based combustion. However, the high water vapour concentrations associated with hydrogen and particularly hydrogen-oxyfuel combustion increase the relevance of moist-basis measurements. The implications for emission reporting are discussed in the following section.

10.3 Challenges of Current NO_x Reporting for Hydrogen Combustion

Although current NO_x measurement methodologies remain theoretically applicable to hydrogen combustion, several challenges arise regarding the reporting and comparison of NO_x emissions. These challenges are primarily related to changes in off-gas composition caused by fuel-flexible operation and the use of alternative

oxidisers such as oxygen-enriched air and oxyfuel. They become particularly significant for hydrogen-oxyfuel combustion, where the off-gas consists predominantly of water vapour.

Influence of Fuel Composition on Reported NO_x Emissions

As discussed in Section 10.2, current NO_x emission limits are typically defined as concentrations in dry off-gas ($\text{mg}/\text{m}^3_{\text{dry,ref}}$) at a specified reference oxygen concentration. Consequently, the reported NO_x emission value is directly linked to the volume and composition of the off-gas. Switching from natural gas to hydrogen significantly alters the off-gas composition due to the increased water vapour content and the absence of carbon dioxide. Figure 10.1: Differences in minimum off-gas volume moist $v_{\text{og,min,moist}}$ and dry $v_{\text{og,min,dry}}$ ($\lambda = 1$) for the combustion of natural gas H and hydrogen with air. [32] illustrates the differences in specific moist and dry off-gas volumes per unit of fuel energy for natural gas and hydrogen combustion, while Figure 10.2: Calculated moist off-gas composition for the combustion of natural gas H and hydrogen with air (a) and oxygen (b) for different air ratios λ (bal. N_2). [32] presents the corresponding off-gas compositions for the combustion of natural gas and hydrogen with air and oxyfuel at a constant air ratio of $\lambda = 1$.

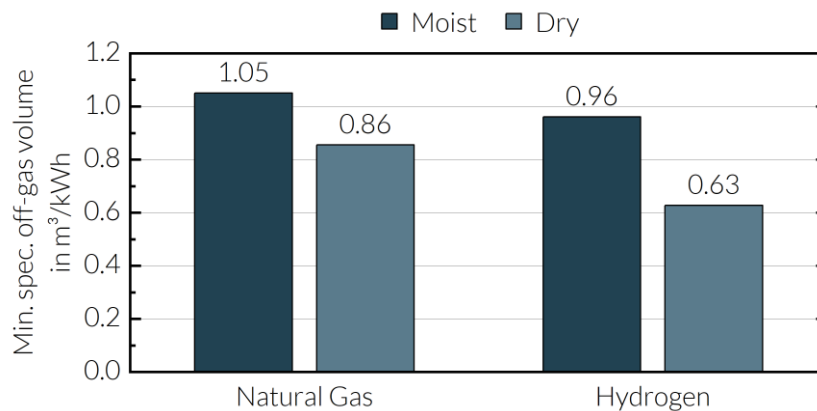


Figure 10.1: Differences in minimum off-gas volume moist $v_{\text{og,min,moist}}$ and dry $v_{\text{og,min,dry}}$ ($\lambda = 1$) for the combustion of natural gas H and hydrogen with air. [32]

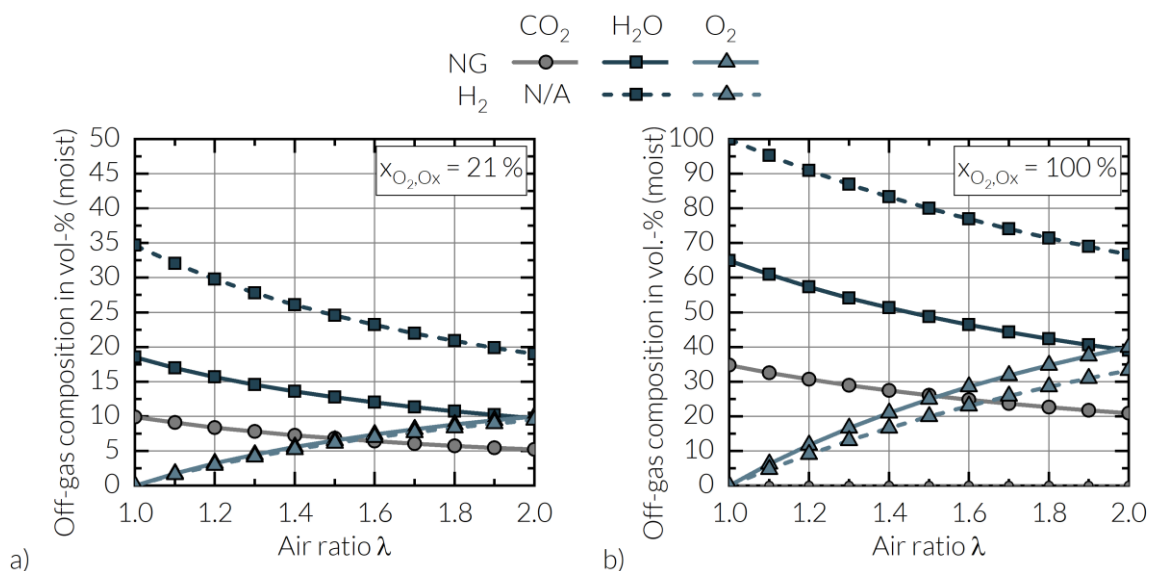


Figure 10.2: Calculated moist off-gas composition for the combustion of natural gas H and hydrogen with air (a) and oxygen (b) for different air ratios λ (bal. N_2). [32]

The comparison shows significant differences in both the off-gas composition and the specific off-gas volume. While the specific volume of moist off-gas differs by approximately 8.5%, the difference increases to approximately 26.7% for dry off-gas. This behaviour is caused by the higher water vapour content resulting from hydrogen combustion compared to natural gas combustion. For stoichiometric combustion with air, water vapour accounts for approximately 35 vol% of the off-gas for hydrogen combustion, compared to only

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

about 18.5 vol% for natural gas combustion. For oxyfuel combustion, the water vapour content changes from approximately 65 vol% to 100 vol% under stoichiometric conditions.

As current NO_x regulations are based on concentrations in the dry off-gas, these differences directly influence the reported emission values. Identical NO_x concentrations expressed in ppmv_{dry} result in identical values in mg/m³_{dry,ref} after conversion and correction to the applicable reference oxygen concentration (cf. Eq. (1) and (2)), regardless of the fuel used. However, the corresponding total NO_x mass flow emitted by the process may differ significantly due to the different off-gas volumes associated with each fuel.

To quantify this effect, the methodology proposed by Schmitz et al. [32], developed within the framework of the HyInHeat project, is summarised in the following. The theoretical study considers a measured NO_x concentration of 180 ppmv_{dry} at an oxygen concentration of 2 vol% in the dry off-gas and investigates the impact of fuel composition for both air-fuel and oxyfuel-combustion on resulting NO_x values using the current reporting methodology. After conversion to mg/m³_{dry,ref} and correction to a reference oxygen concentration of 3 vol% in the dry off-gas using Eq. (1) and (2), the resulting NO_x emission value is 350.6 mg/m³_{dry,ref} for both natural gas and hydrogen combustion.

This calculation complies with the current standards and regulations. However, as discussed above, the difference in off-gas volume between natural gas and hydrogen is not reflected in this value. To account for this effect, the NO_x emissions can be converted into a mass flow according to Eq. (4), thereby enabling a direct comparison of the actual pollutant release.

$$\dot{m}_{NO_x} = Q_{NO_x,dry} \left[\frac{mg}{m^3_{dry}} \right] * \dot{V}_{og,dry} \quad (4)$$

The measured NO_x concentration of 180 ppmv_{dry} at a thermal power input of 1 kW results in NO_x mass flows of 350.14 mg/h for natural gas and 256 mg/h for hydrogen combustion with air.

These calculations demonstrate that identical NO_x concentrations measured in ppmv_{dry} lead to identical reported emissions in mg/m³_{dry,ref} after conversion and correction according to the current reporting methodology. However, the corresponding NO_x mass flows differ due to the different off-gas volumes associated with the respective fuels. In the example considered here, the NO_x mass flow for hydrogen combustion is approximately 27% lower than for natural gas combustion, despite the reported emission concentration being identical.

This example demonstrates that concentration-based reporting methodologies, as defined in existing standards and regulations, do not fully reflect the actual pollutant release when comparing different fuels. While the existing framework provides a consistent basis for emission reporting, the interpretation of reported NO_x values becomes challenging for fuel-flexible systems, as variations in off-gas composition and volume influence the relationship between the reported concentration and the actual NO_x mass emitted.

This issue is particularly relevant for future industrial furnaces expected to operate with varying fuel compositions ranging from natural gas to pure hydrogen. Under these conditions, identical reported NO_x concentrations may correspond to different pollutant mass flows. Consequently, the interpretation of concentration-based emission limits becomes increasingly complex as the fuel composition changes over time.

Challenges for Hydrogen-Oxyfuel Combustion

Additional challenges arise when applying existing reporting methodologies to oxyfuel combustion systems. While concentration-based NO_x reporting on a dry off-gas basis remains applicable for most conventional fuels, the approach becomes problematic for pure hydrogen combustion. For an air ratio of $\lambda = 1$, i.e. in the absence of excess oxygen, the off-gas consists exclusively of water vapour and therefore no dry off-gas is available for measurement. For $\lambda > 1$, oxygen becomes the only major species present in the dry off-gas besides trace pollutants and may therefore approach concentrations close to 100 vol%. Under these conditions, the measurement of oxygen in the dry off-gas becomes impractical and is associated with high uncertainty. Furthermore, the alternative correction approach based on measured and reference CO₂ concentrations, as introduced in Eq. (3), cannot be applied because no carbon dioxide is present in the off-gas during pure hydrogen combustion.

These considerations demonstrate that reporting methodologies based on dry off-gas concentrations and reference oxygen or carbon dioxide concentrations are difficult to apply to pure hydrogen oxyfuel combustion systems. Consequently, alternative reporting methodologies are required for future hydrogen-oxyfuel applications to ensure a robust evaluation of NO_x emissions.

10.4 Alternative Reporting Approaches

While concentration-based reporting in mg/m³_{dry,ref} under specified reference conditions represents the most widely used methodology in industrial emission regulation for the steel and aluminium industry, several alternative approaches for reporting NO_x emissions have been proposed in the literature. These approaches aim to improve the comparability of combustion systems operating with different fuels or oxidisers. The following sections discuss the most relevant reporting methodologies identified by Schmitz et al. [32] and Ripoll Kameid et al. [33].

Mass-flow based reporting

A first alternative is to report NO_x emissions as a mass flow, typically expressed in mg/h or kg/year. In this approach, the measured NO_x concentration is combined with the corresponding off-gas volume flow according to Eq. (4). The calculation can be performed on either a dry or moist off-gas basis, provided that the corresponding off-gas volume flow is used.

Unlike concentration-based approaches, mass-flow-based metrics directly represent the absolute amount of NO_x emitted by a combustion process. Consequently, the comparison of different fuel-oxidiser combinations is not influenced by differences in off-gas composition, reference oxygen concentrations or dilution effects. Such metrics are therefore particularly suitable for environmental assessments where the total pollutant release is of primary interest.

However, the resulting NO_x mass flow strongly depends on the thermal power and operating conditions of the process. Consequently, larger furnaces generally exhibit higher NO_x mass flows than smaller furnaces, even when operating with comparable emission performance. Mass-flow-based metrics are therefore less suitable for comparing different combustion technologies or furnaces and provide only limited information regarding the environmental performance of a process relative to its energy input or production output.

Moist concentration-based reporting

Another alternative is the use of concentration-based reporting on a moist off-gas basis. The motivation behind this approach is that hydrogen combustion results in significantly higher water vapour concentrations than natural gas combustion. Consequently, reporting emissions on a moist basis may reduce the influence of fuel-dependent differences in off-gas composition.

A first option is to measure the NO_x concentration directly in the moist off-gas using an appropriate off-gas analyser. If a moist-based analyser is not available, the measured NO_x concentration can alternatively be converted from a dry to a moist basis, by measuring the water vapour concentration y_{H_2O} in the off-gas and taking it into account according to Eq. (5). The concentration in $ppmv_{moist}$ can then be converted into a mass concentration in mg/m^3_{moist} using the density of NO₂, as shown in Eq. (6). Finally, the concentration can be corrected to a reference oxygen concentration in the moist off-gas in $mg/m^3_{moist,ref}$ according to Eq. (7). As discussed previously, a reference oxygen concentration of $y_{O_2,dry,ref} = 3.0$ vol% is commonly used for industrial combustion systems. Based on theoretical combustion calculations for natural gas, this corresponds approximately to an oxygen concentration of 2.5 vol% in the moist off-gas.

$$Q_{NO_x,moist} [ppmv_{moist}] = Q_{NO_x,dry} [ppmv_{dry}] * (1 - y_{H_2O}) \quad (5)$$

$$Q_{NO_x,moist} \left[\frac{mg}{m^3_{moist}} \right] = Q_{NO_x,moist} [ppmv_{moist}] * \rho_{NO_2} \quad (6)$$

$$Q_{NO_x,moist,ref} \left[\frac{mg}{m^3_{moist,ref}} \right] = Q_{NO_x,moist} \left[\frac{mg}{m^3_{moist}} \right] * \left(\frac{x_{O_2,Ox} - y_{O_2,moist,ref}}{x_{O_2,Ox} - y_{O_2,moist,M}} \right) \quad (7)$$

Compared to conventional reporting on a dry off-gas basis, the moist-based approach accounts for the significantly higher water vapour concentrations associated with hydrogen combustion. Consequently, the influence of fuel-dependent differences in off-gas composition is reduced. However, the approach does not fully account for the remaining differences in total moist off-gas between fuels. As a result, identical NO_x mass flows may still lead to different reported emission values when comparing fuels with different off-gas volumes, such as natural gas and hydrogen.

