Environmental impacts of NO_X reduction technologies in Waste to Energy facility in United States

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Executive Summary

The most widely used alternative to landfill of residual municipal solid waste (MSW) is combustion for production of energy, i.e. Waste to Energy (WtE). The waste is used as fuel to produce heat and generate electricity. In 2015 about 250 million tons of MSW were processed globally in the over 1,000 WTE facilities (Nixon et al., 2013). The nitrogen content of MSW is relatively low, with its main sources being textiles, leather, rubber, and proteins from food waste; and ranges between 0.1% and 1.3 mass% (dry basis) (Harris et al., 2015; Guiterrez et al., 2005).

The N_2 during combustion is converted to nitrogen-containing pollutants, primarily NO (Van Caneghem et al., 2016; Zeldovich J., 1946), and other compounds, such as NO_2, N_2O, NH_3, and HCN (Van Caneghem et al., 2016; Basu, 2007). The pollutant species formed during combustion of MSW depends principally on the temperature and fuel/oxygen ratio in the combustion zone (De Greef et al., 2013). NOx contributes to acid rain, eutrophication, the formation of ozone and photochemical smog. Because NOx is transparent to most wavelengths of light, it allows the vast majority of photons to pass through with a lifetime of at least several days (European Environment Agency, 2015).

To protect human health and the environment from the negative effects of NOx, Directive 2010/ 75/EU on industrial emissions (IED) and the Maximum Achievable Control Equipment (MACT) in the US implements emission limit values (ELVs) for NOx, which differs based on the type of combustion plants. For waste combustion plants the ELV is 200 mg/Nm^3 (European Commission, US EPA).

WTE plants operate with primary and secondary measures for NOx destruction that takes place in the combustion occurring during the first pass in the boiler. Primary measures include air or fuel staging. Two techniques widely applied in WTE plants are the low NOx (LN) and the very low NOx (VLN) technologies. The main difference is the distribution of air, where in the VLN technique uses less air in the first pass of the boiler, and therefore less NOx is produced. In addition, VLN is typically used in new installations, while LN is mainly for retrofits.

The aim of this paper is to compare the environmental impact of the use of SNCR, LN/SNCR and SCR in WTE plants by using life cycle analysis. The aim of this paper is to compare the environmental and cost impacts of several SNCR techniques and SCR by using Life cycle analysis. The parameters considered, which is the novelty of the research paper, consists of the system pressure drop, ammonia slip, and its requirements to meet the ELV.

It was assumed that the initial feedstock produces 300ppm NO_X@7% O_2. Three scenarios were assessed, with regard to the reduction potential of each system.

- 150ppmdv NO_X@7% O_2 by Selective Non-Catalytic Reduction (SNCR) only
- 80ppmdv NO_X@7% O_2 by Low NO_X technologies followed by SNCR (LN/SNCR)
- 45ppmdv NO_X@7% O_2 by tail end Selective Catalytic Reduction (SCR) only

The key findings of this study were:

- LN/SNCR has shown the best environmental performance amongst the three technologies
- For SNCR and LN/SNCR, the reagent production and the flue gas emission to ambient air after the APC system are the two main categories that influence the environmental impact, while reheating of the flue gas is the major contribution to the environment for the SCR system.
- Fuel selection has a significant impact in the overall environmental performance of the SCR system. Natural gas would provide SCR with the best environmental performance followed by MSW incineration in second place.
- SCR with natural gas as reheating source has the best performance in mitigating the negative environmental impact compared to LN/SNCR and SNCR
- Adjusting the operating conditions in SCR, particularly reducing the operating temperature or recovering waste heat, would reduce the negative impact from resource depletion and global warming. However, the mitigated negative environmental impact is still higher than SNCR and LN/SNCR.

Contents

1 Introduction 2
  1.1 Legislation 2
  1.2 NO_X formation 4
  1.3 NO_X control techniques 8
    1.3.1 Primary measures 8
    1.3.2 Secondary method 11
  1.4 SCR 15
    1.4.1 Catalyst volume estimation 16
    1.4.2 SCR Size estimation 19
    1.4.3 Pressure drop and energy for Induced fan 20
2 Methodology 21
  2.1 Definition of goal and scope 21
  2.2 Life cycle inventories 26
    2.2.1 Production of materials 26
    2.2.2 Transportation of materials 29
    2.2.3 Operation 29
  2.3 Life cycle impact assessment (LCIA) 31
3 Life cycle impact analysis 32
  3.1 Overview 32
  3.2 Unit process and components 33
  3.3 Sensitivity analysis 46
    3.3.1 Sensitivity analysis for fuel type 46
    3.3.2 Sensitivity analysis for operating temperature and energy recovery 48
4 Discussion 60
5 Conclusions 64
References 65

List of Figures

FIGURE 1.1 SUMMARY FOR FUEL NO FORMATION PROCESS 6
FIGURE 1.2 EMISSION OF THE NO AS A FUNCTION OF TOTAL EXCESS AIR WITH DIFFERENT PROPOSED MSW IN DIFFERENT COMPOSITION 6
FIGURE 1.3 EMISSION OF NO AS A FUNCTION OF TOTAL EXCESS AIR 7
FIGURE 1.4 BRUTO-NO_X VALUES AS FUNCTION OF THERMAL LOAD OF BOILER 7
FIGURE 1.5 SCHEME OF STAGED COMBUSTION 9
FIGURE 1.6 NO_X FORMATION VERSUS THERMAL LOAD 10
FIGURE 1.7 REACTION PATHS OF NH_3 AND NO 11
FIGURE 1.8 SNCR VERSUS TEMPERATURE WITH AMMONIA AS REAGENT 13
FIGURE 1.9 SNCR VERSUS TEMPERATURE WITH UREA AS REAGENT 13
FIGURE 1.10 NO_X REDUCTION EFFICIENCY VERSUS AMMONIA SLIP 13
FIGURE 1.11 NO_X REDUCTION EFFICIENCY VERSUS NSR 13
FIGURE 1.12 NO_X REMOVAL EFFICIENCY WITH SNCR DEPENDING ON TEMPERATURE AND NSR 14
FIGURE 1.13 14
FIGURE 1.14 14
FIGURE 1.15 16
FIGURE 1.16 16
FIGURE 1.17 NO_X REMOVAL EFFICIENCY VERSUS TEMPERATURE 16
FIGURE 1.18 NO_X REMOVAL EFFICIENCY VERSUS SPACE VELOCITY CONSIDERING MOLAR RATIO [20] 17
FIGURE 2.1 PROCESS FLOW DIAGRAM FOR NO_X FLOW IN SNCR 24
FIGURE 2.2 PROCESS FLOW DIAGRAM FOR NO_X FLOW IN LN/SNC 24
FIGURE 2.3 PROCESS FLOW DIAGRAM FOR NO_X FLOW IN SCR 25
FIGURE 2.4 MASS FLOW DIAGRAM FOR SNCR 25
FIGURE 2.5 MASS FLOW DIAGRAM FOR LN/SNCR 25
FIGURE 2.6 MASS FLOW DIAGRAM FOR SCR 25
FIGURE 3.1 CHARACTERIZATION RESULTS OF SCENARIOS COMPARED TO UNTREATED GAS (CML 2 BASELINE 2000) 36
FIGURE 3.2 CHARACTERIZATION RESULTS OF SCENARIOS COMPARED TO UNTREATED GAS (TRACI) 37
FIGURE 3.3 PROPORTION OF CHARACTERIZATION RESULTS IN EACH UNIT PROCESS (CML 2 BASELINE 2000) 38
FIGURE 3.4 PROPORTION OF CHARACTERIZATION RESULTS IN EACH UNIT PROCESS (TRACI) 39
FIGURE 3.5 PROPORTION OF CHARACTERIZATION RESULTS IN EACH COMPONENT (CML 2 BASELINE 2000) 40
FIGURE 3.6 PROPORTION OF CHARACTERIZATION RESULTS IN EACH COMPONENT (TRACI) 41
FIGURE 3.7 PROPORTION OF CHARACTERIZATION RESULTS FOR SNCR (CML) 42
FIGURE 3.8 PROPORTION OF CHARACTERIZATION RESULTS FOR LN/SNCR (CML) 42
FIGURE 3.9 PROPORTION OF CHARACTERIZATION RESULTS FOR SNCR MANUFACTURE (CML) 42
FIGURE 3.10 PROPORTION OF CHARACTERIZATION RESULTS FOR LN/SNCR MANUFACTURE (CML) 42

FIGURE 3.11 PROPORTION OF CHARACTERIZATION RESULTS FOR SNCR OPERATION (CML).............................42
FIGURE 3.12 PROPORTION OF CHARACTERIZATION RESULTS FOR LN/SNCR (CML).............................42
FIGURE 3.13 PROPORTION OF CHARACTERIZATION RESULTS FOR SCR (CML).............................43
FIGURE 3.14 PROPORTION OF CHARACTERIZATION RESULTS FOR SCR MANUFACTURE (CML).............................43
FIGURE 3.15 PROPORTION OF CHARACTERIZATION RESULTS FOR SCR OPERATION (CML).............................43
FIGURE 3.16 PROPORTION OF CHARACTERIZATION RESULTS FOR SNCR (TRACI).............................44
FIGURE 3.17 PROPORTION OF CHARACTERIZATION RESULTS FOR LN/SNCR (TRACI).............................44
FIGURE 3.18 PROPORTION OF CHARACTERIZATION RESULTS FOR SNCR MANUFACTURE (TRACI).............................44
FIGURE 3.19 PROPORTION OF CHARACTERIZATION RESULTS FOR LN/SNCR MANUFACTURE (TRACI).............................44
FIGURE 3.20 PROPORTION OF CHARACTERIZATION RESULTS FOR SNCR OPERATION (TRACI).............................44
FIGURE 3.21 PROPORTION OF CHARACTERIZATION RESULTS FOR LN/SNCR (TRACI).............................44
FIGURE 3.22 PROPORTION OF CHARACTERIZATION RESULTS FOR SCR (TRACI).............................45
FIGURE 3.23 PROPORTION OF CHARACTERIZATION RESULTS FOR SCR MANUFACTURE (TRACI).............................45
FIGURE 3.24 PROPORTION OF CHARACTERIZATION RESULTS FOR SCR OPERATION (TRACI).............................45
FIGURE 3.25 CHARACTERIZATION RESULTS FOR SCR OPERATION WITH DIFFERENT HEATING ENERGY SOURCES (CML 2 BASELINE 2000).............................50
FIGURE 3.26 CHARACTERIZATION RESULTS FOR SCR OPERATION WITH DIFFERENT HEATING ENERGY SOURCES (TRACI).............................51
FIGURE 3.27 CHARACTERIZATION RESULTS FOR SCR OPERATION WITH DIFFERENT HEATING ENERGY SOURCES IN A PERCENTAGE VIEW DETAILED IN COMPONENT (CML).............................52
FIGURE 3.28 CHARACTERIZATION RESULTS FOR SCR OPERATION WITH DIFFERENT HEATING ENERGY SOURCES IN A PERCENTAGE VIEW DETAILED IN COMPONENT (TRACI).............................53
FIGURE 3.29 CHARACTERIZATION RESULTS FOR SNCR, LN/SNCR, SCR WITH NATURAL GAS, SCR WITH MSW INCINERATION AND UNTREATED GAS (CML).............................54
FIGURE 3.30 CHARACTERIZATION RESULTS FOR SNCR, LN/SNCR, SCR WITH NATURAL GAS, SCR WITH MSW INCINERATION AND UNTREATED GAS (TRACI).............................55
FIGURE 3.31 NORMALIZATION RESULTS FOR SCENARIOS WITH SCR IN NATURAL GAS AND MSW INCINERATION FOR HEATING AND COMPARED TO UNTREATED GAS (CML).............................56
FIGURE 3.32 NORMALIZATION RESULTS FOR SCENARIOS WITH SCR IN NATURAL GAS AND MSW INCINERATION FOR HEATING AND COMPARED TO UNTREATED GAS (TRACI).............................57
FIGURE 3.33 NORMALIZATION RESULT FOR SCR OPERATING WITH DIFFERENT OPERATING TEMPERATURE (TRACI)..58
FIGURE 3.34 NORMALIZATION RESULT FOR SCR OPERATING WITH ENERGY RECOVERY.............................59
FIGURE 4.1 THE WEIGHTED ENVIRONMENTAL POTENTIALS OF SCENARIOS GIVEN BY LIANG ET AL.............................63
FIGURE 4.2 INFLUENCE OF NO_X REDUCTION SYSTEM ON EFFICIENCY.............................63

List of Tables

TABLE 1.1 LEGISLATION FOR AIR EMISSION FOR MUNICIPAL WASTE INCINERATION 2

TABLE 1.2 NO_X EMISSIONS LIMIT FOR EXISTING LMWC IN VARIOUS TYPE OF COMBUSTOR BASED ON 3

TABLE 2.1 OPERATING CONDITIONS FOR SCENARIOS IN HYPOTHETIC WTE PLANTS IN U.S. 23

TABLE 2.2 THE SCR DESIGN SPECIFICATION 28

TABLE 2.3 MATERIALS MANUFACTURE FOR SCENARIOS 28

TABLE 2.4 TRANSPORTATION FOR SCENARIOS..29

TABLE 2.5 OPERATION FOR SCENARIOS 30

TABLE 2.6 INFORMATION ABOUT METHODOLOGIES APPLIED IN THIS STUDY 31

TABLE.3.1 CHARACTERIZATION RESULTS OF SCENARIOS COMPARED TO UNTREATED GAS (CML) 35

TABLE 3.2 CHARACTERIZATION RESULTS OF SCENARIOS COMPARED TO UNTREATED GAS (TRACI)..................35

TABLE 3.3 CHARACTERIZATION RESULTS FOR SCR IN COMPOSITION (CML) 43

TABLE 3.4 CHARACTERIZATION RESULTS FOR SCR IN COMPOSITION (TRACI)...45

TABLE 4.1 CHARACTERIZATION RESULT FROM CML METHODOLOGY 62

TABLE 4.2 CHARACTERIZATION RESULT FROM TRACI METHODOLOGY 62

TABLE 4.3 NORMALIZATION RESULT FROM CML METHODOLOGY...63

TABLE 4.4 NORMALIZATION RESULT FROM TRACI METHODOLOGY 63

1 Introduction

The emission of NO_X, a byproduct of combustion processes, has been the focus of research and environmental studied in recent decades due to its undeniable influence on acidification, eutrophication, global warming and health hazard. NO_X is the generic term for nitrogen oxides which could be formed as nitric oxide (NO), nitrogen dioxide (NO_2) and nitrous oxide (N_2O) during the process of waste combustion [1]. About 95% of NO_X from waste incineration is present in the form of NO, but the emission limit of NO_X given and applied is converted from NO_2 value. Shortly after emission to the atmosphere, the relatively harmless NO gas would be oxidized by ozone or oxygen in air to form a brown, irritating and acidic gas of NO_2 within a few minutes to hours. NO_2 would further react with hydroxyl radicals to form nitric acid that contributes to acid rain and eutrophication. [2, 3] In addition, nitrogen oxides also play an important role in global warming according by reacting with volatile organic carbons (VOC) to further form photochemical smog causing global warming and a health hazard. [1]

1.1 Legislation

Table 1.1 Legislation for air emission for municipal waste incineration

	European Union (EU) (mg/Nm^3@11% O_2)		**US standards (ppmdv@7% O_2)**		**Chinese standards (mg/Nm^3@11% O_2)**	
Reference	**BAT reference document for waste treatment (2017) [4]**		**EPA 40 CFR Part 60 (NSPS) [5-7]**		**GB18485-2014 [8]**	
	New plant	**Existing plant**	**SMWC$^{(a)}$ (New/Existing plant)**	**LMWC$^{(b)}$ (New/Existing plant)**	**Daily**	**1 hour**
HCl	2-6$^{(c)}$	2-8$^{(c)}$	25/250$^{(d)}$	25$^{(e)}$ /29$^{(e)}$	50	60
SO_2	10-30	10-40	30$^{(f)}$ /77$^{(g)}$	30$^{(f)}$ /29$^{(h)}$	80	100
NO_x	50-120$^{(i)}$	50-180$^{(i)(j)}$	500/NA$^{(k)}$	150$^{(l)}$ /varies by combustor type	250	300
CO	10-50	10-50	Varies by combustor type	Varies by combustor type	80	100
Dioxins	<0.01-0.06 (ng TEQ/m^3)	<0.01-0.08 (ng TEQ/m^3)	13/125 (ng/m^3)	13/30$^{(m)}$ (ng/m^3)	0.1 (ng TEQ/m^3)	
Ammonia slip	2-10$^{(n)}$	2-10$^{(n)(o)}$	NA$^{(k)}$	NA$^{(k)}$	NA$^{(k)}$	

(a) Small municipal waste combustors (SMWC) is operating no greater than 250 tons of municipal solid waste (MSW) per day
(b) Large municipal waste combustors (LMWC) is operating greater than 250 tons of municipal solid waste (MSW) per day
(c) The lower end of the BAT-AEL range could be achieved with wet scrubber, while the higher end might for dry sorbent injection
(d) Or 50% reduction of HCl
(e) Or 95% reduction of HCl
(f) Or 80% reduction of SO_2
(g) Or 50% reduction of SO_2
(h) Or 75% reduction of SO_2
(i) The lower end of range can be achieved when employ SCR
(j) The higher end of the range is for when SCR is not applicable
(k) Data not available
(l) For first year operation could be 180ppm, while 150ppm for after first year operation
(m) 35 ng/m^3 when without electrostatic precipitator (ESP) based emission control system
(n) The lower end could be achieved when employ SCR
(o) For existing plant employing SNCR without wet abatement techniques, the higher end of range is 15mg/Nm^3

Table 1.2 NO_X emissions limit for existing LMWC in various type of combustor based on EPA 40 CFR Part 60 (NSPS) [7]

Combustor types	Designated facilities on and after April 28, 2009	Designated facilities included in an emissions averaging plan at a MWC plant on and after April 28, 2009
Mass burn waterwall	205	185
Mass burn rotary waterwall	210	190
Refuse-derived fuel combustor	250	230
Fluidized bed combustor	180	165
Mass burn refractory combustors	No limit	May not included in the emission averaging plan

Over the recent last few years, stringent legislations and tax bonus mechanisms in the European country were implemented in various countries to further reduce the NO_X emission to below 100mg/Nm^3 [1, 9]. For example, the emission limit is 80mg/Nm^3 for Switzerland and 70mg/Nm^3 for Netherlands and Austria, while high NO_X is asked in Sweden. [10]

1.2 NO_X formation

The formation of NO_X in combustion processes is very complex and has not been entirely understood in existing research [2]. Only close approximations were proposed. Theoretically, based on current research, there are three possible mechanisms for NO_x formation during the combustion process, i.e. Thermal NO_x, Prompt NO_x and Fuel NO_x. Thermal NO_x only appears at extremely high temperatures (above 1500℃) via the oxidation of atmospheric molecular nitrogen in the combustion air. However, the operating temperature for municipal solid waste incineration (MSWI) is relatively low. Thus, the formation of Thermal NO_X in the MSWI could be regarded as negligible. However, several researches [1, 2, 11] still included its influence on the NO_x formation during MSWI. Indicated by Goff et al that the formation thermal NO_X related to O_2 and N_2, temperature and residence time. The formation of NO_X would not be significant when flame temperature is lower than 1100℃ [12].

Compared to thermal NO_x, prompt NO_x is produced in a relative lower temperature range (below 750℃) via the combination of $N \equiv N$-triple bond from atmospheric N_2 molecules and hydrogen radicals in the flame zone (primary reaction zone) under fuel-rich conditions. However, given its low production rate, its contribution is insignificant compared to the overall NO_x formation in waste combustion.

Fuel NO_x is regarded as the principle NO_X formation mechanism in MSWI. It is produced via the conversion of chemical bound nitrogen that was initially released from municipal solid waste (MSW) in the form of organic or inorganic (e.g. NH_3 and HCN) to N_2 or NO depending on combustion conditions, NH_i is commonly formed as an intermediate compound. The reaction pathways for fuel NO_x formation is presented in following Figure 1.4.

From the theory of fuel NO_x formation mechanism and its reaction pathways shown in Figure 1.1, it could be found that the formation of NO_x in the MSWI would be influenced by parameters such as nitrogen content in the MSW, oxygen content and temperature. Several researches have reported finding on these parameters [1, 2, 13]:

Nitrogen content: Tezanou et al have investigated the influence of waste composition on NO_x emissions from incinerators with modification in the composition of combustible part of waste feedstock in the EU. The relationship between composition, excess air and NO emission is shown in Figure 1.2. It is obvious from the results that the composition has a small influence on the NO emissions in a general perspective, but a significant influence on temperatures and NO emission is assumed in this type of combustor (with secondary air injection in a fixed bed combuster) when there is a large modification of the wood and plastic concentration. [14] However, another research reported by Rigo et al about the relationship between high nitrogen municipal solid waste composition (such as food and yard waste) and NO_x in a staged mass burn water wall municipal waste combustor with staged combustion where a portion of the combustion air is introduced under the grate. It was reported that there is no influence from fuel nitrogen content on the NO_x emissions. This result agrees well the expected staged combustor system performance. [11]

Oxygen content: From the reaction pathway indicated in Figure 1.1, NO is more likely to be produced in oxygen rich condition, while fuel rich condition is preferred by reaction pathway to produce N_2. The effects of different airflows on the NO formation was investigated by Rogaume et al. [15]. The relationship between NO emission and total excess air presented in different amounts of primary air is shown in Figure 1.3 which is similar to Figure 1.2 which indicates that the NO yield increases with the increase of total excess airflow. In addition, the results given by Rogaume et al also indicate the NO production from the experimental combustor with two stage air injection seems to be controlled only by oxygen concentration in the secondary combustion zone.

Temperature: High temperature would accelerate the reaction on NO_x reduction under fuel rich condition, while it would also lead to an increase of the NO_x formation under oxygen rich condition [2]. As reported by Vilani et al, under the operation of industrial waste to energy (WtE) plant, NO_x formation would increase with the increase of thermal load. The relationship is shown in Figure 1.4, while the NO_x formation was referring to the Bruto NO_x in the study. [1]

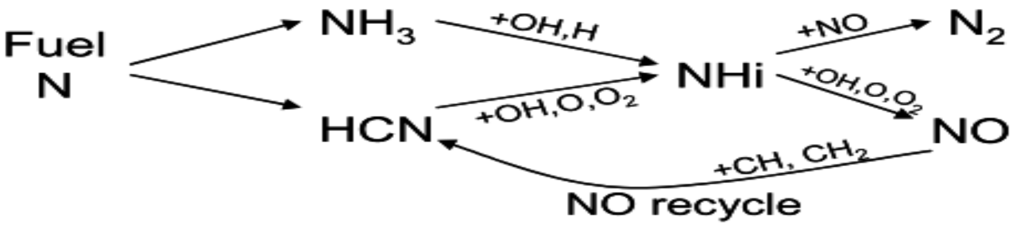
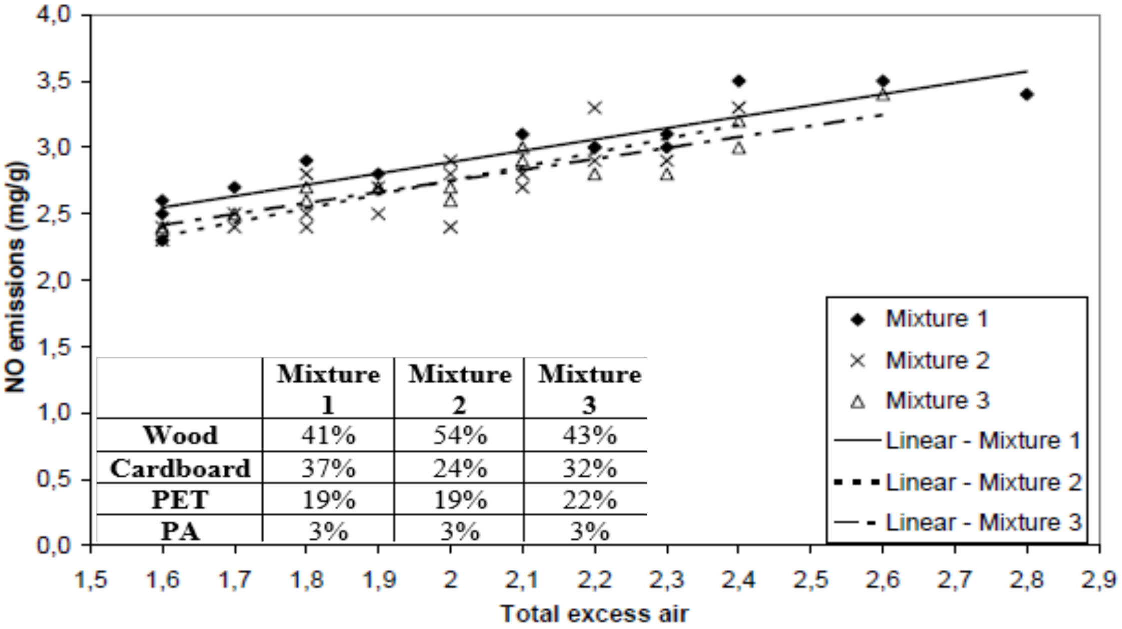