To evaluate the suitability of moist concentration-based reporting, Schmitz et al. [32] investigated whether a NO_x limit expressed in mg/m³_{moist} results in a comparable limit definition for different fuels and oxidiser combustions. For this purpose, the calculations presented in Section 10.3 were performed in reverse. Instead of assuming a fixed NO_x concentration in ppmv_{dry}, a constant NO_x mass flow of 300 mg/h at a thermal power input of 1 kW was defined for all investigated fuel-oxidiser combinations. The corresponding NO_x concentrations were then calculated for natural gas and hydrogen combustion with air, oxygen-enriched air (40 vol% O₂) and pure oxygen. The resulting values are summarised in Table 10.2.

Table 10.2: Calculated NO_x concentrations on a moist basis for different fuel-oxidiser combinations assuming a constant NO_x mass flow of 300 mg/h

Oxidiser	Fuel	NO _x emission in mg/m ³ _{moist}	NO _x emission in mg/h
Air	NG	251.5	300
	H ₂	274.9	
Oxygen-enriched (40 vol%)	NG	469.5	
	H ₂	481.6	
Oxyfuel	NG	976.3	
	H ₂	876.5	

For combustion with air, the resulting NO_x concentrations were 251.5 mg/m³_{moist} for natural gas and 274.9 mg/m³_{moist} for hydrogen. For oxyfuel combustion, the calculated values increased to 976.3 mg/m³_{moist} for natural gas and 876.5 mg/m³_{moist} for hydrogen. Although all cases correspond to the same NO_x mass flow, significant differences in the reported emission values remain. This demonstrates that moist concentration-based emission reporting does not eliminate the influence of fuel and oxidiser on reported emission values.

Finally, the practical implementation of this approach for hydrogen-oxyfuel combustion remains challenging. Measurement system capable of reliably measuring in moist off-gases with high water vapour concentrations (> 40 vol%) are currently not commercially available [34], and are still under development [35].

Input-based reporting

A further alternative is the use of input-based or energy-based emission metrics, in which NO_x emissions are related to the fuel energy input, for example in units of mg/MJ_{fuel} or mg/kWh_{fuel}. In contrast to concentration-based metrics, energy-based approaches are independent of fuel-dependent changes in off-gas composition and volume, as the reported emissions are directly related to the amount of energy supplied to the combustion process. Such metrics are frequently used in combustion research and facilitate the comparison between different fuel compositions and combustion concepts.

One approach discussed by Schmitz et al. [32] is based on the methodology defined in EN 267 [36] and EN 676 [37] for forced-draught burners operating with air as oxidiser (x_{O₂,Ox} = 0.21) and dry off-gas as basis. In this approach, the measured NO_x concentration is related to both the net calorific value of the fuel and the theoretical off-gas volume. The corresponding equation for measurements on a dry off-gas basis is given by Eq. (8). Alternatively, the calculation can also be performed on a moist off-gas basis, as shown in Eq. (9).

$$Q_{NO_x} \left[\frac{mg}{kWh} \right] = Q_{NO_x,dry} [ppmv_{dry}] * \rho_{NO_2} * \left(\frac{x_{O_2,Ox}}{x_{O_2,Ox} - y_{O_2,dry,M}} \right) * \frac{v_{og,dry,min}}{H_i} \quad (8)$$

$$Q_{NO_x} \left[\frac{mg}{kWh} \right] = Q_{NO_x,moist} [ppmv_{moist}] * \rho_{NO_2} * \left(\frac{x_{O_2,Ox}}{x_{O_2,Ox} - y_{O_2,moist,M}} \right) * \frac{v_{og,moist,min}}{H_i} \quad (9)$$

To evaluate the suitability of input-based reporting, the same methodology as described for the moist concentration-based approach was applied. A constant NO_x mass flow of 300 mg/h at a thermal power input of 1 kW was assumed for all investigated fuel-oxidiser combinations. The corresponding NO_x concentrations were then calculated for natural gas and hydrogen combustion with air, oxygen-enriched air (40 vol%) and pure oxygen. The resulting values are given in Table 10.3.

Table 10.3: Calculated NO_x emissions expressed in mg/kWh for different fuel-oxidiser combinations assuming a constant NO_x mass flow of 300 mg/h

Oxidiser	Fuel	NO _x emission in mg/kWh	NO _x emission in mg/h
Air	NG	300	300
	H ₂	300	
Oxygen-enriched (40 vol%)	NG	300	
	H ₂	300	
Oxyfuel	NG	300	
	H ₂	300	

Unlike the dry and moist concentration-based approaches discussed previously, the conversion of the emissions according to Eqs. (8) and (9) results in a constant value of 300 mg/kWh for all investigated fuel-oxidiser combinations. The calculations therefore demonstrate that input-based metrics account for differences in fuel properties, off-gas composition and combustion characteristics. Consequently, NO_x limits expressed in mg/kWh provide a consistent basis for comparing combustion systems operating with different fuels and oxidisers. In principle, the approach is also applicable to fuel-flexible operation, where the fuel composition varies continuously over time.

However, the determination of input-based metrics requires additional information on fuel properties, particularly the net calorific value and fuel composition required to determine the theoretical off-gas volume. For fuel-flexible operation, these properties may vary continuously with the fuel mixture being used. Consequently, accurate fuel composition and fuel flow measurements are required, increasing the complexity of the reporting methodology compared to conventional concentration-based approaches.

Output-based reporting

The final approach discussed here is the use of output-based or production-based metrics, in which NO_x emissions are normalised to the amount of product manufactured. Typical units include mg/t_{steel}, mg/t_{aluminium} or, more generally, pollutant mass per unit of product. In addition, normalisation to the useful process output, for example in units of mg/MJ_{useful heat}, has also been proposed in the literature [33].

In contrast to concentration-based and input-based metrics, output-based metrics directly relate emissions to the industrial output of the process. As a result, they provide a direct measure of the environmental impact associated with the production of a given quantity of material and may therefore be particularly relevant for the evaluation of industrial processes. From a theoretical perspective, output-based metrics provide the most direct link between pollutant emissions and industrial production. Since the emissions are related to the useful output of the process, they offer a potentially fair basis for comparing different fuels, oxidisers, combustion technologies and processes.

An additional advantage of output-based metrics is their applicability to hybrid energy systems. Future industrial processes are expected to combine different energy sources, including hydrogen combustion, natural gas combustion and electrical heating technologies. In such cases, input-based metrics linked solely to fuel consumption become increasingly difficult to apply, whereas output-based metrics remain valid regardless of the energy carrier used. They therefore allow a fair comparison between different decarbonisation approaches, regardless of the energy source used.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

However, the implementation of output-based metrics within a harmonised regulatory framework remains challenging. In contrast to concentration-based and input-based approaches, output-based metrics require process-specific information such as production rates, product quantities or useful heat output. The definition of a suitable output parameter may vary considerably between industrial sectors and even between different processes within the same sector. Production rates can be influenced by factors unrelated to combustion performance, such as operating schedules and process efficiency. Consequently, the development of standardised output-based emission limits applicable across different process types may be challenging.

Comparison of the reporting approaches

To directly compare the reporting approaches presented above, the calculated NO_x emission values for natural gas and hydrogen combustion with air are summarized in Table 10.4: Different NO_x limit specifications for the combustion of NG and H₂ with air, based on a measured concentration of 180 ppmv_{dry}; reference O₂ concentrations in the off-gas: 3.0 vol% (dry) and 2.5 vol% (moist) [32]. The calculations are based on a fixed measured NO_x concentration of 180 ppmv_{dry} at an oxygen concentration of 2 vol% in the dry off-gas. The reported values were subsequently converted according to the different reporting methodologies discussed above. The reference oxygen concentrations were set to 3.0 vol% in the dry off-gas and 2.5 vol% in the moist off-gas. Since output-based metrics require process-specific information such as production rates, product quantities or useful heat output, they cannot be assessed within the scope of this comparison. Consequently, the following analysis focuses on concentration-based, input-based and mass-flow-based reporting approaches.

Table 10.4: Different NO_x limit specifications for the combustion of NG and H₂ with air, based on a measured concentration of 180 ppmv_{dry}; reference O₂ concentrations in the off-gas: 3.0 vol% (dry) and 2.5 vol% (moist) [32]

Relation to	NO _x limit specification	NG	H ₂	Eq.
Dry off-gas	ppmv _{dry}	180.00	180.00	Measured
	mg/m ³ _{dry}	370.08	370.08	(1)
	mg/m ³ _{dry,ref}	350.60	350.60	(2)
Moist off-gas	ppmv _{moist}	149.28	121.54	(5)
	mg/m ³ _{moist}	306.93	249.88	(6)
	mg/m ³ _{moist,ref}	293.58	235.26	(7)
Net calorific value	mg/kWh	350.14	256.74	(8)
Mass flow	mg/h (P _{th} = 1 kW)	350.14	256.74	(4)

The results clearly demonstrate the influence of the selected reporting metric on the interpretation of NO_x emissions. As expected, concentration-based metrics expressed in ppmv_{dry}, mg/m³_{dry} and mg/m³_{dry,ref} achieve identical values for natural gas and hydrogen, despite the differences in off-gas composition and volume. In contrast, moist-based, input-based and mass-flow-based metrics result in lower NO_x emission values for hydrogen combustion. These differences are directly related to the lower specific off-gas volume and higher water vapour concentration associated with hydrogen combustion, as discussed previously.

A similar comparison was carried out for oxyfuel combustion and is summarized in Table 10.5: Different NO_x limit specifications for the combustion of NG and H₂ with pure oxygen, based on a measured concentration of 180 ppmv_{moist}; reference O₂ concentration in the off-gas: 2.5 vol% (moist) [32]. As discussed in Section 10.3, the use of dry off-gas concentrations is not applicable for pure hydrogen-oxyfuel combustion. Consequently, only moist-based reporting approaches were considered. For the comparison, a measured NO_x concentration of 180 ppmv_{moist} and an oxygen concentration of 2.5 vol% in the moist off-gas were assumed.

For oxyfuel combustion, identical NO_x concentrations expressed in ppmv_{moist} and mg/m³_{moist,ref} again result in identical reported emission values for both fuels. However, differences become apparent when the emissions are related to the fuel energy input or expressed as an absolute NO_x mass flow. In contrast to air combustion, the input-based and mass-flow-based emission values are higher for hydrogen than for natural gas for this case. This highlights that the interpretation of NO_x emissions depends not only on the selected fuel but also on the oxidiser and reporting methodology.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 10.5: Different NO_x limit specifications for the combustion of NG and H₂ with pure oxygen, based on a measured concentration of 180 ppmv_{moist}; reference O₂ concentration in the off-gas: 2.5 vol% (moist) [32]

Relation to	NO _x limit specification	NG	H ₂	Eq.
Moist off-gas	ppmv _{moist}	180.00	180.00	Measured
	mg/m ³ _{moist}	370.08	370.08	(6)
	mg/m ³ _{moist,ref}	370.08	370.08	(7)
Net calorific value	mg/kWh	113.72	126.66	(8)
NO _x mass flow	mg/h (P _{th} = 1 kW)	113.72	126.66	(4)

Finally, an overview of the four NO_x reporting metrics discussed above, including advantages and limitations is given in Table 10.6.

Table 10.6: Comparison of NO_x emission reporting approaches for industrial combustion systems

Reporting metric	Typical Unit	Advantage	Limitations
Mass-flow based	mg/h kg/year	Represents absolute emissions, independent of fuel composition	Dependent on furnace capacity and thermal power input, limited suitability for comparing different combustion technologies or processes
Concentration-based (dry and moist)	ppmv _{moist} ppmv _{dry} mg/m ³ _{dry} mg/m ³ _{moist}	Well established, easy regulatory implementation, no fuel property measurements required	Influenced by off-gas composition, off-gas volume and dilution, comparability between different fuels and oxidisers may be limited
Input-based	mg/kWh _{fuel} mg/MJ _{fuel}	Provides a consistent basis for comparing different fuels, fuel mixtures and oxidisers, independent of off-gas composition and volume	Requires accurate fuel property measurements, implementation is more complex
Output-based	mg/t _{product} mg/MJ _{useful heat}	Directly relates emissions to industrial production or process performance, applicable to hybrid heating concepts	Requires process-specific output data and clearly defined system boundaries, difficult to standardise across sectors and processes

10.5 Measurement and Monitoring Requirements for Alternative Approaches

The applicability of a given NO_x reporting methodology depends not only on its suitability for comparing different combustion systems, but also on the measurement effort required for its implementation. Different reporting metrics require different process parameters, analysers and monitoring procedures. Consequently, the choice of a reporting methodology has direct implications for the measurement technology and data acquisition.

Measurement methods for concentration-based reporting have already been discussed in Section 10.2 and in Deliverable D1.2. Mass-flow-based metrics are not considered further, as they are strongly dependent on the thermal power of the installation and are therefore not suitable for comparing systems with different production capacities or energy inputs. The following sections therefore focus on the measurement requirements associated with input-based and output-based reporting approaches.

Input-Based Reporting

For input-based reporting, the following parameters must be measured according to Schmitz et al. [32]:

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

- NO_x concentration: the NO_x concentration should be measured in the moist off-gas. In principle, the moist NO_x concentration can be calculated from a dry measurement if the water vapour concentration is known. However, as discussed above, dry off-gas measurement is not applicable to pure hydrogen-oxyfuel combustion. Consequently, a universally applicable input-based NO_x reporting methodology, capable of covering all fuel and oxidiser combinations from conventional air-fuel combustion to pure hydrogen-oxyfuel systems, requires NO_x measurement on a moist off-gas basis. An alternative approach would be to determine NO_x emissions from measurements in the dry off-gas combined with a quantitative analysis of nitrate in the condensate. However, this would require measurement of the condensate mass flow and additional chemical analysis of the nitrate concentration, which would significantly increase the monitoring effort.
- O₂ concentration: The oxygen concentration must also be measured in the moist off-gas. This is particularly important for hydrogen-oxyfuel combustion, where the air ratio cannot be reliably determined from dry off-gas measurements. A purely calculated oxygen concentration is not sufficient under real operating conditions, since air ingress may influence both the measured oxygen concentration and NO_x formation. Direct measurement of the oxygen concentration is therefore required.
- Fuel mixture composition: The composition of the fuel mixture must be known in order to calculate the theoretical minimum moist off-gas volume $V_{og,min,moist}$ and the net calorific value H_i both of which are required for the conversion of the measured NO_x concentration to mg/kWh. Gas chromatography is currently the most common measurement technology for this purpose. Due to the cost and complexity of continuous gas chromatography, alternative measurement techniques or standardised approximations for common fuels may be considered in the future, like e.g. in EN 676 [37]. However, the use of fixed standard values would limit the applicability of the method for fuel-flexible operation.