Figure 1.1 Summary for fuel NO formation process [13]



	Mixture 1	Mixture 2	Mixture 3
Wood	41%	54%	43%
Cardboard	37%	24%	32%
PET	19%	19%	22%
PA	3%	3%	3%

Figure 1.2 Emission of the NO as a function of total excess air with different proposed MSW in different composition [14]

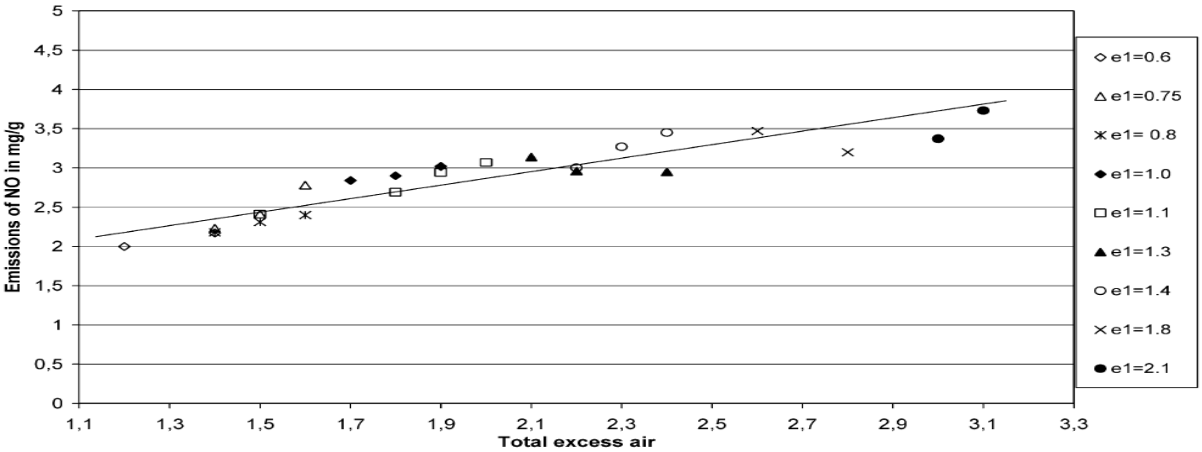


Figure 1.3 Emission of NO as a function of total excess air [15]
(Primary excess air is represented in different symbol)

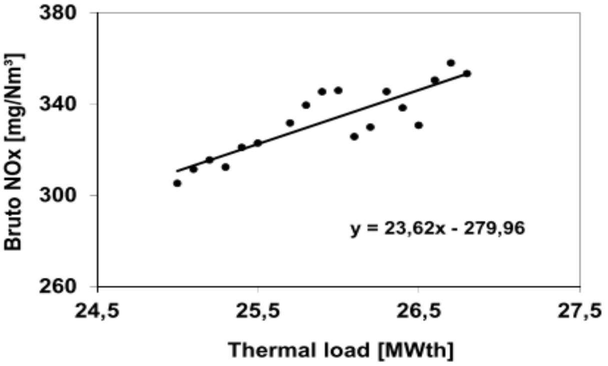


Figure 1.4 Bruto-NO_X values as function of thermal load of boiler [1]

1.3 NO_X control techniques

Various measures could be applied to achieve the denitrification in MSWI, which could mainly be divided into two categories [1, 2, 16]:

- **Primary measures**, implemented prior or during the combustion process, aims to avoid or reduce the NO_x generation from the combustion process by acting on parameters which would have an impact on NO_x formation
- **Secondary measures (post-combustion measures)**, implemented before the flue gas being discharged to the environment to achieve the emission limit which typically could not be met only by primary measures, aims to reduce the NOx emission by injecting reagent to convert the generated NOx to N_2.

1.3.1 Primary measures

The idea of primary measures is to reduce to NO_x formation by modifying the parameters which would influence its formation such as temperature and air to fuel ratio. The potential of several denitrification techniques' application in MSWI have been critically investigated, such as air staged combustion and flue gas recirculation [1, 2, 16].

Air staged combustion, as one of the most common primary measures for denitrification in almost all waste to energy plants, divides the combustion process into consecutive combustion zones: a primary zone feeding air in substoichiometric amount and a secondary zone supplying excess air to ensure a complete combustion of oxidized gases generated by the primary zone. In some cases, the excess oxygen is achieved until a tertiary air feeding in the third burnout zone. The substoichiometric amount of air not only suppresses the conversion of fuel-bound nitrogen to NO_x (fuel NO_x), but also reduces the peak temperatures which would minimize the thermal NO_x formation. [1, 2]

Fuel staged combustion involves the injection of fuel (such as natural gas) into the furnace above the main burners in order to create a fuel-rich reburn zone. In this zone, NO_x generated in the primary zone would mix with the reburning fuel to initiate the reaction between hydrocarbon radicals and NO_x to reduce NO_x to molecular nitrogen. The comparison of air staged and fuel staged is shown in following Figure 1.5. The reaction is presented in Figure 1.1 in NO recycling pathways. However, unlike the common application of air staged combustion, fuel staged is not attractive to be utilized in waste to energy facilities, because the use of fossil fuel would offset the effort on improving energy efficiency and minimizing CO_2 emission during MSWI.[2]

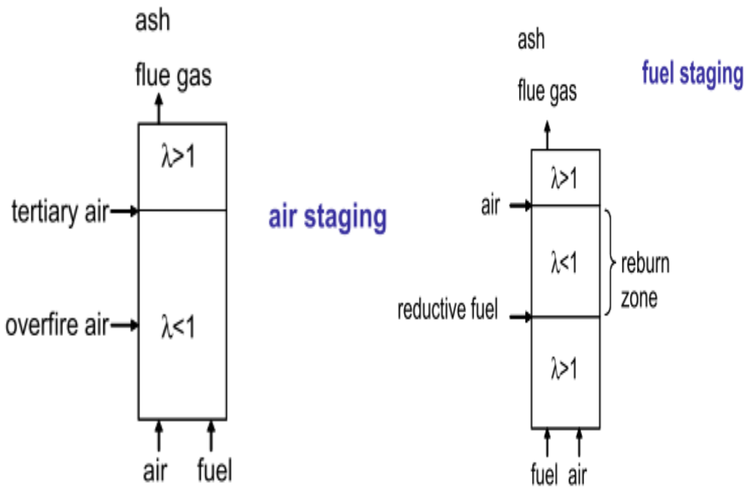
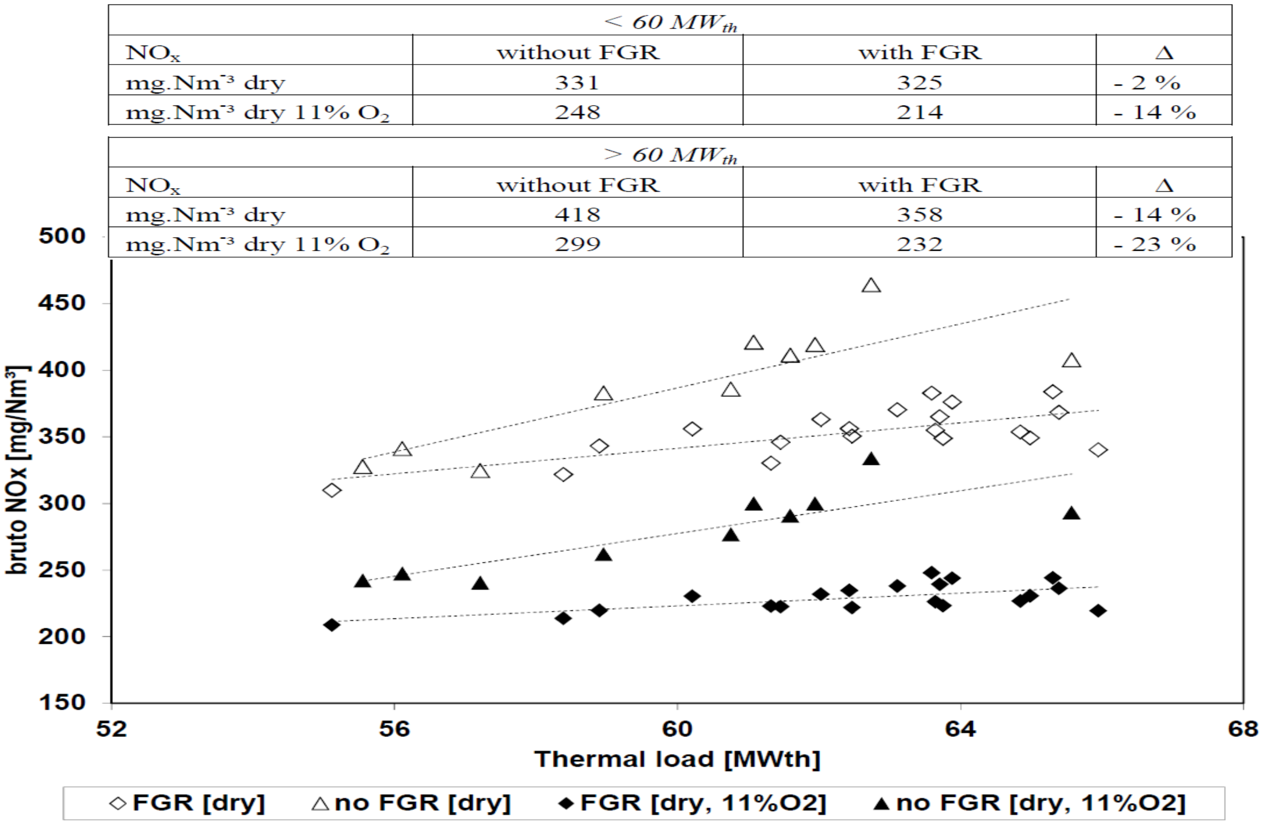


Figure 1.5 Scheme of staged combustion [2]

Fuel gas recirculation (FGR) refers to the staged combustion air supply which involves introducing part of the generated combustion gas containing lower oxygen levels (from downstream of boiler) to the furnace, which would reduce the O_2 and N_2 content as well as the flame temperature. It was reported by Vianli et al that in an experiment on Belgian waste to energy facility with FGR as the only denitrification measures, there is a clear distinction in the efficiency on reducing NO_x formation by FGR between lower and higher thermal loads. A 2% NO_x formation reduction was recorded when the thermal load was lower than 60MW while 14% when higher than 60MW. Details about the influence from FGR on NO_x formation is shown in following Figure 1.6

Figure 1.6 NO_X formation versus thermal load [1]

. However, when considering an O_2 reference with 11% O_2, the percentage of reduction would significantly increase from 2% to 14% and from 14% to 23% respectively. [1] In addition, Rigo et al indicated that the nitrogen content in fuel would not influence the NO_x formation when FGR is used [11].



< 60 MW_{th}			
NO_X	without FGR	with FGR	Δ
$mg.Nm^{-3}$ dry	331	325	- 2 %
$mg.Nm^{-3}$ dry 11% O_2	248	214	- 14 %

> 60 MW_{th}			
NO_X	without FGR	with FGR	Δ
$mg.Nm^{-3}$ dry	418	358	- 14 %
$mg.Nm^{-3}$ dry 11% O_2	299	232	- 23 %

Figure 1.6 NO_X formation versus thermal load [1]

Covanta Low-NO_X (LN) technology, involving the combustion air system modification, is a cost-effective NO_X removal technology for MSWI. Conventionally, there are two source of air flow entering the MSWI furnace: primary air supplied under the moving grate with minimized excess air and secondary air injected in the waterwall above the grate typically supply 60% to 100% excess air. The idea for LN technology is shift the 50% to 100% of air supplied by secondary air to a new tertiary air without changing the total amount of air.[12] The minimal impact on boiler performance and unaffected remainder of plant make the LN technology a feasible applications for retrofit. It is reported that Low NO_X technology without SNCR operation can achieve about 50% of NO_X removal efficiency to achieve a typical NO_X emission in 130 to 180ppm. Higher efficiency could be achieved to reduce NO_X to 70 to 90 ppm with SNCR operation and ammonia slip lower than 10ppm. [10]

Covanta Very-low NO_X (VLN) technology is to reintroduce the "VLN gas" from the rear end of grate back to furnace at just below the SNCR ammonia injection position. In this way, it could not only promote the fuel NO_X reduced to nitrogen, but also cool down the flue gas and enhance their mixing with injected ammonia [2]. The utilization of VLN with SNCR could achieve the NO_X emission lower than 60ppm with ammonia slip lower than 10ppm. [10]

1.3.2 Secondary method

Selective Non-Catalytic Reduction (SNCR) and Selective Catalytic Reduction (SCR) are two typical secondary measures. An aqueous solution of either ammonia (NH_3) or urea ($CO(NH_2)_2$) is injected in the flue gas for both systems to achieve the conversion from NO to N_2. The reaction between NO and NH_3 is shown in following Figure 1.7, while the overall reaction equation is listed as follow [1, 2, 17, 18]:

Ammonia: $$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$$

Urea: $$CO(NH_2)_2 + 2NO + 0.5O_2 \rightarrow 2N_2 + CO_2 + 2H_2O$$

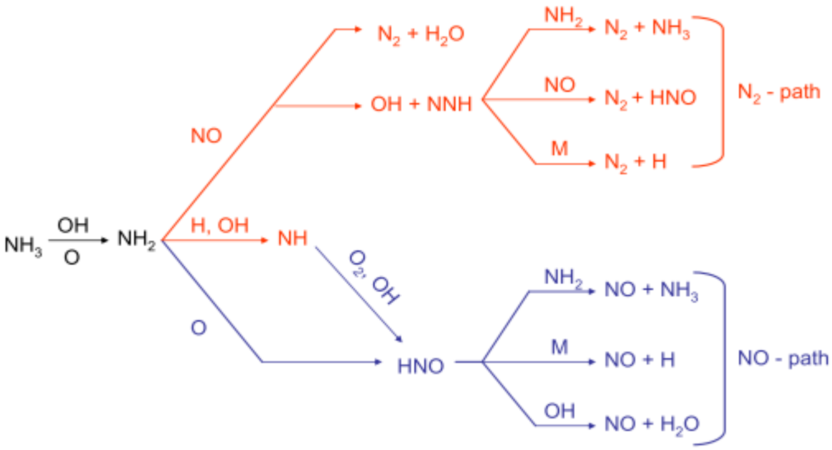


Figure 1.7 Reaction paths of NH_3 and NO [13]

1.3.2.1 SNCR

The range of SNCR operating temperature is from 850 to 1150℃ [2, 9, 13] and can achieve 30% to 75% NO_X removal efficiency for MSWI with 5 to 10mg/m^3 of ammonia slip (unreacted ammonia) discharge [9]. There is a certain minimum temperature for SNCR operation, otherwise the reduction reaction would not occur. However, when the temperature is excessively, ammonia would decomposes and react with O_2 to produce NO. [2] Several parameters might influence the efficiency of NO_X removal, including temperature, reagent injection rate, residence time, mixing of reagent and flue gas and uncontrolled NO_X level. [9] Temperature and NSR are two of most investigated parameters. The equation for NO_x removal efficiency and NSR was shown in **Equation 1.1** and **Equation 1.2** respectively. The relationship between removal efficiency and temperature was investigated to find an empirical formula by Suwala et al [19] and the results was shown in following **Figure 1.8** and **Figure 1.9**. Relationship between removal efficiency and ammonia slip and between reduction efficiency with NSR given by EPA was shown in following **Figure 1.10** and **Figure 1.11** respectively. In the graph given by EPA, moles of uncontrolled NO_X used for NSR equation refers to the difference of moles of NO_2 before and after equipment with lb/MMBtu as unit. The relationship among removal efficiency, temperature and NSR was reported by Gohlke et al [13] and was demonstrated in **Figure 1.12**. In this figure, moles of uncontrolled NO_X refers to the difference of moles of NO before and after equipment. However, Gohlke et al also indicated the NSR is required to be 2 to achieve 50% to 60% removal efficiency. In addition, Villani et al [1] investigated the ammonia fate during the SNCR process with different removal efficiency and results was shown in Figure 1.13 and Figure 1.14.

NO_X removal efficiency:

$$\eta_{NO_x} = \frac{NO_{x_{in}} - NO_{x_{out}}}{NO_{x_{in}}}$$

Equation 1.1

Normalized stoichiometric Ratio (NSR):

$$NSR = \frac{moles\ of\ equivalent\ NH_3\ injected}{moles\ of\ uncontrolled\ NO_x}$$
$$= \frac{moles\ of\ equivalent\ NH_3\ injected}{moles\ of\ NO_x\ before\ equipment - moles\ of\ NO_x\ after\ equipment}$$

Equation 1.2

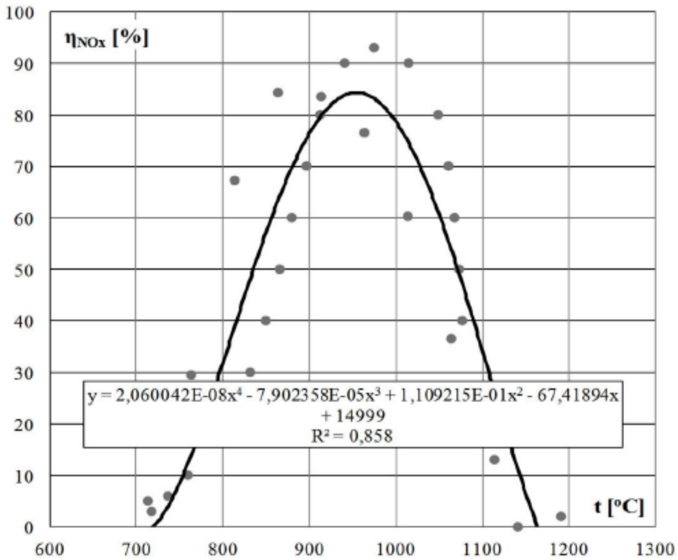


Figure 1.8 SNCR versus temperature with ammonia as reagent [19]

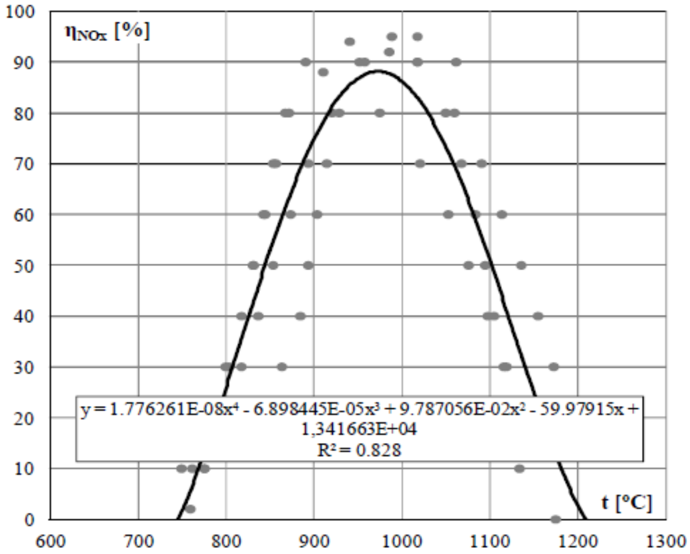


Figure 1.9 SNCR versus temperature with urea as reagent [19]

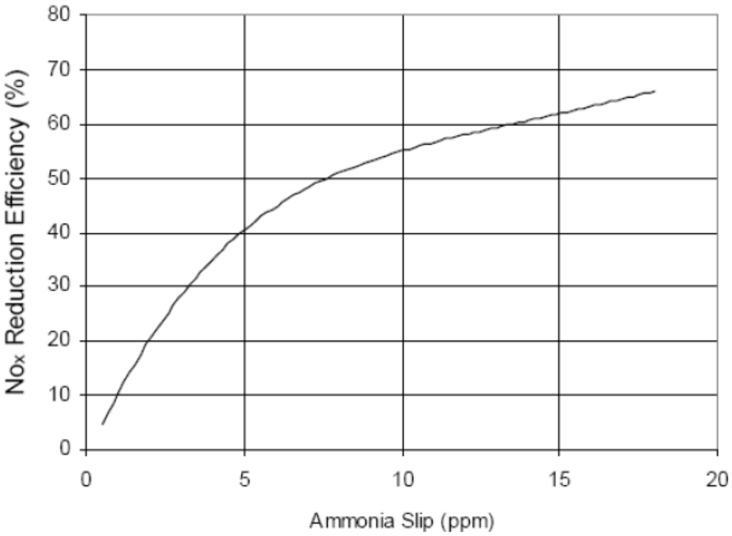


Figure 1.10 NO$_X$ reduction efficiency versus ammonia slip **[18]**

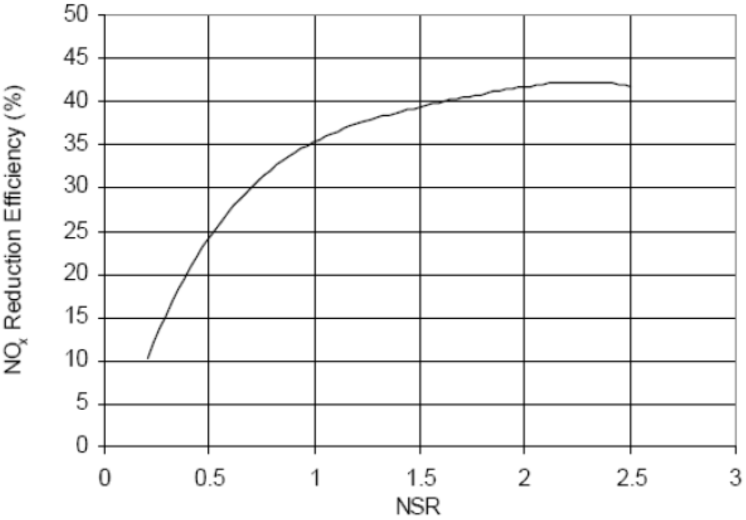


Figure 1.11 NO$_X$ reduction efficiency Versus NSR **[18]**

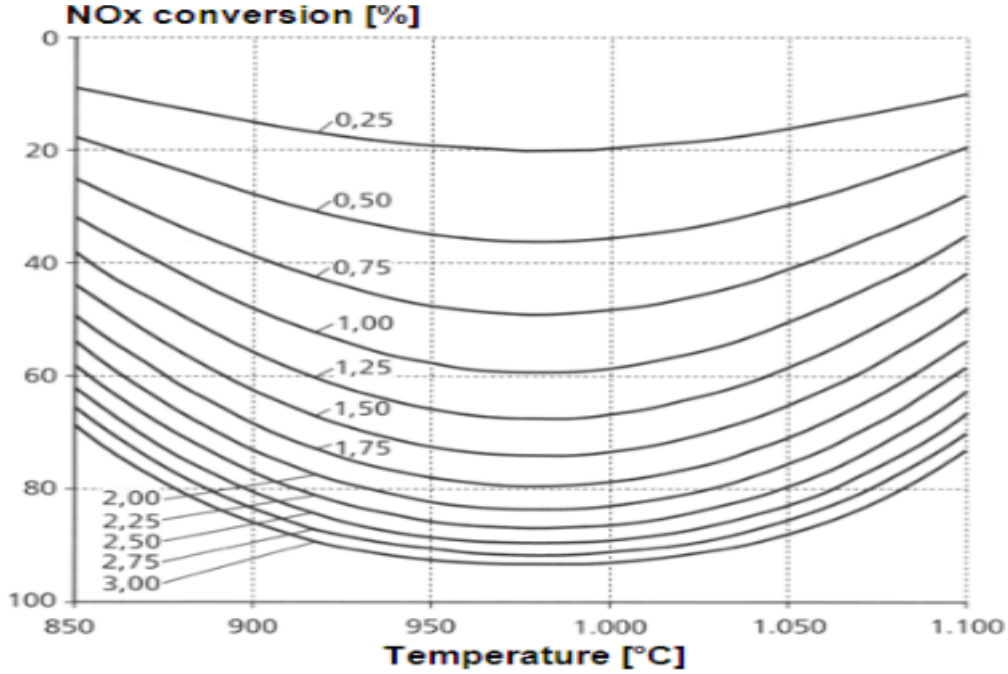


Figure 1.12 NO_X removal efficiency with SNCR depending on [13]
temperature and NSR