In addition to these measured quantities, two values must be calculated from the fuel composition:

- Net calorific value: The calculation of the net calorific value H_i of a gaseous fuel can be performed according to EN ISO 6976 [38].
- Minimum specific volume of moist off-gas: The calculation of the theoretical minimum moist off-gas volume $V_{og,min,moist}$ requires the determination of basic combustion characteristics, including the minimum oxygen demand, the minimum oxidiser requirement and the resulting amounts of N₂, CO₂ and H₂O in the off-gas. The corresponding equations are given in Schmitz et al. [32]. It should be noted that, while calorific value calculation is standardised, the complete calculation of the combustion characteristics required for $V_{og,min,moist}$ is not yet defined in a dedicated emission reporting standard.

Once the fuel mixture composition is known, the calculations are relatively easy to implement into a certified Continuous Emission Monitoring System (CEMS). An overview of the calculation procedure for the proposed universal input-based emissions is given in Figure 10.3: Schematic for NO_x emission calculation; current standards and regulations (a) and proposed universal limit definition (b) [32].

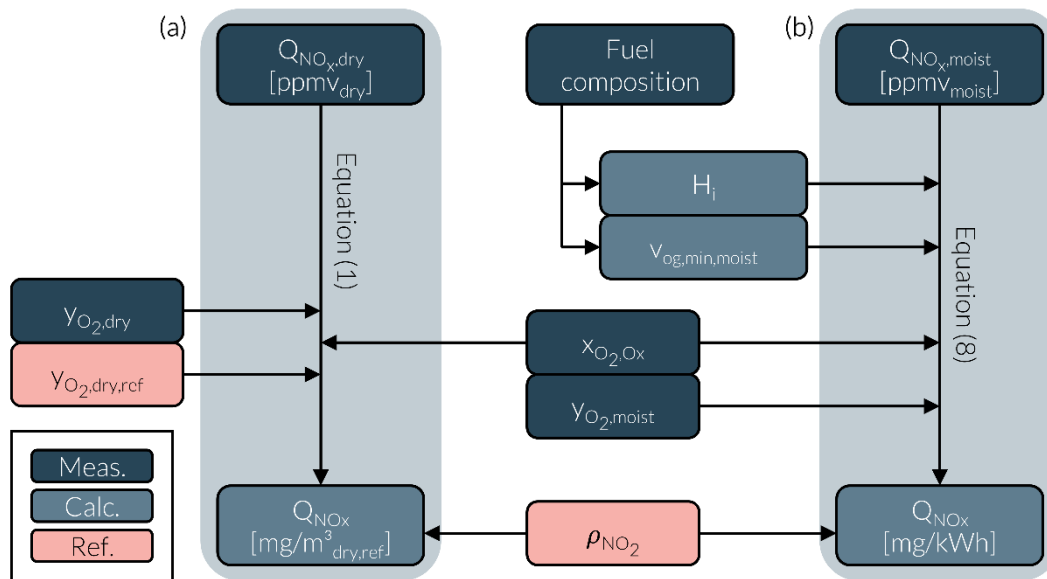


Figure 10.3: Schematic for NO_x emission calculation; current standards and regulations (a) and proposed universal limit definition (b) [32]

Output-Based Reporting

In addition to the emission measurements required for input-based reporting, output-based metrics require a clearly defined and continuously quantified process output. Depending on the application, this may correspond to the mass of saleable product, processed product or the amount of heat transferred to the product. The definition of the product output itself may not always be straightforward. For example, in some cases, it must be clearly defined whether the reported output refers only to the final product or also includes internally recycled material and scrap streams. Consequently, different sectors and applications would require different definitions, calculation methods and system boundaries, making the standardisation and implementation of output-based NO_x limits considerably more challenging than for input-based approaches.

Nevertheless, the following parameters would generally be required:

- **NO_x concentration:** As for the input-based approach, the NO_x concentration must be measured using a suitable emission monitoring system in the moist off-gas.
- **Fuel composition and energy input:** If the NO_x emissions are first converted to an input-based or mass-flow-based value, the same fuel-related parameters as described for input-based reporting may be required, including fuel composition, net calorific value and theoretical off-gas volume. These parameters may be necessary to determine the thermal energy input and to estimate the corresponding off-gas flow rate or NO_x mass flow prior to relating the emissions to the process output.
- **Production output or useful heat output:** the useful process output must be clearly defined and determined. For production-based metrics, this may correspond to the mass of product treated or produced per unit time, such as tonnes of steel or aluminium. For heat-based metrics, the useful heat transferred to the product or process would need to be quantified.

10.6 Demonstrator Results

The theoretical assessment presented in the previous sections indicates that the selected reporting metric can significantly influence the interpretation of NO_x emissions. The following section applies the investigated reporting approaches to available measurements from the HyInHeat demonstrators. The objective is both to assess the practical applicability of the different metrics and to determine whether the effects identified theoretically can also be observed in experimental data. The available NO_x emission data within the HyInHeat project are however limited to two demonstrators, one each from the aluminium and the other from the steel sector.

Overview of Investigated Demonstrators

The first demonstrator consists of the **aluminium reverberatory furnace operated by CTEC**. The furnace was operated with natural gas, hydrogen and mixtures of these fuels with oxyfuel. The demonstrator provided continuous measurements of NO_x and O₂ concentrations in the wet off-gas using three different gas analysers. Further gas analysers were installed but are not relevant for this study. In addition, information on fuel composition, net calorific value, thermal power input and product output was available. Consequently, this demonstrator enables a comprehensive comparison of all NO_x reporting approaches discussed in the previous sections.

The second demonstrator consists of the **pilot walking beam furnace operated by SWERIM**. The furnace was operated with fuel oil and hydrogen using air, oxygen-enriched air (with 40 vol% O₂) and pure oxygen as oxidiser. The available dataset includes measurements of NO_x and O₂ concentrations in the wet off-gas using four different analysers. Information on fuel composition, net calorific value and thermal power input were also available. However, information on the production rates were not available. Therefore, only a partial comparison of the different reporting approaches, excluding output-based metrics, could be performed for this demonstrator.

An overview of the investigated demonstrators and the available data is provided in Table 10.7.

Table 10.7: Overview of the available data from the demonstrators

Sector	Partner	Process	Furnace type	Fuel(s)	Oxidiser(s)	Available data	Furnace temperature
Aluminium	CTEC	Melting	Reverberatory Furnace	- NG - H ₂ - NG/H ₂ blends	- Oxyfuel	NO _x , O ₂ , NCV, fuel composition, product output	900 °C
Steel	SWERIM	Reheating	Pilot Walking Beam furnace	- Oil - H ₂	- Air - Oxygen-enriched air (40 vol%) - Oxyfuel	NO _x , O ₂ , NCV, fuel composition	N/A

Demo 1: Aluminium Reverberatory Furnace (CTEC)

NO_x emissions at the CTEC demonstrator are monitored using three different gas analysers operating on a wet basis. In addition, oxygen concentration in the wet off-gas was continuously measured. Two of the analysers are based on in-situ measurements, where the sample gas is transported through the probe tube to the sensors, which is flanged to the probe tube outside the furnace. The third analyser is a hot-extractive system. An overview of the analyser specifications is given in Table 10.8.

All measurement systems are installed in the off-gas duct downstream of the furnace. The sampling probes are positioned approximately in the centre of the off-gas duct, with probe inclinations of 5° for Analysers 1 and 2 and 15° for Analyser 3. During operation, off-gas temperatures of up to 1,200 °C and a pressure of approximately 9 Pa(g) were encountered at the measurement location. The maximum gas temperature at the probe position was about 450 °C for Analyser 1 and about 200 °C for Analysers 2 and 3. All analysers were operated continuously throughout the measurement campaign, with data recorded at a frequency of 1 Hz. No filtering of the raw measurement data was applied.

The natural gas composition was provided by the gas supplier. Based on this information, the net calorific value and the theoretical specific off-gas volume were calculated for the different operating conditions. However, no continuous measurements of the fuel composition or fuel properties were available at the demonstrator. The oxygen quality was also specified by the operator, with a minimum purity of 99.5 vol%. The remaining impurities mainly consist of nitrogen, argon and trace amounts of methane.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 10.8: Overview of specifications of relevant analysers used at the CTEC demonstrator for NO_x and O₂ measurements

Analyser	1	2	3
Manufacturer	Lamtec	Lamtec	EHS
Type	Sensor: KS2DNOx Control unit: NT1	Sensor: KS1D Control unit: LT3	MCS300P
Measurement Basis	Wet	Wet	Wet
Sampling method	In-situ	In-situ	(Hot)-extractive
Species measured	NO _x , O ₂	O ₂ , CO	NO, NO ₂ , CO, CO ₂ , H ₂ O, O ₂ ,
Measurement principle	<u>NO_x, O₂</u> : Solid-state electrolytic sensor	<u>O₂, CO</u> : Solid-state electrolytic sensor	<u>NO, NO₂, CO, CO₂</u> : Interference and gas filter correlation <u>O₂</u> : ZrO ₂ sensor
Measuring range set	<u>NO_x</u> : 0...1,000 ppm <u>O₂</u> : 0...100 vol%	<u>O₂</u> : 0...10 vol% <u>CO</u> : 0...1,000 ppm	<u>NO</u> : 0...2,200 ppm <u>NO₂</u> : 0...1,500 ppm <u>CO</u> : 0...1,200 ppm <u>CO₂</u> : 0...30 vol% <u>H₂O</u> : 0...100 vol% <u>O₂</u> : 0...21 vol%
Measurement uncertainty	<u>NO_x</u> : ± 10 % of measuring value, not better than ± 3 ppm <u>O₂</u> : ± 8 % of measuring value, not better than ± 0.2 vol%	<u>O₂</u> : ± 5 % of measuring value, not better than ± 0.3 vol% <u>CO</u> : ± 25 % of measuring value, not better than ± 20 ppm	<u>NO, NO₂, CO, CO₂</u> : ± 2 % full scale value of measuring range
Calibration gases	<u>Gas 1</u> : 400 ppm NO, rest N ₂ <u>Gas 2</u> : 3 vol% O ₂ , rest N ₂	<u>Gas 1</u> : 3 vol% O ₂ , rest N ₂	<u>Gas 1</u> : 400 ppm NO, rest N ₂ <u>Gas 2</u> : 3 vol% O ₂ , rest N ₂ <u>Gas 3</u> : 400 ppm CO, 10 vol% CO ₂ , rest N ₂ <u>Gas 4</u> : 200 ppm NO ₂ , rest synthetic air

The investigations are performed with pure oxygen as oxidiser for six different fuel compositions: 0, 28, 54, 78, 91 and 100 vol% H₂ in natural gas, corresponding to 0, 10, 25, 50, 75 and 100% of the fuel power input supplied by hydrogen, respectively. The investigated operating points are summarised in Table 10.9.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Table 10.9: Overview of operating conditions during the trials at the CTEC demonstrator

Value	Unit	1	2	3	4	5	6
Thermal power	kW	1800	1800	1800	1800	1800	1800
H ₂ content in NG	vol%	0	28	54	78	91	100
NCV of fuel	kWh/m ³	10,28	9,55	8,46	6,64	4,82	3,00
Min. off-gas volume wet	m ³ _{og,wet} /m ³ _{fuel}	3,13	2,53	1,98	1,47	1,19	1,00
O ₂ content in oxidiser	vol%	100	100	100	100	100	100
Air ratio	-	1,059	1,0567	1,0532	1,0474	1,0423	1,0365
Spec. energy demand	kWh/t _{Aluminium}	460	460	460	460	460	460

Figure 10.4 compares the measured NO_x and O₂ concentrations obtained with the different gas analysers installed at the CTEC demonstrator. Although all analysers operated on a wet basis, systematic differences between the measured values can be observed. For the NO_x measurements (Figure 10.4a), Analyser 3 consistently shows higher concentrations than Analyser 1 over the entire range of investigated fuel compositions. While the absolute values differ considerably, both analysers exhibit a similar trend with increasing hydrogen content. A similar behaviour is observed for the oxygen measurements (Figure 10.4b). All three analysers show the same variation with fuel composition, but with a systematic offset between the measured values. Analyser 3 consistently shows the highest O₂ concentrations, followed by Analyser 1, whereas Analyser 2 measures the lowest values.