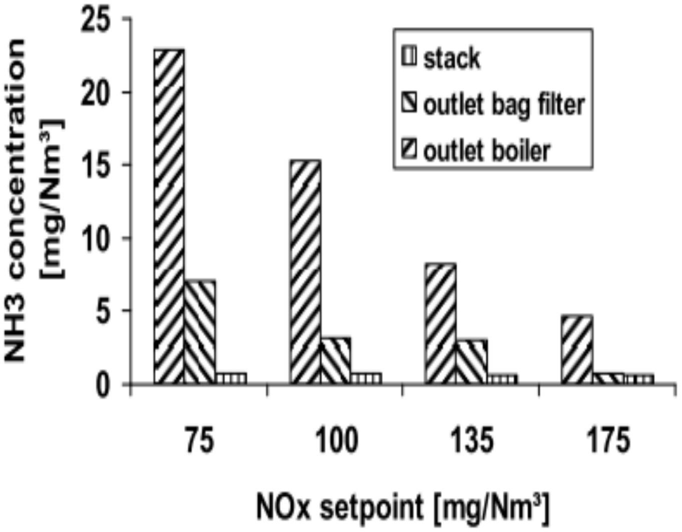


Figure 1.13 **Ammonia slip concentration in a process with initial concentration of 350mg/Nm^3@ 11% O_2 [1]**

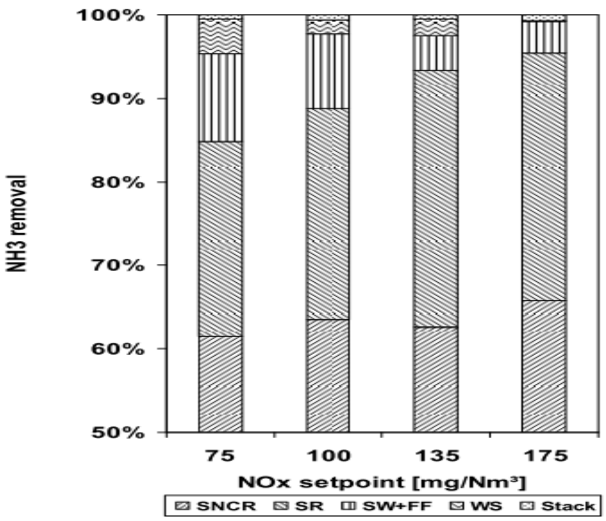


Figure 1.14 **Ammonia fate and distribution in a process with initial concentration of 350mg/Nm^3@ 11% O_2 (SR= side reaction in boiler, SW+FF= semi-wet reactor and fabric filter, WS=wet scrubbing system) [1]**

1.4 SCR

The operation of SCR is accomplished by injecting ammonia into the flue gas stream and react with NO_X on a catalyst bed. It can achieve a nearly 100% removal efficiency, but in most case it operates at around 90% efficiency and achieve the emission from 20 to 70 mg/Nm^3@11% O_2. [9] Although the efficiency is higher, several disadvantages on SCR operation has been reported by Gohlke et al, such as high energy consumption for reheating and overcome pressure drop built up in catalyst bed, high capital and operating cost and limited lifetime for catalyst [2]. The gas temperature after air pollution control unit was typically in 140 to 150°C, but the operating temperature was in a range from 180 to 350°C, while 250°C is recommended. Although the operating temperature between 180 and 220°C has been tested out, it is still lack of sufficient experience. [9] TiO2, WO3, V2O5 are typical catalyst carrier. When utilizing activated carbon, it is possible for temperature to go lower than 100°C. [14]

The relationship between removal efficiency and temperature on stoichiometry view as well as between removal efficiency and ammonia slip was reported by Cho et al [20] and the figure was roughly shown in **Figure 1.15** and **Figure 1.16** respectively. It is indicated by EPA [17] that up to 85% of removal efficiency could be achieved with NSR at 1.05 and 90% removal efficiency typically with 2ppm ammonia slip emission. Ebert et al reported an operating NSR range from 1 to 1.1[16]. The relationship between removal efficiency and temperature given by EPA [17] was presented in following Figure 1.17.

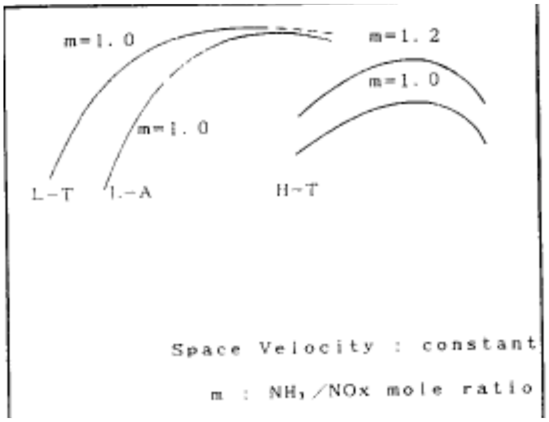


Figure 1.15 **NOx removal efficiency VS temperature** **[20]**

Figure 1.16 **Removal efficiency versus ammonia slip** **[20]**

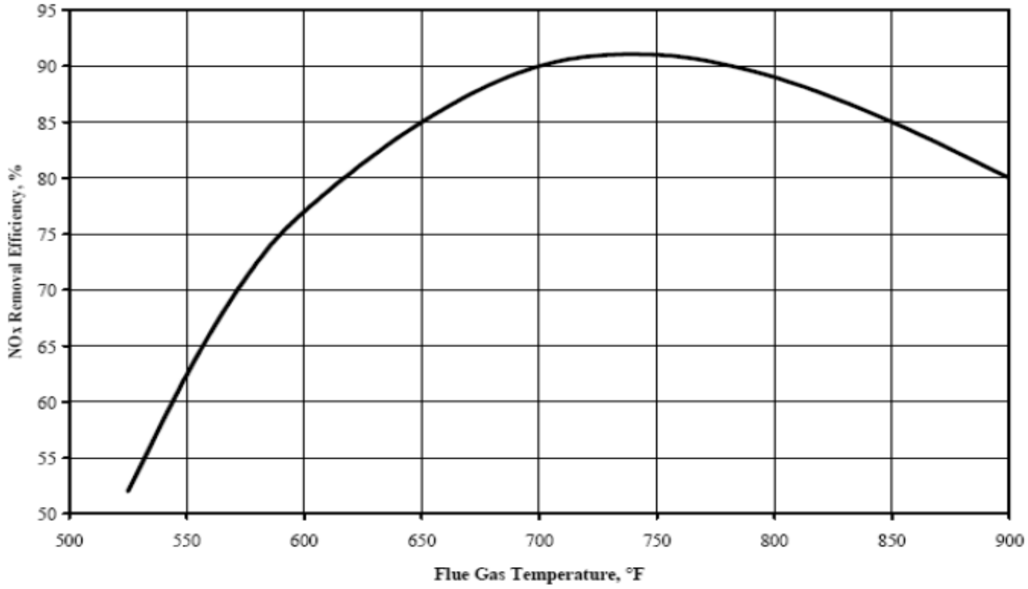


Figure 1.17 NO_X removal efficiency versus Temperature **[17]**

1.4.1 Catalyst volume estimation

1.4.1.1 Space velocity

Indicated by [20], the catalyst **volume could be estimated by space velocity (SV)**:

$$SV = \frac{Volumetric\ gas\ flow\ rate}{Superficial\ volume\ of\ the\ catalyst}$$

Equation 1.3

Based on the reaction kinetics, the NO_X removal efficiency could be expressed in terms of SV:

$$\eta = NSR \cdot \left(1 - e^{-\frac{K}{SV}}\right)$$

Equation 1.4

Where K is activity constant which can be influenced by many parameters such as:

- Catalyst composition
- Diffusion characteristics of ammonia and NO_X in the catalyst gas stream and catalyst layer
- Oxygen concentration (its influence is significant only when its content less than 2 to 3%)
- Water vapor concentration
- Gas temperature and velocity
- Catalyst aging

The typical catalyst characteristic performance in terms of removal efficiency, space velocity and NSR is shown as following Figure 1.18.

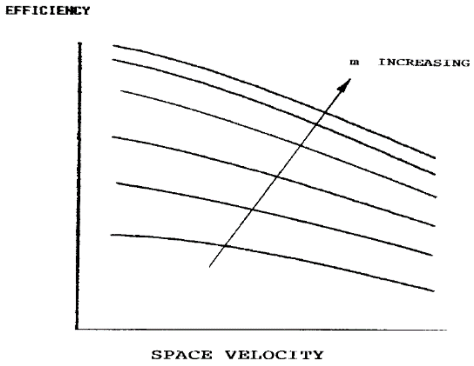


Figure 1.18 NO_X removal efficiency versus Space velocity considering molar ratio [20]

1.4.1.2 Theoretical catalyst volume calculation

From [17], there are methods for catalyst volume estimation.

Theoretical catalyst volume required for the SCR system

$$Vol_{catalyst} = \frac{-\left(q_{flue\ gaas} \times \ln\left[1-\left(\frac{\eta_{NO_x}}{NSR}\right)\right]\right)}{K_{catalyst} \times A_{specific}}$$

Equation 1.5

$$where\ both\ K_{catalyst}\ and\ A_{specific}\ are\ typically\ provided\ by\ the\ catalyst\ manufacturer$$

$$K_{catalyst} = constant\ for\ catalyst\ activity, change\ over\ time\ (t)$$

$$A_{specific} = the\ specific\ surface\ area\ of\ the\ catalyst\ divided\ by\ the\ catalyst\ volume$$

1.4.1.3 Empirical equation

Empirical equation for catalyst volume

$$Vol_{catalyst} = 2.81 \times Q_B \times \eta_{adj} \times Slip_{adj} \times NO_{x_{adj}} \times S_{adj} \times \frac{T_{adj}}{N_{SCR}}$$

Equation 1.6

- $Maximum\ heat\ input\ to\ the\ boiler\ \left(\frac{MMBtu}{hr}\right)$:

$$Q_B = HHV \times \dot{m}_{fuel} \times \frac{1}{10^6}$$

Equation 1.7

$$where \quad HHV = High\ heating\ value;$$
$$\dot{m}_{fuel} = maximum\ fuel\ input\ rate$$

- $NO_x\ efficiency\ adjustment\ factor, \eta_{adj}$:

$$\eta_{adj} = 0.2869 + (1.058 \times \eta_{NO_x})$$

Equation 1.8

- $Ammonia\ slip\ adjustment\ factor, Slip_{adj}\ (for\ ammonia\ slips\ between\ 2\ and\ 5\ ppm)$:

$$Slip_{adj} = 1.2835 - (0.0567 \times Slip)$$

Equation 1.9

- $NO_x\ adjustment\ factor\ for\ inlet\ NO_x, NO_{x_{adj}}$:

$$NO_{x_{adj}} = 0.8524 + (0.3208 \times NO_{x_{in}})$$

Equation 1.10

- $Sulfur\ in\ coal\ adjustment\ factor, S_{adj}$:

$$S_{adj} = 0.9636 + (0.0455 \times S)$$

Equation 1.11

$$where\ S\ is\ the\ fulfur\ content\ of\ the\ fuel\ by\ dry\ weight\ fraction$$

- $The\ temperature\ adjuctsment\ factor, T_{adj}, for\ gas\ temperatures\ otoher\ than$ 700°F:

$$T_{adj} = 15.16 - (0.03937 \times T) + (2.74 \times 10^{-5} \times T^2)$$

Equation 1.12

$$where\ T\ is\ the\ temperature\ at\ reactor\ inlet\ in\ °\mathrm{F}$$

1.4.2 SCR Size estimation

Typical superficial velocity is 16 ft/s

$$A_{catalyst}(ft^2) = \frac{q_{fluegas}}{16\ ft/s \times 60\ s/min}$$

Equation 1.13

$$A_{SCR}(ft^2) = 1.15 \times A_{catalyst}$$

Equation 1.14

$$l = w = \sqrt{(A_{SCR})}$$

Equation 1.15

Nominal height for the catalyst, $h'_{layer} = 3.1\ ft$

First estimation of number of catalyst layers

$$n_{layer} = \frac{V_{catalyst}}{h'_{layer} \times A_{catalyst}}$$

Equation 1.16

Must be at least catalyst layers

$$h_{layer} = \left[\frac{V_{catalyst}}{n_{layer} \times A_{catalyst}}\right] + 1$$

Equation 1.17

Need to be within 2.5-5ft

$$n_{total} = n_{layer} + n_{empty}$$

Equation 1.18

$$h_{SCR} = n_{total}\left(c_1 + h_{layer}\right) + c_2$$

Equation 1.19

Based on common industry practice of $c_1 = 7\ ft;\ c_2 = 9\ ft$

1.4.3 Pressure drop and energy for Induced fan

Indicated by Gohlke et al, the power consumption caused by pressure drop in reactor is assumed about 8 kWh per ton of waste , while Cho et al suggested a typical pressure drop for SCR system ranging from 50 mm to 100 mm water [2].