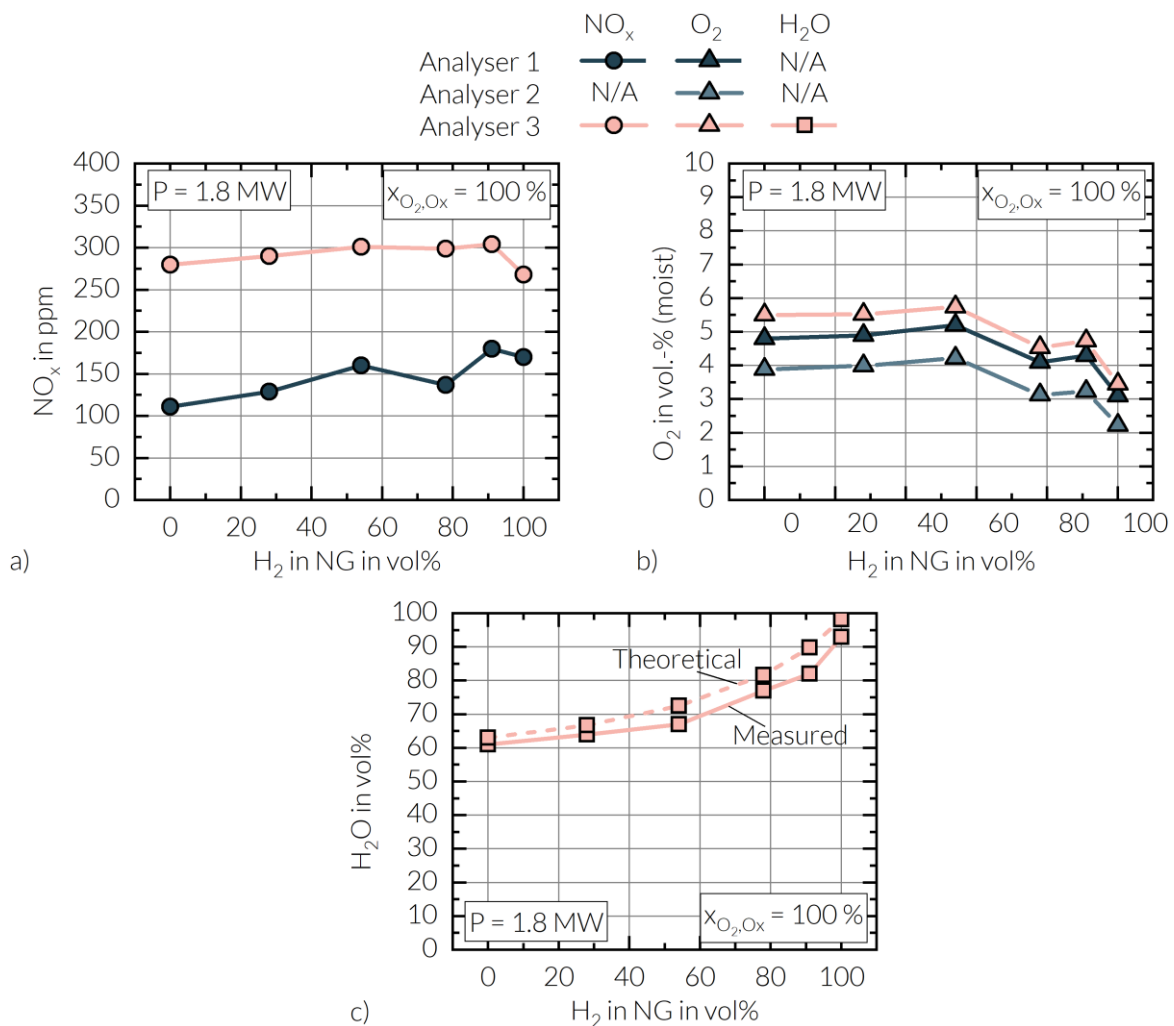


Figure 10.4: Comparison of a) NO_x values and b) O₂ values and c) H₂O values of the different analysers at the CTEC demonstrator

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

The observed deviations may result from differences in measurement principles or probe design. Since all probes were installed within the exhaust gas duct, large differences caused only by the sampling location would not be expected. Since no independent reference measurement is available, it is not possible to determine which analyser provides the most accurate values. The comparison nevertheless demonstrates that the choice of analyser can significantly influence the reported NO_x and O_2 concentrations, even under identical operating conditions.

Finally, the water vapour content was measured using Analyser 3 and is shown in Figure 10.4c. The results show that the water vapour content increases from approximately 61 vol% for pure natural gas combustion to 93 vol% for pure hydrogen combustion. The trend of the measured values is in good agreement with the theoretical values calculated based on the fuel composition, although the analyser values are consistently around 2 to 8 vol% lower. Possible explanations for this deviation include dilution by air ingress, local condensation in cooler parts of the sampling system or limitations of the analyser at very high water vapour concentrations. Overall, the high measured water vapour contents clearly illustrate the strongly increased water vapour content in the off-gas during hydrogen/oxyfuel combustion.

The following analysis focuses on the influence of the selected reporting methodology on the reported NO_x emissions. The evaluation is based on the measurements obtained with Analyser 3, as this analyser provides direct measurements of NO_x , O_2 and H_2O . In addition to the directly measured moist concentrations, the NO_x values were converted to several alternative reporting approaches: dry basis in ppmv_{dry} , dry basis corrected to a reference oxygen content of 3 vol% in $\text{mg}/\text{m}^3_{\text{dry,ref}}$, moist basis in $\text{ppmv}_{\text{moist}}$, moist basis corrected to a reference oxygen content of 2.5 vol% in $\text{mg}/\text{m}^3_{\text{moist,ref}}$, energy-related emissions in mg/kWh , and product-related emissions in $\text{g}/\text{t}_{\text{Aluminium}}$. The values are shown in Figure 10.5.

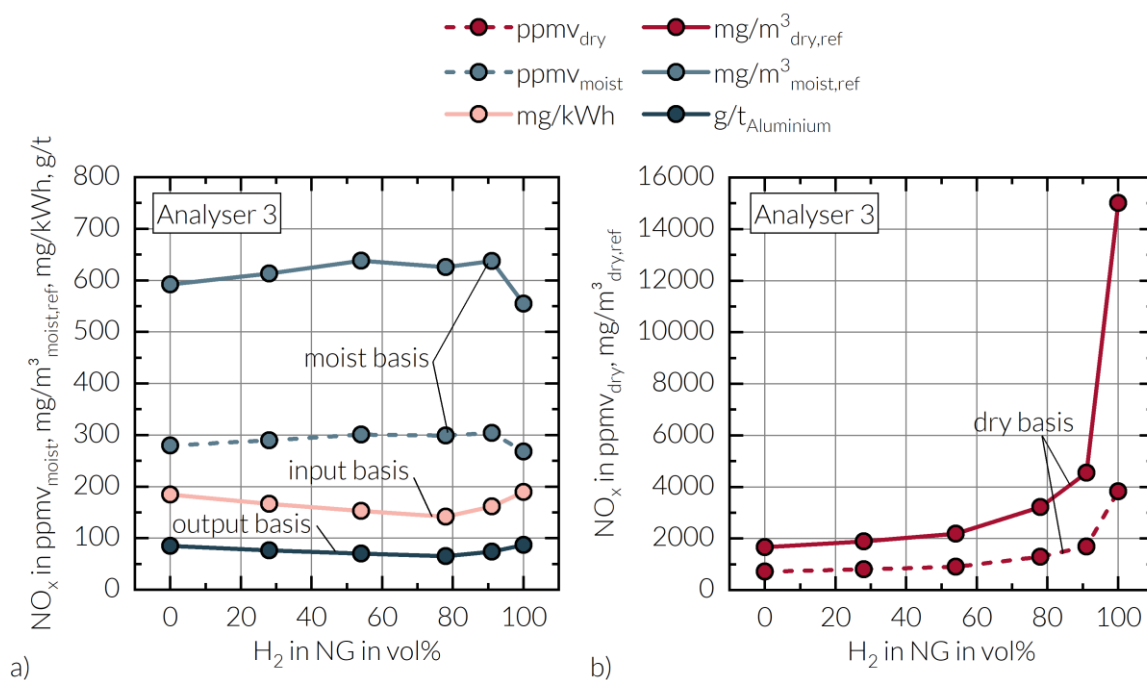


Figure 10.5: Comparison of different NO_x reporting approaches for the analyser 3 at the CTEC demonstrator a) on a moist basis and b) on a dry basis

The NO_x emissions reported on a moist basis, both as $\text{ppmv}_{\text{moist}}$ and as $\text{mg}/\text{m}^3_{\text{moist,ref}}$, show only a moderate variation over the investigated fuel range. The values slightly increase from pure natural gas combustion up to hydrogen fractions of approximately 90 vol% in the fuel and then decrease again for pure hydrogen combustion. In contrast, the values converted to a dry basis show a strong increase with increasing hydrogen content, especially above 80 vol% H₂. This trend is mainly caused by the increasing water vapour content in the off-gas, typical of hydrogen-oxyfuel combustion, as already discussed earlier. As a result, the NO_x values reported on a dry basis are approximately 2.8 times higher than the corresponding moist-basis values for pure natural gas combustion and up to about 27 times higher for pure hydrogen combustion. These values illustrate that dry-basis reporting becomes increasingly unintuitive for hydrogen oxyfuel combustion, where very high water vapour concentrations amplify the reported dry-based NO_x concentration.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

The same measurements are also expressed as input-based emissions in mg/kWh. These values are approximately three times lower than the values reported in $\text{mg/m}^3_{\text{moist,ref}}$. In contrast to the concentration-based values, the mg/kWh values show a decreasing trend up to hydrogen fractions of around 80 vol%, followed by an increase towards pure hydrogen combustion. Finally, the emissions are converted to product-related values in $\text{g/t}_{\text{Aluminium}}$. Numerically, these values correspond to approximately 0.46 times the corresponding values in mg/kWh, based on the specific energy demand of $460 \text{ kWh/t}_{\text{Aluminium}}$. Since the same specific energy demand is assumed for all fuel compositions, the product-based values necessarily follow the same trend as the input-based values. The comparison here therefore does not yet demonstrate the ability of the output-based metric to account for changes in process efficiency.

Demo 2: Pilot Walking Beam Furnace (SWERIM)

NO_x emissions at the SWERIM demonstrator are monitored using two gas analysers (Analysers 1 and 3), both operating on a wet basis. In addition, oxygen concentrations in the wet off-gas are continuously measured using Analysers 1 and 4, while the water vapour concentration is measured using Analyser 2. Analysers 1, 3 and 4 were based on in-situ measurements. Analyser 2 is originally designed for in-situ operation but was modified to enable hot-extractive measurements. An overview of the analyser specifications is given in Table 10.10.

Table 10.10: Overview of specifications of relevant analysers used at the SWERIM demonstrator for NO_x and O_2 measurements

Analyser	1	2	3	4
Manufacturer	Lamtec	EHS	EHS	EHS
Type	Sensor: KS2DNOx Control unit: NT1	GM35	GM32 (cross-duct)	ZIRKOR200
Measurement Basis	Wet	Wet	Wet	Wet
Sampling method	In-situ	Extractive	In-situ (cross-duct)	In-situ
Species measured	NO_x , O_2	CO_2 , CO , H_2O	NO , NO_2	O_2
Measurement principle	NO_x , O_2 : Solid-state electrolytic sensor	CO_2 , CO , H_2O : interference and gas filter correlation	NO , NO_2 : Differential optical absorption spectroscopy (DOAS)	O_2 : Zirconium dioxide sensor
Measuring range set	NO_x : 0...1,000 ppm O_2 : 0...10 vol%	CO_2 : 0...24 vol% CO : 0...1,500 ppm H_2O : 0... 100 vol%	NO : 0...350 ppm NO_2 : 0...300 ppm	O_2 : 0...25 vol%
Measurement uncertainty	NO_x : $\pm 10\%$ of measuring value, not better than ± 3 ppm O_2 : $\pm 8\%$ of measuring value, not better than ± 0.2 vol%	CO_2 , CO , H_2O : $\pm 2\%$ full scale value of the measuring range	NO , NO_2 : $\pm 2\%$ full scale value of measuring range	O_2 : $\pm 0.5\%$ of measuring value or ± 0.02 vol%
Calibration gases	Gas 1 for NO_x : 100 ppm NO , rest N_2 Gas 2 for O_2 : 3 vol% O_2 , rest N_2	Gas 1: 1,000 ppm CO , 5 vol% CO_2 , rest N_2	No	Gas 1: Instrument Air

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

Analysers 1 and 2 are installed in the furnace dark zone upstream of the off-gas outlet. Their probe tubes are inserted approximately 450 mm and 460 mm, respectively, from the inner furnace wall at an inclination of approximately 10°, with the probe tips located close to the off-gas outlet. In contrast, Analysers 3 and 4 are installed in the off-gas duct upstream of the heat exchanger, with the probe tips positioned in the centre of the duct. The sampling line of the hot-extractive analyser (Analyser 2) are approximately 40 m long and, together with the analyser measurement chamber, are heated to 180 °C to prevent water condensation.

During operation, the furnace pressure was approximately 1.3 mmWC, while the pressure in the off-gas duct was close to atmospheric pressure. Gas temperatures at the probe locations ranged between approximately 600 and 700 °C. All analysers were operated continuously throughout the measurement campaign, with measurement values recorded every 5 s. No filtering of the raw measurement data was applied.

The composition of the fuel oil is only approximately known, with an estimated carbon content of 85 wt.% to 87 wt.% and a hydrogen content of 12 wt.% to 14 wt.%. The NCV of the oil is specified as 11.7 kWh/kg by the operator. However, the exact fuel composition of the fuel oil not available. Consequently, the theoretical specific off-gas volume for the oil-fired operating conditions can only be estimated based on the available information. The oxygen purity is specified as >99.95 vol%. In addition, no data on the product output are available. As a result, the assessment is limited to a comparison of wet- and dry-basis concentration-based as well as input-based reporting approaches.

Four different fuel/oxidiser combinations were investigated: oil with air, H₂ with air, H₂ with oxygen-enriched air with 40 vol% O₂ and hydrogen with pure oxygen, as given in Table 10.11.

Table 10.11: Overview of operating conditions during the trials at the SWERIM demonstrator

Value	Unit	1	2	3	4
Thermal power	kW	1250	1116	924	878
Fuel	-	Fuel oil E01	H ₂	H ₂	H ₂
NCV of fuel	-	11,7 kWh/kg	3,00 kWh/m ³	3,00 kWh/m ³	3,00 kWh/m ³
Min. off-gas volume wet	-	11,66 m ³ _{og,wet} /kg _{fuel}	2,88 m ³ _{og,wet} /m ³ _{fuel}	1,75 m ³ _{og,wet} /m ³ _{fuel}	1,00 m ³ _{og,wet} /m ³ _{fuel}
O ₂ content in oxidiser	vol%	21	21	40	100
Air ratio	-	1,21	1,16	1,09	1,05
Spec. energy demand	kWh/t _{Steel}	N/A	N/A	N/A	N/A

Figure 10.6 compares the measured NO_x, O₂ and H₂O concentrations obtained with the different gas analysers installed at the SWERIM demonstrator. The values are plotted against the oxygen concentration in the oxidiser (21, 40 and 100 vol% O₂). As for the CTEC demonstrator and although all analysers operated on a wet basis, systematic differences between the measured values can be observed.

For the NO_x measurements (Figure 10.6a), Analyser 3 consistently reports higher NO_x concentrations than Analyser 1, particularly for hydrogen/air combustion. For oil/air combustion, the difference between both analysers is considerably smaller. For hydrogen combustion with oxygen-enriched air and pure oxygen, no data from Analyser 1 are available. In addition, the measured NO_x concentrations decrease significantly with increasing oxygen content in the oxidiser.

For the oxygen concentrations (Figure 10.6b), Analysers 1 and 4 show very similar values for oil-air combustion. However, when switching to hydrogen/air combustion, a systematic offset of approximately 1.3 vol% to 1.5 vol% O₂ can be observed, with Analyser 4 reporting consistently higher oxygen concentrations. Again, no data from Analyser 1 are available for hydrogen-oxyfuel combustion.

The measure water vapour concentration obtained with Analyser 2 are shown in Figure 10.6c. Values of approximately 0 vol% to 3 vol% are measured for combustion with air, around 10 vol% for oxygen-enriched combustion and around 48 vol% for oxyfuel combustion. These values are significantly lower than the

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

theoretical water vapour concentrations expected for hydrogen combustion of approximately 30 vol%, 53 vol% and 97 vol%, respectively. This discrepancy may be caused by air ingress into the sampling system, condensation of water vapour before the analyser or a malfunction of the measurement system.

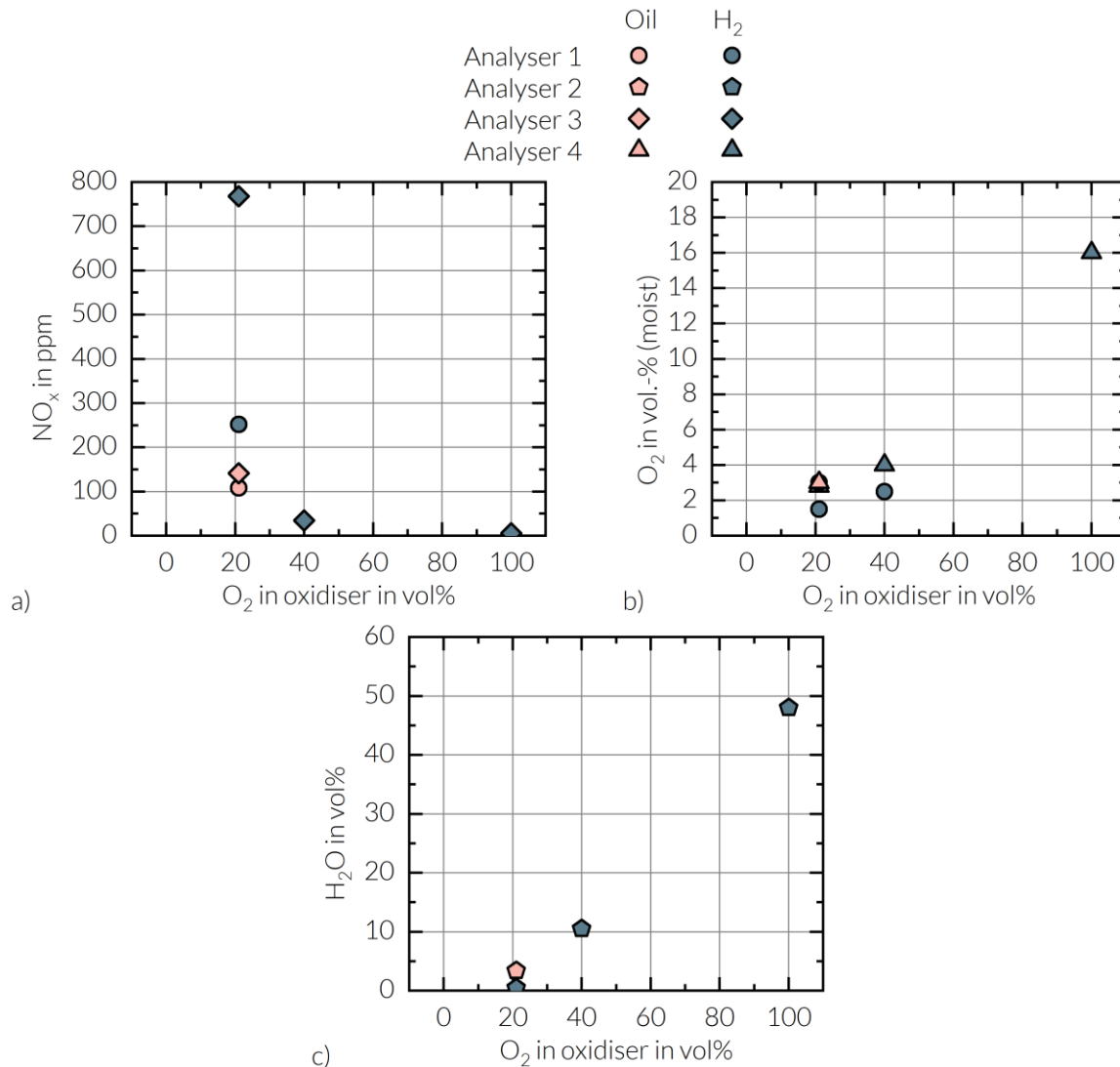


Figure 10.6: Comparison of a) NO_x values for the analysers 1 and 3 and b) O₂ values of the analysers 1 and 4 and c) H₂O values for the analyser 2 at the SWERIM demonstrator

As for the CTEC demonstrator, the different NO_x reporting approaches were subsequently applied to the available measurement data. For the comparison, the NO_x concentrations measured by Analyser 3 and the O₂ concentrations measured by Analyser 4 were used. Because the measured water vapour concentrations deviate significantly from the expected theoretical values, they were not used for the conversion of the reporting metrics. Instead, the theoretical water vapour concentrations were used for all subsequent calculations. In addition to the directly measured moist NO_x concentrations, the emissions were converted to dry-basis concentrations (ppmv_{dry} and mg/m³_{dry,ref}) corrected to a reference oxygen concentration of 3 vol%, moist-basis concentrations (ppmv_{moist} and mg/m³_{moist,ref}) corrected to a reference oxygen concentration of 2.5 vol%, and energy-related emissions expressed in mg/kWh. The results are shown in Figure 10.7.

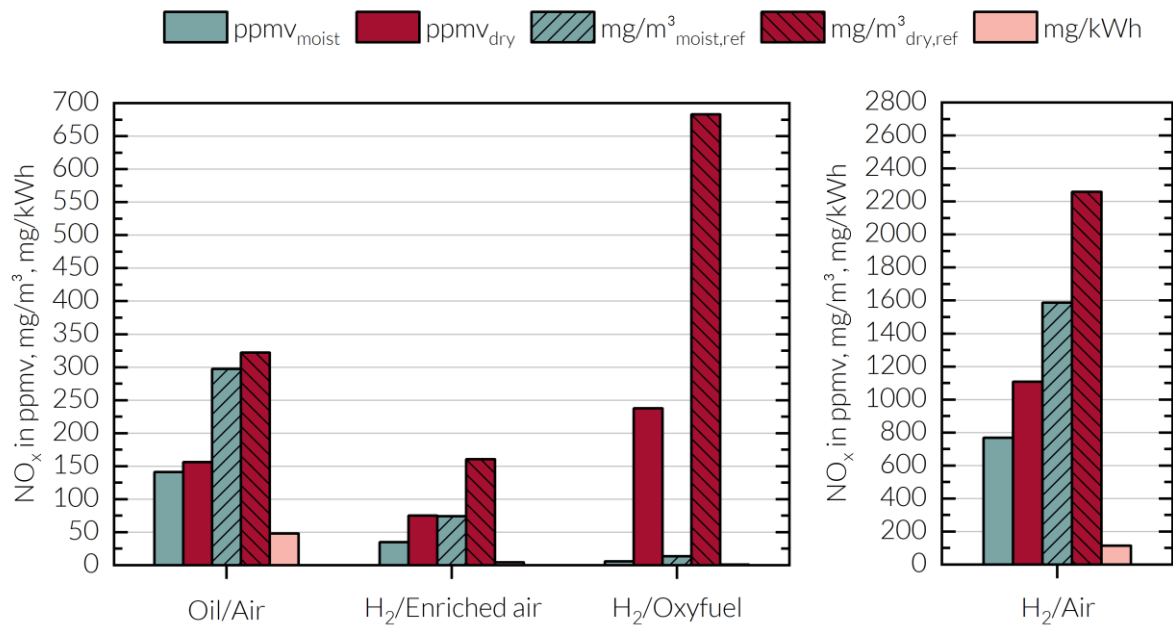


Figure 10.7: Comparison of different NO_x reporting approaches for the Analyser 3 at the SWERIM demonstrator

The different reporting approaches lead to different interpretations of the NO_x emissions. When reported on a moist basis, both in ppmv_{moist} and mg/m³_{moist,ref}, hydrogen-air combustion shows considerably higher NO_x emissions than oil/air combustion. Increasing the oxygen concentration in the oxidiser leads to a strong reduction in the measured NO_x emissions, with very low values obtained for hydrogen-oxyfuel combustion. The energy-related emissions (mg/kWh) show the same overall trend.

In contrast, the dry-basis reporting approaches provide a different trend for oxyfuel combustion. While the measured moist concentration is only 6 ppmv_{moist}, the corresponding dry concentration increases to almost 238 ppmv_{dry}, resulting in a dry concentration of approximately 683 mg/m³_{dry,ref}. Consequently, oxyfuel combustion appears to exhibit significantly higher NO_x emissions than suggested by the moist-basis and energy-related reporting approaches, and even higher than hydrogen combustion with oxygen-enriched air. This apparent increase is again caused by the very small dry off-gas volume during hydrogen-oxyfuel combustion and therefore illustrates the limitations of conventional dry-basis reporting for combustion systems producing high water vapour concentrations, as discussed in Section 10.3 and for the first demonstrator results.

10.7 Conclusions

This deliverable assessed the applicability of current and alternative NO_x reporting approaches to industrial combustion systems operating with natural gas, hydrogen and fuel mixtures, using air, oxygen-enriched air or pure oxygen as the oxidiser. The assessment combined a review of the limitations of current NO_x reporting approaches with an evaluation of alternative reporting approaches based on theoretical calculations. In addition, the different approaches were applied to measurement data from the CTEC and SWERIM demonstrators. The main findings can be summarised as follows:

- Limitations of current concentration-based reporting:**
 Current NO_x emission limits are expressed as **concentrations in the dry off-gas corrected to a defined reference oxygen concentration (mg/m³_{dry,ref})**. While this approach provides an established and comparatively simple framework for conventional air-fuel combustion, its interpretation **becomes increasingly difficult when the fuel or oxidiser composition changes**. Switching from natural gas to hydrogen in otherwise identical conditions changes both the composition with regard to water vapour and the specific volume of the off-gas. Consequently, identical dry NO_x concentrations may correspond to different absolute NO_x mass flows, making direct comparisons between different fuels potentially misleading. This limitation becomes particularly significant for pure hydrogen-oxyfuel combustion, where the off-gas consists predominantly of water vapour and only a very small dry off-gas volume remains. Under these conditions, reporting on a dry concentration-basis can strongly increase the emission values and challenge the assessment of the actual NO_x emissions.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

- Suitability of alternative reporting approaches:
 - Reporting NO_x concentrations on a **moist basis (mg/m³_{moist,ref})** reduces the influence of the high water vapour content associated with hydrogen combustion and remains applicable to hydrogen-oxyfuel systems. However, moist concentration-based values remain dependent on the total off-gas volume and therefore do not provide fully comparable values across all fuel and oxidiser combinations.
 - **Mass-flow-based metrics (mg/h, kg/year)** directly represent the absolute pollutant release but are strongly dependent on furnace capacity and thermal power.
 - **Output-based metrics (mg/t_{product}, mg/MJ_{useful heat})** directly relate the emissions to industrial production or useful process output and are also applicable to hybrid heating systems. However, their implementation requires clearly defined system boundaries and additional production data, making their standardisation across different sectors and applications challenging.
- Potential of input-based reporting and moist off-gas measurements:

Among the approaches investigated, **input-based metrics expressed in mg/kWh** provide the most consistent basis for comparing combustion systems operating with different fuels and oxidisers. The reverse calculations presented by Schmitz et al [32] show that identical NO_x mass flows at the same thermal input result in identical input-based emission values, independently of the fuel and oxidiser combination. Input-based reporting is therefore particularly suitable for fuel-flexible combustion systems and requires less process-specific information than output-based approaches. However, its implementation requires reliable information on the fuel composition, net calorific value and theoretical minimum moist off-gas volume. In addition, NO_x and O₂ concentrations should be measured in the moist off-gas to obtain a universal measurement methodology applicable to all fuel and oxidiser combinations, including pure hydrogen-oxyfuel combustion. Although moist concentrations can in principle be calculated from dry measurements if the water vapour content is known, this approach is not generally applicable where little or no dry off-gas is available.
- Application of the reporting approaches to the demonstrator data:

The available demonstrator results generally confirm the findings of the theoretical assessment. At both CTEC and SWERIM, conversion of the measured moist concentrations to a dry basis led to an increase in the reported NO_x values as the water vapour concentration increased. For hydrogen-oxyfuel combustion, dry-basis reporting resulted in a different interpretation of the emissions compared with moist-basis and input-related or output-related reporting. The comparison of the installed analysers also revealed systematic differences in measured NO_x and O₂ concentrations, despite operation under nominally identical conditions.

Overall, input-based reporting combined with measurements in the moist off-gas appears to be the most suitable approach for comparing future combustion systems operating with different fuels and oxidisers. It provides better comparability than concentration-based reporting while requiring less process-specific information than output-based approaches. Output-based metrics may additionally be relevant for sector-specific assessments and hybrid heating systems but would require separate definitions for individual processes and sectors.