From Berkenpas, Frey [21], the flue gas pressure drop in SCR system includes pressure drops including:

- Ductwork and ammonia injection grid
- Dummy catalyst layers for erosion control
- Actively utilized catalyst layers
- Air preheater because of deposits build up

The total pressure drop in inches of water, across the SCR system is:

$$\Delta P_{SCR} = n \cdot \Delta P_{cat} + n_d \cdot \Delta P_{dum} + \Delta P_{duct} + \Delta P_{aph,inc}$$

Equation 1.20

The theoretical calculation to estimate the pressure drop in catalyst bed was given by Farrauto, Dorazio [22]

$$-\frac{1}{\rho_g}\frac{dP}{dZ} = \frac{2fu^2}{g_c d_p}$$

Equation 1.21

$where \ \frac{dP}{dZ} \ is \ the \ change \ in \ pressure \ drop \ as \ a \ function \ of \ distance;$

$\rho_g = \ the \ gas \ density; f = \ friction \ factor; \ g_c = gravitional \ constant; \ d_p = particle \ diameter$

$$u \ (m/hr) = linear \ velocity = \frac{Volumetric \ gas \ flow \ rate}{flow \ area \ of \ the \ gas \ through \ the \ catalyst};$$

The energy consumption for induced fan can be determined by it power:

$$P = \frac{Gas \ volume \ delivered \ by \ fan (m^3/s) \times total \ pressure \ drop \ (Pa)}{Fan \ efficiency}$$

2 Methodology

2.1 Definition of goal and scope

This study aims to quantitatively compare environmental impact among three different NOX removal technologies (SNCR, LN/SNCR and SCR) utilized in a hypothetical waste to energy plants in the United States (operating condition of three scenarios in the hypothetical plants are listed in Table 2.1 in a life cycle perspective. The functional unit is the reduction of NOX within the combustion gas produced by conventional furnace from 300 ppm@7% O_2 to a typical level the respective de-NO_X technology could achieved under normal operation during one year. Three scenarios are considered (detailed process flow diagram and simplified mass flow diagram is shown from Figure 2.1 to Figure 2.6):

- SNCR as the only NO_X removal techniques to reduce NO_X to 150 ppmdv@7%O_2 which could achieve the U.S. emission limit for new plant: 80% excessed air injected into furnace in as primary and secondary air; NH_3 is injected to combustion gas in furnace before it enter boiler with 50% NO_X removal efficiency.
- Retrofit LN/SNCR to reduce NO_X to 80 ppmdv@7%O_2 which could achieve the emission limit of 120mg/Nm^3@11%O_2 (82 ppm@7%O_2) required by the E.U. for new plant without SCR equipment: 80% excessed air injected into furnace as primary, secondary and tertiary air to reduce 50% of NO_X formation; NH_3 is injected to combustion gas in furnace before it enter boiler with 46.7% NO_X removal efficiency
- Tail end SCR to reduce NO_X to 45 ppmdv@7%O_2 which could achieve the emission limit of 70mg/ Nm^3@11%O_2 (48 ppm@7%O_2) required in several European counties: 80% excessed air injected into furnace in as primary and secondary air; NH_3 is injected just before the SCR with 85% removal efficiency which is located at downstream of semi-dry reactor and baghouse filter and before the chimney. A heat exchanger is located before the SCR to reheat the combustion gas from 140℃ to 343.3℃, while an induced fan is applied to overcome the pressure build up in the SCR.

In this study, only processes related to NO_X removal are considered. The scope of the life cycle analysis is divided into three unit process and listed as follow:

- Production of construction materials and operating reagent, including steel for SNCR, LN/SNCR and SCR construction, reduction agent (liquid ammonia) used during operation as well as catalytic materials which only required in SCR
- Transportation of these materials from manufacturer to plant and waste produced from plant to landfill
- Operation of NO_X removal technologies including energy consumption for induced fan to overcome pressure and combustion gas reheating, environmental impact of flue gas emission to ambient air and solid waste disposal in landfill

Several aspects are not included in this life cycle analysis because of their minor impact to the system or lack of reliable data:

- Energy consumption for ammonia injection and preparation
- Catalyst aging
- Maintenance of equipment
- Furnace, chimney, other air pollution control equipment, such as semi-dry reactor and baghouse filter
- Energy consumption in furnace

Table 2.1 Operating conditions for scenarios in hypothetic WtE plants in U.S.

	Unit	SNCR	LN/SNCR	SCR	Reference
MSW input	t/hr	55.8			
Heating value	MJ/kg	10			9 to 13.5 MJ/kg for MSW in USA [23]
Flue gas	m^3/hr	223,200			3500 to 5500m^3 flue gas per t of MSW [23]
Operating time	hours	8000			[9]
Initial NO_X concentration	ppm @7% O_2	300			[10]
NO_X concentration at stack	ppm	150	80	45	[4, 7, 9]
Overall NO_X removal efficiency	%	50	50	85	50% with LN technology [10]
NO_X removal efficiency (reacted with NH_3)	%	50	46.7	85	SNCR efficiency [9] SCR efficiency [17]
NSR (NH_3/NO_2)		1.3	1.3	1.05	NH_3/NO=2 for SNCR with 50% efficiency [13]; SCR [17]
Ammonia slip concentration after boiler	ppm @7% O_2	8	6	2	SNCR from [18]; SCR from [17]
Ammonia slip concentration @stack	ppm @7% O_2	1	0.75	2	Ammonia fate [1]
Ammonia slip concentration @fly ash	ppm @7% O_2	7	5.25	0	