11 Bibliography

- [1] European Aluminium Agency, Methodological guidance for the environmental assessment of aluminium intermediate and semi-finished products, www.european-aluminium.eu, 2023.
- [2] N. Santero, J. Hendry, Harmonization of LCA methodologies for the metal and mining industry, *Int J Life Cycle Assess* 21 (2016) 1543–1553.
- [3] International Energy Agency (IEA), Electricity generation sources, Greece, 2024, 2025, <https://www.iea.org/countries/greece/electricity>, accessed 25 March 2026.
- [4] International Energy Agency (IEA), Largest sources of electricity generation in Spain, 2024, 2024, <https://www.iea.org/countries/greece/electricity>, accessed 22 February 2026.
- [5] International Energy Agency (IEA), Largest sources of energy in France, 2024, 2024, <https://www.iea.org/countries/france/energy-mix>, accessed 2 March 2026.
- [6] C. Schmitz (Ed.), Handbook of aluminium recycling: Mechanical preparation, metallurgical processing, heat treatment, 2nd ed., Vulkan-Verl., Essen, 2014.
- [7] ISO 13579-3:2013, Industrial furnaces and associated processing equipment - Method of measuring energy balance and calculating efficiency - Part 3: Batch-type aluminium melting furnace, 2013.
- [8] J. Leicher, A. Giese, C. Wieland, Electrification or Hydrogen? The Challenge of Decarbonizing Industrial (High-Temperature) Process Heat, *J 7* (2024) 439–456.
- [9] E. Busson, M. Sanders, N. Schmitz, M. Mühlbach, J. Wünnig, C. Wuppermann, in: R. Reis (Ed.), 15th European conference on industrial furnaces and boilers, 2026.
- [10] Destatis. Statistisches Bundesamt, Electricity production in the first quarter of 2025 (in german), 2025, https://www.destatis.de/DE/Presse/Pressemitteilungen/2025/06/PD25_200_43312.html, accessed 25 May 2026.
- [11] Swiss centre for Life Cycle Inventories, Ecoinvent database, 2025.
- [12] Danish Energy Agency, Technology Data for Renewable Fuels, 2026.
- [13] M. Gardiner, DOE Hydrogen and Fuel Cells Program Record, 2009, <https://www.hydrogen.energy.gov/>.
- [14] European Hydrogen Observatory, The hydrogen landscape at a glance, 2026, <https://observatory.clean-hydrogen.europa.eu/>.
- [15] IMARC, Oxygen Prices, Trend, Chart, Demand, Market Analysis, News, Historical and Forecast Data Report 2026 Edition, 2026, <https://www.imarcgroup.com/oxygen-pricing-report>.
- [16] Claight corporation, Nitrogen Pricing, Demand and Supply Overview, 2026, <https://www.expertmarketresearch.com/price-forecast/nitrogen-price-trends>.
- [17] IMARC, Argon Prices, Trend, Chart, Demand, Market Analysis, News, Historical and Forecast Data Report 2026 Edition, 2026, <https://www.imarcgroup.com/argon-pricing-report>.
- [18] L. Hooey, A. Boden, M. Larssib, M. Knights, J. Johns, V. Abraham, A. Tobiesen, Hoffm K.A., G. Haugen, S. Goldthorpe, Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill), 2013, <https://ieaghg.org/publications/iron-and-steel-ccs-study-techno-economics-integrated-steel-mill/>.
- [19] Eurostat, Gross electricity production by fuel, EU, 2000-2024, 2025, <https://ec.europa.eu/eurostat/statistics-explained/>, accessed 1 July 2026.
- [20] European Parliament and the council, Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control), 2010.
- [21] E. Aries, J. Gómez Benavides, S. Mavromatis, G. Klein, G. Chronopoulos, S. Roudier, Best available techniques (BAT) reference document for the ferrous metals processing industry Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control), Publications Office of the European Union, 2022.
- [22] G. Cusano, L. Delgado Sancho, F. Farrell, M. Rodrigo Gonzalo, S. Roudier, Best available techniques (BAT) reference document for the non-ferrous metals industries: Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control), Publications Office of the European Union, 2017.

D7.2 Report on the LCAs of the developed technologies in industrial plant environment

- [23] DIN Deutsches Institut für Normung e. V., Stationary source emissions - Determination of mass concentration of nitrogen oxides - Standard reference method: chemiluminescence, Beuth Verlag, Berlin, Germany, 2017.
- [24] DIN Deutsches Institut für Normung e. V., Stationary source emissions - Quality assurance of automated measuring systems, Beuth Verlag, Berlin, Germany, 2015.
- [25] DIN Deutsches Institut für Normung e. V., Air quality - Certification of automated measuring systems - Part 1: General principles, Beuth Verlag, Berlin, Germany, 2009.
- [26] DIN Deutsches Institut für Normung e. V., Air quality - Certification of automated measuring systems - Part 2: Initial assessment of the AMS manufacturer's quality management system and post certification surveillance for the manufacturing process, Beuth Verlag, Berlin, Germany, 2009.
- [27] DIN Deutsches Institut für Normung e. V., Air quality - Certification of automated measuring systems - Part 3: Performance criteria and test procedures for automated measuring systems for monitoring emissions from stationary sources, Beuth Verlag, Berlin, Germany, 2008.
- [28] DIN Deutsches Institut für Normung e. V., Air quality - Certification of automated measuring systems - Part 4: Performance criteria and test procedures for automated measuring systems for periodic measurements of emissions from stationary sources, Beuth Verlag, Berlin, Germany, 2017.
- [29] DIN Deutsches Institut für Normung e. V., Stationary source emissions – Determination of volume concentration of oxygen – Standard reference method: Paramagnetism, Beuth Verlag, Berlin, Germany, 2017.
- [30] International Organization for Standardization, Stationary source emissions – Determination of the mass concentration of carbon monoxide, carbon dioxide and oxygen in flue gas – Performance characteristics of automated measuring systems, 2nd ed., ISO, Geneva, 2019.
- [31] N. Schmitz, L. Sankowski, E. Busson, T. Echthor, H. Pfeifer, NO_x Emission Limits in a Fuel-Flexible and Defossilized Industry—Quo Vadis?, *Energies* 16 (2023) 5663.
- [32] N. Ripoll Kameid, H. ApSimon, Pollutant reporting protocols for low-carbon and carbon-free fuels combustion: A review on current challenges and progress, *International Journal of Hydrogen Energy* 143 (2025) 550–560.
- [33] German Environment Agency, Reinhaltung der Luft/Luftüberwachung in Deutschland - Messeinrichtungen: Eignungsgeprüfte kontinuierlich arbeitende Emissionsmesseinrichtungen - Messobjekt: Feuchte, Dessau-Rosslau, Germany, 2021.
- [34] Community Research and Development Information Service (CORDIS), Hydrogen technologies for decarbonization of industrial heating processes (HyInHeat) - Fact Sheet, Publications Office of the European Union, Brussels, Belgium, 2023.
- [35] DIN Deutsches Institut für Normung e. V., Forced draught burners for liquid fuels, Beuth Verlag, Berlin, Germany, 2021.
- [36] DIN Deutsches Institut für Normung e. V., Forced draught burners for gaseous fuels, Beuth Verlag, Berlin, Germany, 2023.
- [37] DIN Deutsches Institut für Normung e. V., Natural gas - Calculation of calorific values, density, relative density and Wobbe indices from composition, Beuth Verlag, Berlin, Germany, 2016.

12 Annex

12.1 Annex A: Umberto 11® model from baseline of case 1

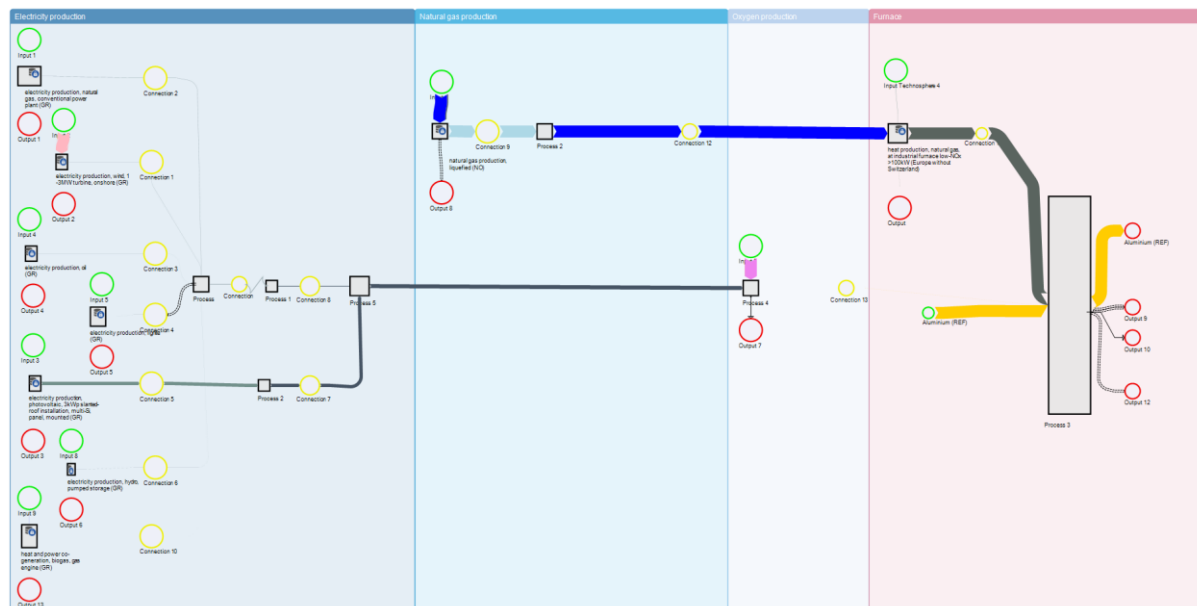


Figure 12.1: Model from the software Umberto 11® for the baseline in case 1

12.2 Annex B: Umberto 11® model from scenario 1 of case 1

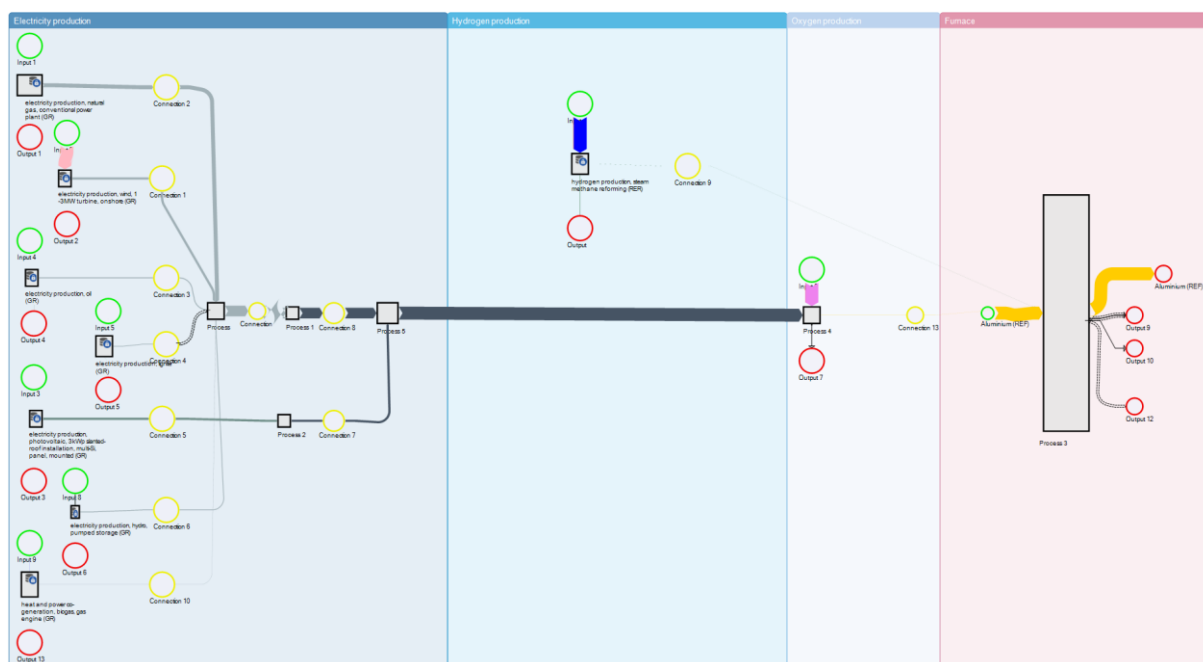


Figure 12.2: Model from the software Umberto 11® for the hydrogen combustion in case 1



12.4 Annex D: Umberto 11® model from scenario 1 of case 2

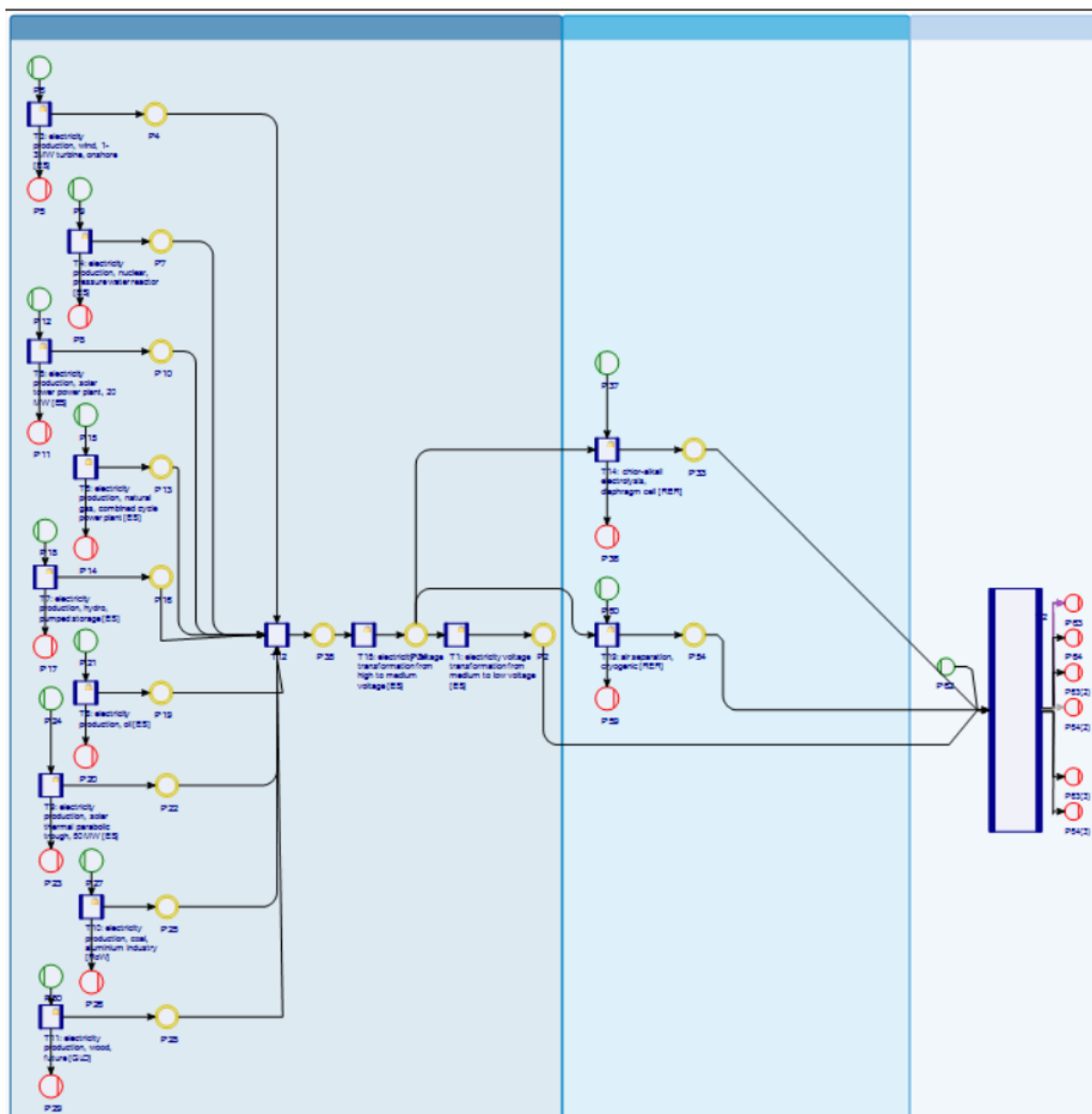


Figure 12.4: Model from the software Umberto 11® for the scenario 1 in case 2

12.5 Annex E: Umberto 11® model from the baseline of case 3

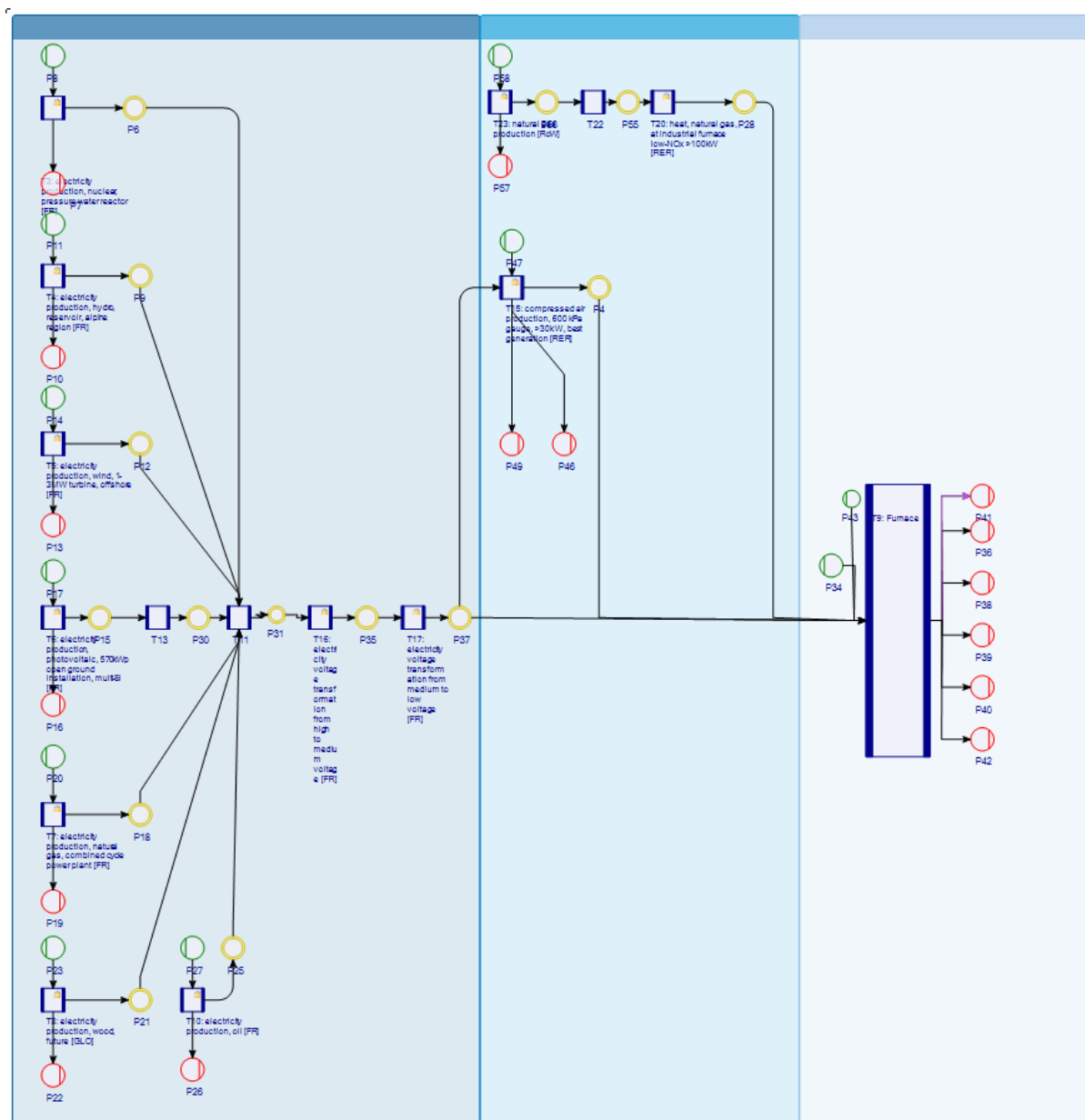


Figure 12.5: Model from the software Umberto for the baseline in case 3

12.6 Annex F: Umberto 11® model from scenario 1 of case 3

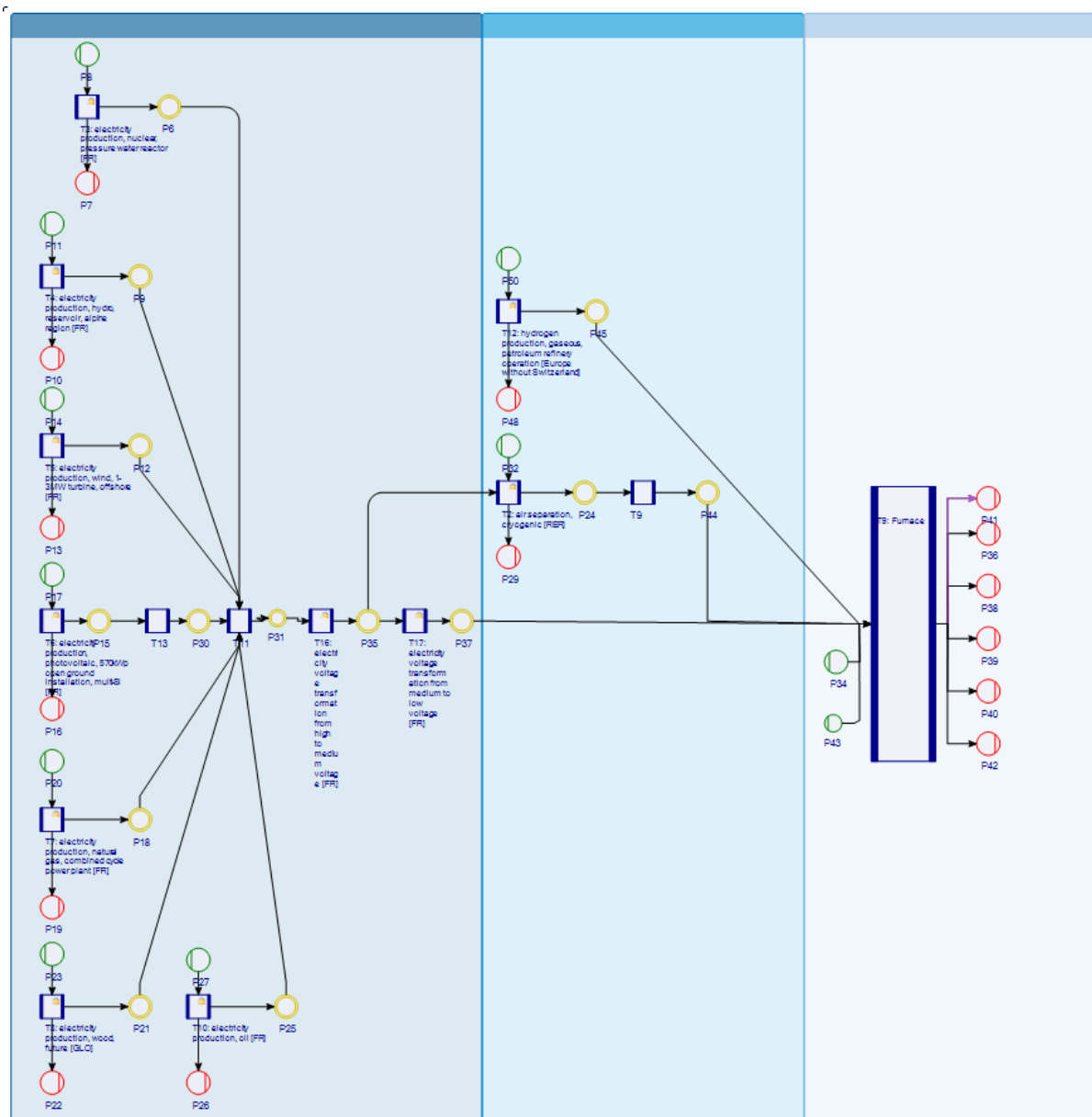


Figure 12.6: Model from the software Umberto 11® for the scenario 1 in case 3

12.7 Annex G: Umberto 11® model from baseline of case 4

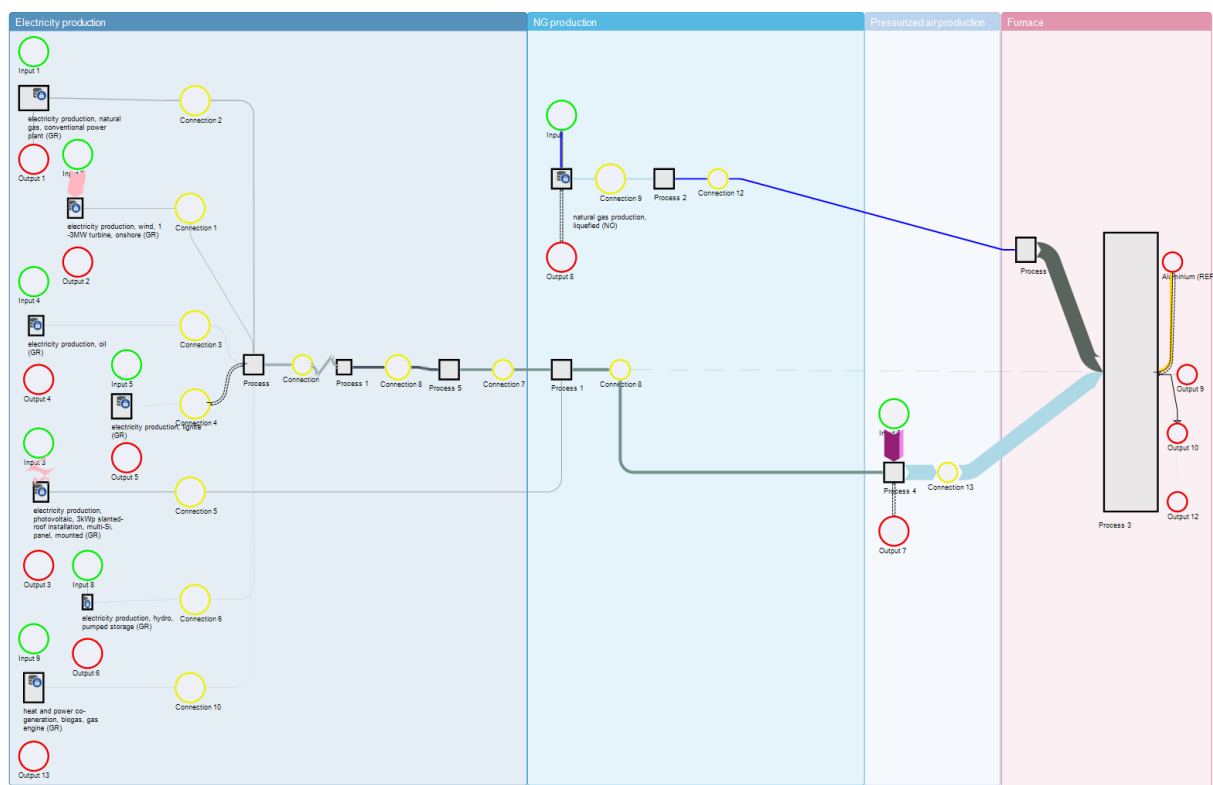


Figure 12.7: Model from the software Umberto 11® for the baseline of case 4

12.8 Annex J: Umberto 11® model from scenario 1 of case 4

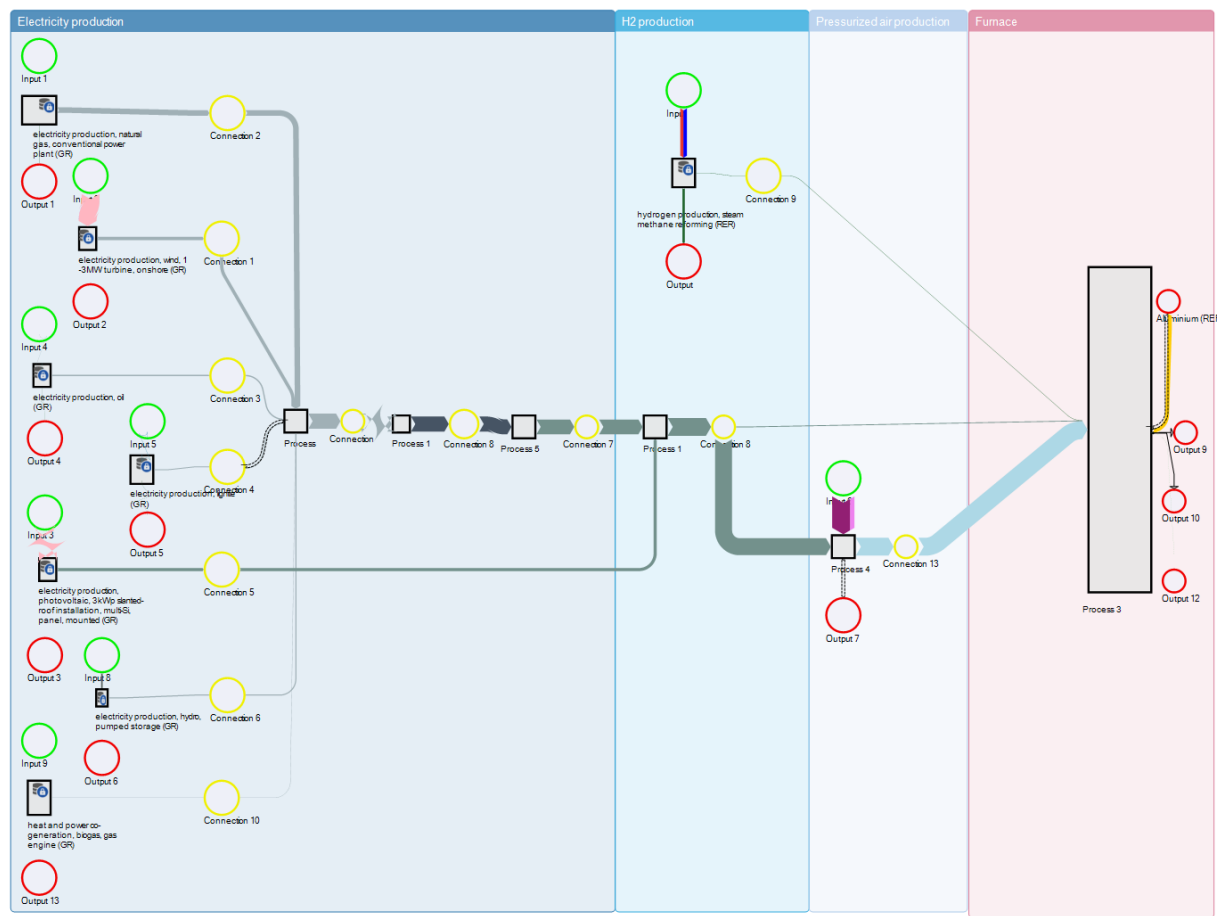


Figure 12.8: Model from the software Umberto 11® for the H2/air combustion of case 4