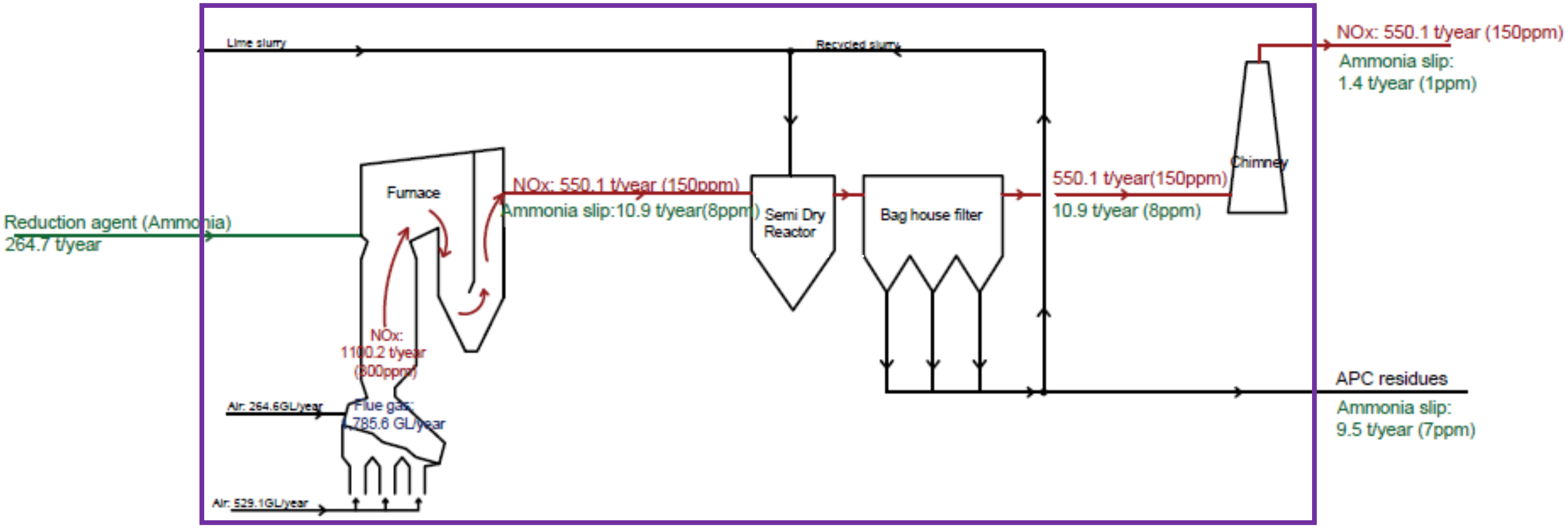


Figure 2.1 Process flow diagram for NO_X flow in SNCR

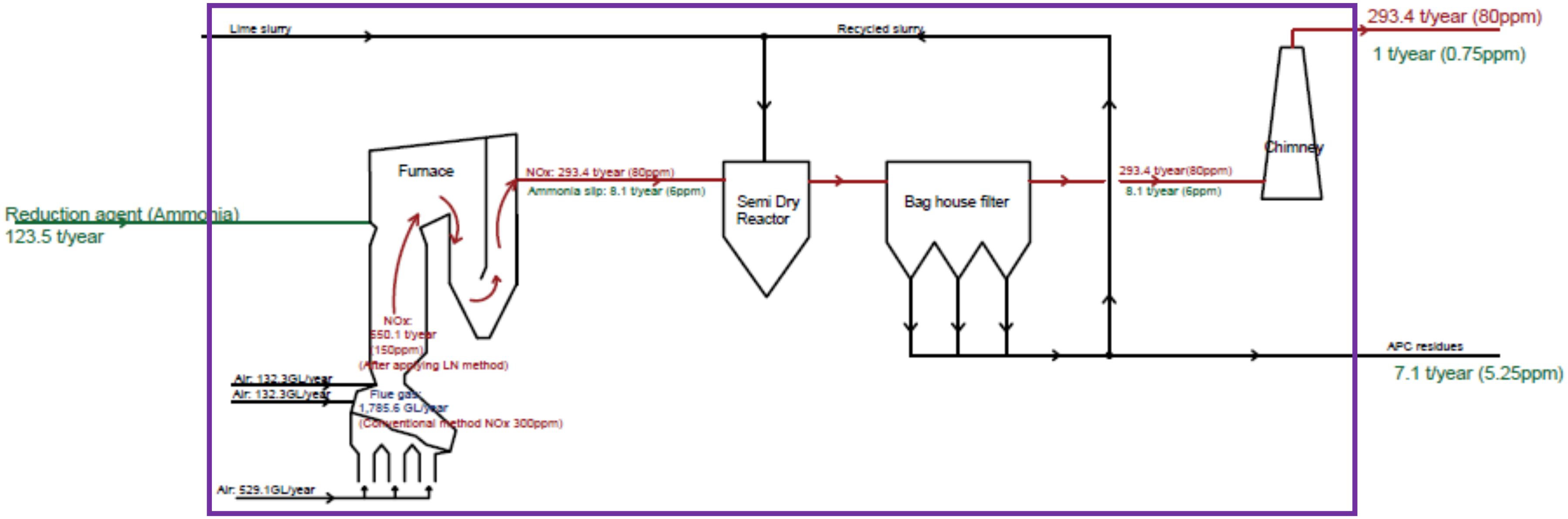


Figure 2.2 Process flow diagram for NO_X flow in LN/SNC

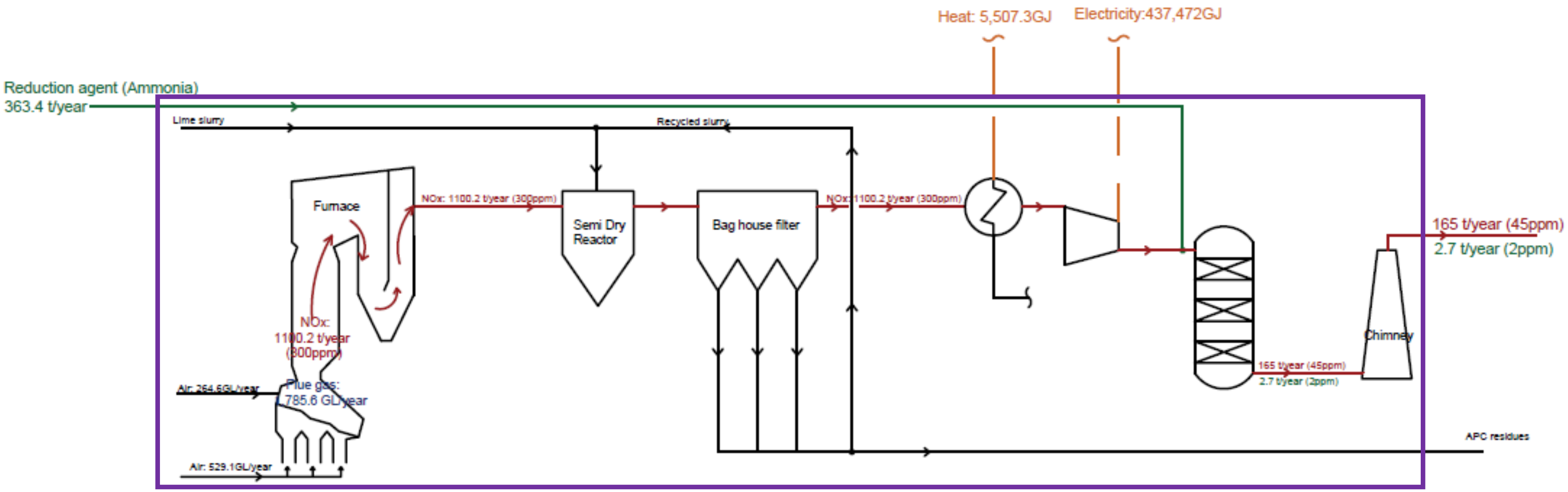


Figure 2.3 Process flow diagram for NO_X flow in SCR

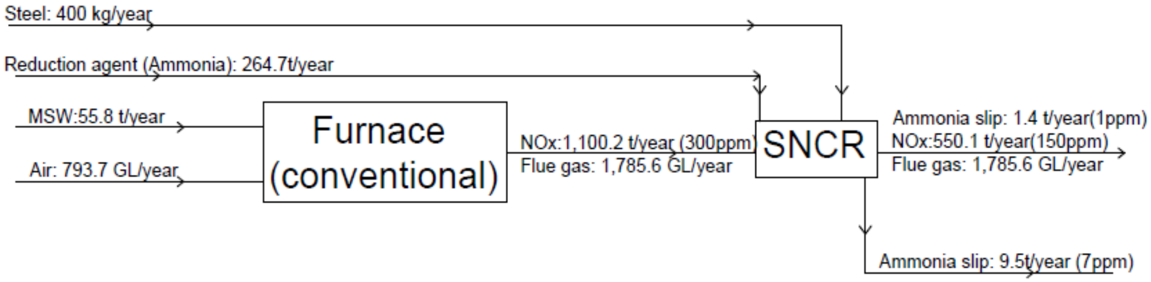


Figure 2.4 Mass flow diagram for SNCR

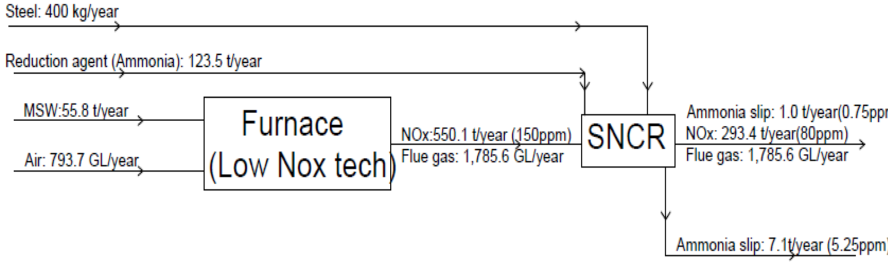


Figure 2.5 Mass flow diagram for LN/SNCR

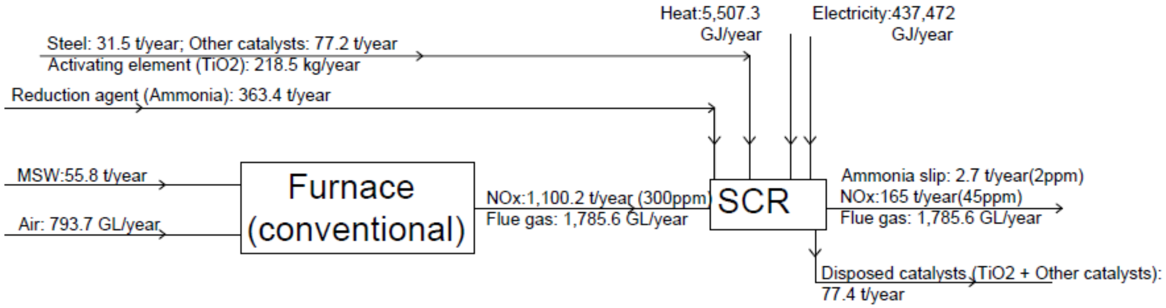


Figure 2.6 Mass flow diagram for SCR

2.2 Life cycle inventories

With SIMAPRO 8 LCA software, the life cycle inventories of liquid ammonia and TiO_2 production, waste and manufacture materials transportation, heat and electricity generation during operation and emission of flue gas as well as disposal of solid waste were provided by Ecoinvent 3.4 database, while the inventories of steel production in the United States were from USLCI database. As neither the Ecoinvent 3.4 nor USLCI provided the inventory for catalytic material (such as V_2O_5 and WO_3 production), the inventories were constructed based on data given by Liang et al and assume same type of catalysts were used.

2.2.1 Production of materials

The production of manufacturing materials included steel for SNCR, LN/SNCR and SCR construction, reduction agent (liquid ammonia) for NO_X removal operation in each scenarios and the activating element and catalytic materials given for SCR. The manufacturing materials required by each scenarios in weight were shown in Table 2.3. The weight of steel for equipment construction, activating element and catalytic materials were estimated based on data given by [24] for one year duration. Thus, same assumption were required, included:

- Flat catalyst with main body made in stainless steel and TiO_2 as activating materials
- 2 years of service life for catalyst and 25 years for steel using on support structure

In [24], for a plant operating with combustion gas in 1,779,000 Nm^3/hr, 400 kg steel per year for SNCR while 100,000 kg steel per year for SCR process. Some assumption were proposed for steel required in this unit process because of lack of information provided by Liang et al:

- 400 kg steel per year for SNCR construction includes the construction of ammonia storage, pretreatment, piping and injection
- As the combustion gas flow rate is much larger than the flow rate in this study, it can be assumed that the size of storage tank and equipment required for SNCR construction were used the same one as Liang's. Thus, 400 kg steel per year for SNCR and LN/SNCR scenarios in this study
- As the SCR process also required construction of ammonia storage, pretreatment, piping and injection as SNCR, steel used for reactor construction in SCR scenario in Liang et al was (100,000-400) kg steel per year

- As the catalytic type and composition was not provided, it can be assumed that the catalyst type and composition in this study were same as Liang et al, which means they had similar conditions (SCR in Liang et al operated at around 350℃ for 80% removal efficiency)

In addition, as the production of additional fan and piping system for air injection in furnace in LN/SNCR were occupied a small portion compared to the whole system, their production were not included in this study.

The weight of catalyst and steel required for SCR scenarios this study was estimated based on Liang et al and the assumption that the mass for construction materials is proportional to their volume. The estimation process was demonstrated in following section.

Catalyst mass ratio:

Assume catalyst in this research is same as that used in Liang et al with same conditions, which means $K_{catalyst}$ and $A_{specific}$ for both research are same. Thus, based on **Equation 1.5**

Then

$$Catalyst\ mass\ ratio = \frac{(V_{catalyst})_{Liang\ et\ al}}{V_{catalyst}} = \frac{(q_{flue\ gas} \times \ln\left[1 - \left(\frac{\eta_{NO_x}}{NSR}\right)\right])_{Liang\ et\ al}}{\left(q_{flue\ gas} \times \ln\left[1 - \left(\frac{\eta_{NO_x}}{NSR}\right)\right]\right)} = 7.7$$

Steel mass coefficient

From equation **Equation 1.13** to **Equation 1.19**, it can be found that steel mass ratio cannot be expressed directly in one equation as catalyst mass ratio, so the size of SCR is calculated step by step as indicated in EPA [17] to find the ratio.

As the catalyst is not given by Liang et al [24], it is not possible to get the value of $K_{catalyst}$ and $A_{specific}$ or performance graph in terms of space velocity. Thus, the volume of catalyst is estimated by empirical method Equation 1.6. Given by reactor [9], the sulfur content was 30mg/m3 at 11% O2 after semi-dry reactor. The calculated results for SCR was shown in **Table 2.2.**

Assume same type of steel is used and the thickness are same, then

$$Steel\ mass\ ratio = \frac{[(w_{SCR}\times l_{SCR} + h_{SCR}\times l_{SCR} + w_{SCR}\times h_{SCR})\times 2\times thickness]_{Liang\ et\ al}}{[(w_{SCR}\times l_{SCR} + h_{SCR}\times l_{SCR} + w_{SCR}\times h_{SCR})\times 2\times thickness]}$$

Equation 2.1

In this study, steel mass ratio=3.2

Assume the steel required for the SNCR equipment construction is also required in SCR and in same mass. Then,

$$Steel\ for\ SCR = (Steel\ for\ Liang\ et\ al - 400kg/year)\times Steel\ mass\ ratio + 400kg/year$$

Equation 2.2

Table 2.2 The SCR design specification

	Unit		Reference
Operating Temperature	℃	343.3	650 °F for 85% removal efficiency given by [17] which was also approved by [25] when use V_2O_5-WO3-MoO_3/TiO_2 as catalyst
Estimated SCR size (W*L*H)	ft*ft*ft	12.3*12.3*85.5	[17]
Catalyst volume	ft^3	2300	[17]
Height of catalyst layer	ft	3.9	[17]
Number of catalyst layers		7	Including one empty catalyst layer for future installation[17]
SCR pressure drop	Pa	2488.4	Same linear velocity, so same 1 in H_2O per layer, 3 in for ductwork, ignore APH and ammonia injection grid
Temperature after baghouse filter	℃	140	Based on [9]
Heat required for operating temperature	MJ/year	437,472,000	Assumed as dry air and estimate by Mollier diagram
Energy for Induced fan	MJ/year	5,507,278	Calculated based on pressure drop
Steel	kg/year	31,506.4	Size calculated by [17] and materials consumption based on data given by [24]
TiO_2	kg/year	77,161.4	
Other catalysts	kg/year	218.5	

Table 2.3 Materials manufacture for scenarios

Materials manufacture	Unit	SNCR	LN/SNCR	SCR
Steel	kg/year	400	400	31,506
Catalyst	kg/year	NA	NA	77,161
Activating element	kg/year	NA	NA	218
Reduction agent	kg/year	264,693	123,524	363,444

Total	kg/year	265,093	123,924	472,330

2.2.2 Transportation of materials

It was assumed that materials were transported in 100 km average distance with 70% of materials transported by train while 30% by diesel truck. As the environmental impact of transportation compared to other unit process was small, the assumption of transport distance and transportation method would not have an obvious influence on final results. This was approved by the results in following sections. The transportation of materials included construction materials (steel for SNCR, LN/SNCR and SCR, activating element and catalyst for SCR), operating materials (reduction reagent for three scenarios) and transportation of solid waste (ammonia slip for SNCR and LN/SNCR to landfill and disposed catalyst to inert landfill). The calculated results was shown in **Table 2.4**.