12.9 Annex K: Umberto 11® model from scenario 2 of case 4

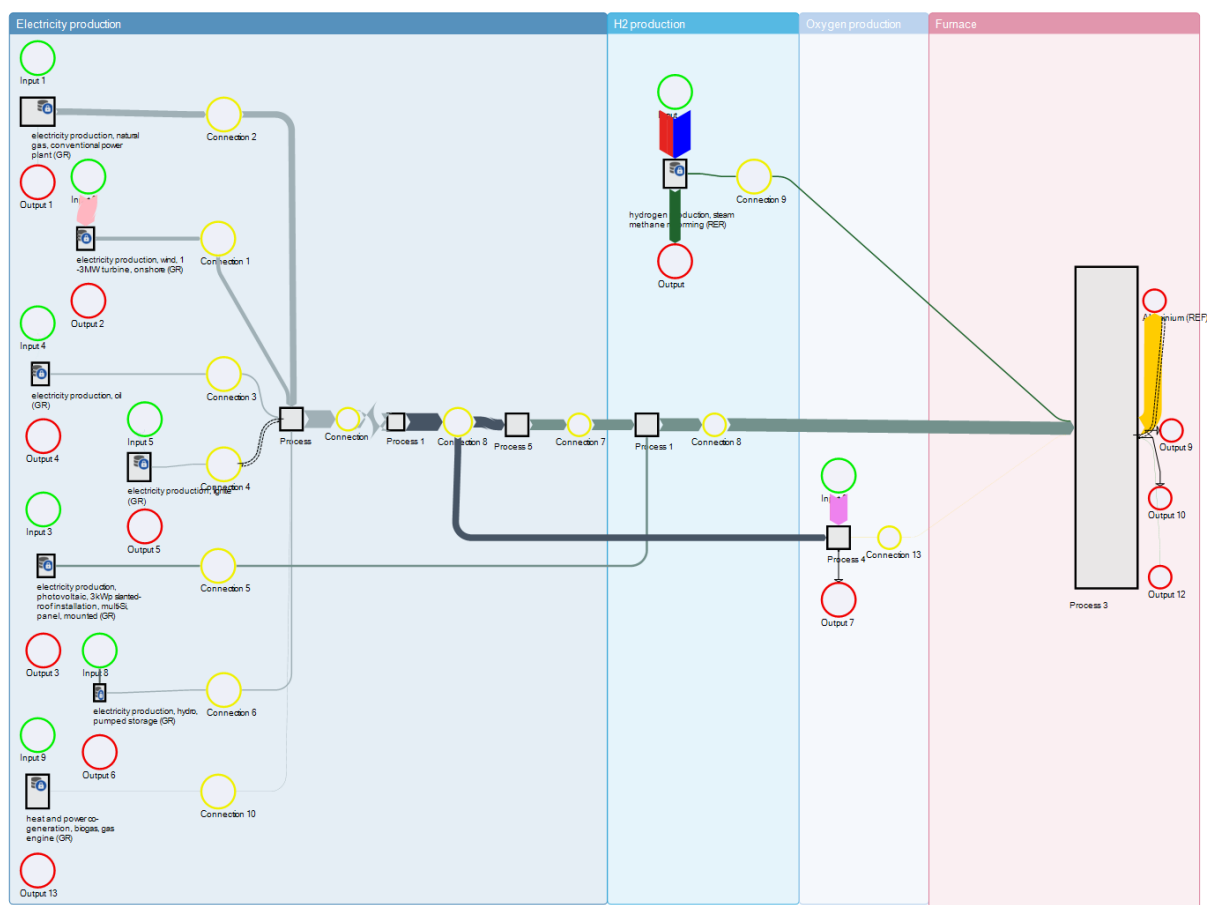


Figure 12.9: Model from the software Umberto 11® for the hydrogen oxycombustion scenario in case 4

12.10 Annex L: Umberto 11® model from baseline of case 5

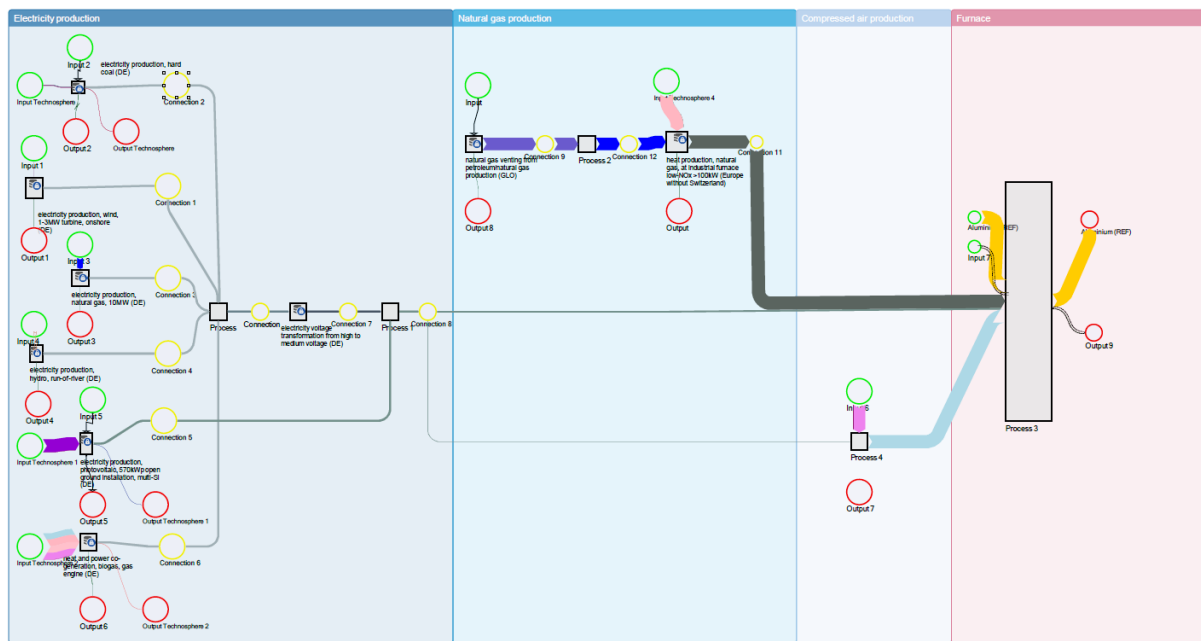


Figure 12.10: Model from the software Umberto 11® for the baseline in case 5

12.11 Annex M: Umberto 11® model from scenario 1 of case 5

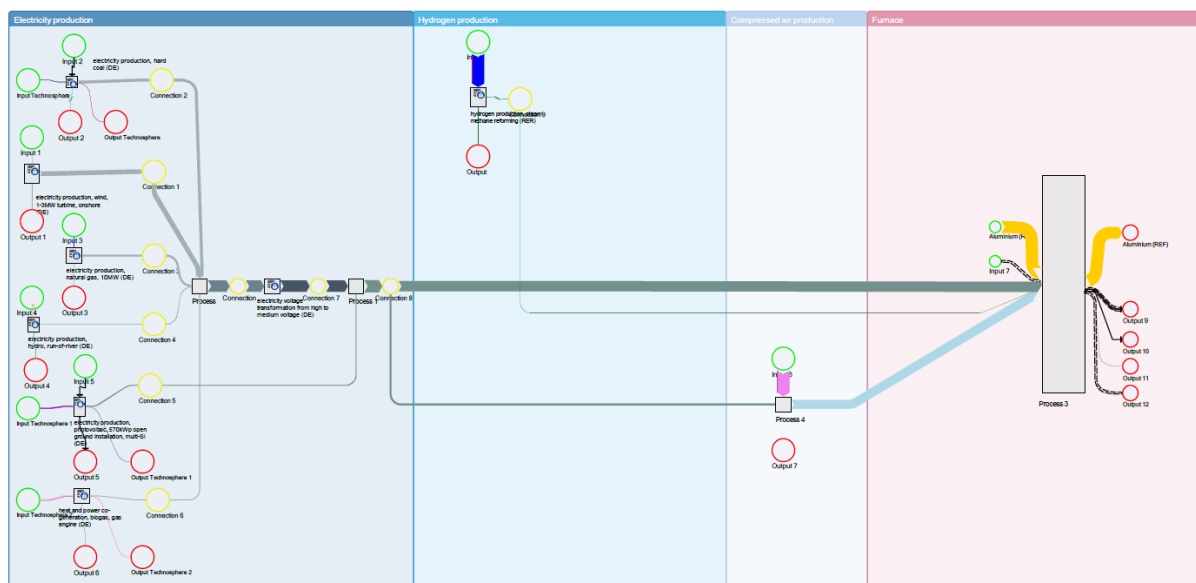


Figure 12.11: Model from the software Umberto 11® for the scenario 1 in case 5

12.12 Annex N: Sphera LCA Expert model for Case 6

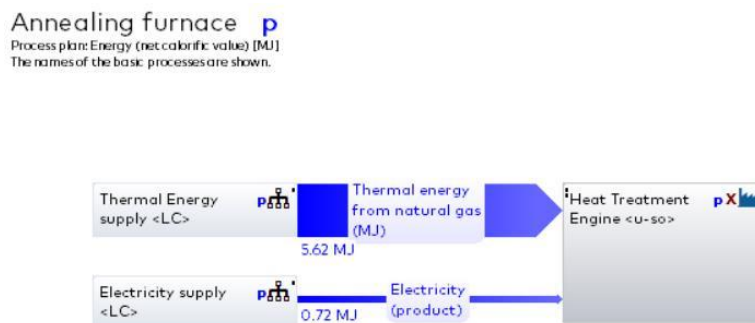


Figure 12.12 Model from Sphera LCA Expert 2026 for case 6 (Annealing Furnace)

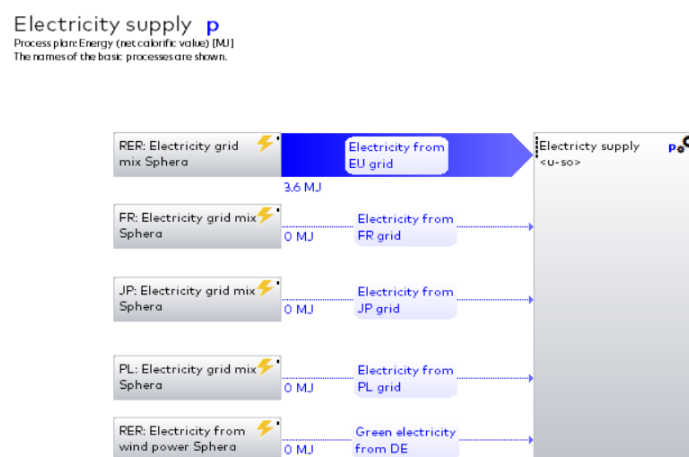


Figure 12.13 Model from Sphera LCA Expert 2026 for case 6 for electricity supply

Get in touch

Website

<http://hyinheat.eu/>

Email address

info@hyinheat.eu