Table 2.4 Transportation for scenarios

Material transportation	Unit	SNCR	LN/SNCR	SCR
Mass for transportation	kg/year	274,596	131,051	549,710
Train (1300 ton) 70%	tkm	19,222	9,174	38,480
Diesel truck (10 ton) 30%	tkm	8,238	3,932	16,491

2.2.3 Operation

In the operation unit process, three aspects was included:

- Energy consumption for reheating flue gas and overcome pressure drop in SCR scenarios
- Flue gas emission to ambient air in three scenarios
- Solid waste: Ammonia slip in fly ash residue disposal to a landfill which would have an environmental impact to surrounding in SNCR and LN/SNCR scenarios as well as the catalytic material disposed to inert landfill

The operation data for estimate the life cycle inventory for each scenarios was listed in **Table 2.5**. Several assumption was proposed for this unit process:

- Ammonia remained in lime slurry was negligible, because the slurry is recycling in the process and only a small portion of NO_X could be absorbed in the slurry

- Energy consumption for air induced fan for furnace are same for three scenarios, because of same amount air input and same pressure in furnace
- The catalyst aging and erosion was not considered, no deposits in air preheater and pressure drop caused by ammonia injection grid was not considered, so only the catalyst layer and ductwork would cause the pressure drop
- The energy consumption for reheating of flue gas was estimated as dry air by Mollier diagram
- Reheating energy was from district and industrial heating provided other than natural gas, while electricity for fan was from grid

Table 2.5 Operation for scenarios

Plant operation	Unit	SNCR	LN/SNCR	SCR
Electricity consumption for fan	MJ/year	NA	NA	5,507,278
Energy consumption for heating	MJ/year	NA	NA	437,472,000
Total operating energy consumption	MJ/year	NA	NA	442,979,278
Flue gas to air				
NOx	kg/year	550,094	293,384	165028
Ammonia slip	kg/year	1,358	1,018	2715
Solid waste				
Ammonia slip in fly ash residue	kg/year	9,503	7,127	NA
Disposed catalyst (Catalyst+ TiO2)	kg/year	NA	NA	77,380
Total solid waste for transportation	kg/year	9,503	7,127	77,380

2.3 Life cycle impact assessment (LCIA)

To have a more comprehensive perspective on the environmental performance on different NO_x removal techniques and to minimize the inaccuracy from the analysis methodologies, the lifecycle impacts were assessed by two different LCIA methodologies in SIMAPRO: methodology of the Centre of Environmental Studies (CML) of the University of Leiden and the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) of the United States Environmental Protection Agency. In this study, the characterization and normalization in each method (CML and TRACI) were calculated according to the characterization and normalization factors provided by CML 2 baseline 2000/World, 1995 and TRACI 2.1/USA, 2008 respectively. The information about environmental categories, units and area of protection were shown in following Table 2.6 and details about the impact categories were provided in [26]. As the unit for normalization factor provided by SIMAPRO 8 are different, to provide a consistent analysis, the unit of normalization factor unit provided in SIMAPRO 8 for TRACI were converted into Impact per year as provided for CML by using the data provided by [27].

Table 2.6 Information about methodologies applied in this study

<table>
<tr><th></th><th>CML 2 baseline 2000/World, 1995</th><th>TRACI 2.1/USA, 2008</th></tr>
<tr><td rowspan="2">Environmental impact categories: Unit for characterization</td><td colspan="2">Global Warming (GWP): kg CO_2 eq.;
Acidification (AP): kg SO_2 eq.;
Eutrophication (EP): kg PO_4^- eq./kg N eq.;
Ozone depletion (ODP): kg CFC-11 eq.</td></tr>
<tr><td>Abiotic depletion (ADP): kg Sb eq.;
Human toxicity (HTP), Freshwater aquatic ecotoxicity (FEP). Marine aquatic ecotoxicity (MEP), Terrestrial ecotoxicity (TEP): kg 1-4 db eq.;
Photochemical Oxidation (PO): kg C_2H_4 eq.;</td><td>Smog: kg O_3 eq.;
Carcinogenics (CP), Non carcinogenics (NCP): CTUh;
Respiratory effects (RE): kg PM2.5 eq.;
Ecotoxicity (ETP): CTUe;
Fossil fuel depletion (FFD): MJ surplus</td></tr>
<tr><td>Areas of protection</td><td>Human health, natural man made environment, human resources [28]</td><td>Human health, ecosystem, resources [28]</td></tr>
<tr><td>Normalization factor unit provided in SIMAPRO 8</td><td>Impact per year</td><td>Impact per person per year</td></tr>
</table>

3 Life cycle impact analysis

3.1 Overview

The characterization results for SNCR, LN/SNCR and SCR scenarios are presented in **Table.3.1** and **Figure 3.1** by CML methodologies and in **Table 3.2** and **Figure 3.2** for TRACI methods. In order to have a better understanding on in what extent the environmental performance was mitigated by these investigated NO_X removal technologies in scenarios compared to without their installation, these results were compared to the characterization results of untreated combustion gas emit to ambient environment directing without any air pollution control measures and with NO_X as the only considering pollutant in the gas for LCIA. Results given by both methods presented the untreated gas has an environmental impacts on acidification, eutrophication and human health (HTP for CML and Smog and RE in for TRACI method). Focus on the environmental impact brought by untreated gas, it was shown by results that:

- CML method, for AP, EP and HTP: SCR>Untreated gas>SNCR>LN/SNCR
- TRACI method, for EP and RE: SCR>Untreated gas>SNCR>LN/SNCR
- TRACI method, for AP: Untreated gas>SCR>SNCR>LN/SNCR
- TRACI method, for Smog: Untreated gas>SNCR>SCR>LN/SNCR

Overall, results given by both CML and TRACI indicates the LN/SNCR has the best environmental performance than other scenarios on all environmental impact categories except ozone depletion and fossil fuel depletion. Although SCR has a better environmental performance than untreated gas for AP and Smog categories with TRACI method, it still has higher characterization value than other two scenarios which has largely mitigated the negative environmental impact could be brought by untreated gas in most of categories. In addition, the results showed these three scenarios had a negative performance most of the categories given by these methods on human health, eco-toxicity, resource depletion and global warming. Although SCR showed a positive performance on ozone depletion, its performance on other categories were obviously worse than the other two techniques. Therefore, based on the higher characterization value on acidification, eutrophication and human toxicity categories compared to other two techniques and even untreated gas when CML method was applied and the extremely higher value in most of the rest impact, the application of SCR technology for NO_X reduction seems unreasonable in environmental perspective.

3.2 Unit process and components

The characterization results for each scenarios constituted by the unit process and component are presented in percentage in **Figure 3.3** and **Figure 3.5** respectively for CML and in **Figure 3.4** and **Figure 3.6** respectively for TRACI to demonstrate their influence to total environmental impacts. For both methodologies, it should be noted that the environmental impact caused by transportation could be regarded as negligible compared to the total in all environmental impact category. Thus, only the influence from manufacturing and operation are discussed in the following sections.

From **Figure 3.3** and **Figure 3.4**, the results given by both methodologies were similar. It was shown that the operation contributed the most proportion of characterization value to the environmental impact in all environmental categories in SCR scenarios. In addition, for both SNCR and LN/SNCR scenarios, operation contributed the most proportion in acidification, eutrophication and human health (human toxicity for CML, smog and RE for TRACI) while the rest of the categories were mainly associated with manufacture process. It was shown in **Figure 3.5** and **Figure 3.6** that energy for reheating was the most considerable component in the characterization result in all categories in SCR scenarios for results given by both results. However, the flue gas had a considerable share in smog categories for SCR by using TRACI methodologies. The environmental impact on acidification, eutrophication and human health (human toxicity for CML, smog and RE for TRACI) was mainly from flue gas and impacts on the rest of categories were most constituted by reagent production in SNCR and LN/SNCR scenarios.

Detailed characterization values constituted by unit process and component in the form of stacked column charts with percentage for each scenario are shown in **Figure 3.7** to **Figure 3.15** as well as **Table 3.3** for CML and in **Figure 3.16** and **Figure 3.24** as well as **Table 3.4** for TRACI. The proportion of each component contributed which contributed to final environmental impact for SNCR and LN/SNCR scenarios was similar, while the characterization value for each component in LN/SNCR scenario was smaller than SNCR scenario. For these two scenarios, production of steel contributed extremely small impact which could be considered negligible compared to the total environmental impacts from manufacturing process in all environmental categories given by both methodologies. Flue gas only contributed to the environmental impacts on acidification, eutrophication and human health (human toxicity for CML, smog and RE for TRACI) while solid waste only contributed to eutrophication by CML method. However, there were not any impact was shown from solid waste in the categories given by TRACI methodology.

In the manufacturing process for SCR scenario, catalyst production had a considerable proportion on AP, GWP and EP for by both methodologies, and was the main component which contributed on PO when applying CML and Smog when applying TRACI. In addition, catalysts production was not shown any impact on other categories based on the data given by Liang et al. The abiotic depletion in CML and Carcinogenic impact categories in TRACI caused by steel production in manufacturing process for SCR scenario was more obvious than in the other two scenarios, although the weight of steel required for SCR constructed was much higher than SNCR and LN/SNCR construction. Compared to the impact caused by heating, flue gas only occupied a small proportion of impact on acidification, eutrophication and human toxicity in operation process of SCR scenario with CML method, while the influence from flue gas on acidification were more obvious and on smog were predominant with TRACI method. Heating contributed a large percentage of impact to ozone layer depletion in negative characterization value, while electricity contributed a small portion of impact in positive value in the operation process of SCR.

Table.3.1 Characterization Results of Scenarios compared to untreated gas (CML)

	SCR	LN/SNCR	SNCR	Untreated gas
Abiotic depletion (kg Sb eq)	3.67×10^{5}	2.47×10^{3}	5.29×10^{3}	NA
Acidification (kg SO2 eq)	5.62×10^{5}	1.49×10^{5}	2.79×10^{5}	5.50×10^{5}
Eutrophication (kg PO4- eq)	4.17×10^{5}	4.12×10^{4}	7.57×10^{4}	1.43×10^{5}
Global warming (GWP100) (kg CO2 eq)	5.70×10^{7}	2.63×10^{5}	5.63×10^{5}	NA
Ozone layer depletion (ODP) (kg CFC-11 eq)	-0.519	3.97×10^{-2}	8.52×10^{-2}	NA
Human toxicity (kg 1,4-DB eq)	4.50×10^{7}	$5.48E\times10^{5}$	1.08×10^{6}	1.32×10^{6}
Fresh water aquatic eco-toxicity (kg 1,4-DB eq)	6.16×10^{7}	4.88×10^{4}	1.05×10^{5}	NA
Marine aquatic eco-toxicity (kg 1,4-DB eq)	1.31×10^{11}	1.52×10^{8}	3.25×10^{8}	NA
Terrestrial eco-toxicity (kg 1,4-DB eq)	1.82×10^{5}	3.00×10^{3}	6.44×10^{3}	NA
Photochemical oxidation (kg C2H4 eq)	1.93×10^{4}	48.2	103	NA

Table 3.2 Characterization Results of Scenarios compared to untreated gas (TRACI)

Impact category	SCR	LN/SNCR	SNCR	Untreated gas
Ozone depletion (kg CFC-11 eq)	-5.15E-01	5.33E-02	1.14E-01	0
Global warming (kg CO_2 eq)	5.70E+07	2.64E+05	5.65E+05	0
Smog (kg O_3 eq)	8.27E+06	7.28E+06	1.37E+07	2.73E+07
Acidification (kg SO_2 eq)	5.78E+05	2.08E+05	3.89E+05	7.70E+05
Eutrophication (kg N eq)	8.90E+05	1.35E+04	2.54E+04	4.87E+04
Carcinogenics (CTUh)	8.54E+00	5.59E-03	1.19E-02	0
Non carcinogenics (CTUh)	3.78E+01	4.67E-02	1.00E-01	0
Respiratory effects (kg PM2.5 eq)	3.55E+05	2.39E+03	4.49E+03	7.95E+03
Ecotoxicity (CTUe)	7.37E+08	1.17E+06	2.52E+06	0
Fossil fuel depletion (MJ surplus)	7204241.9	733802.71	1571306	0

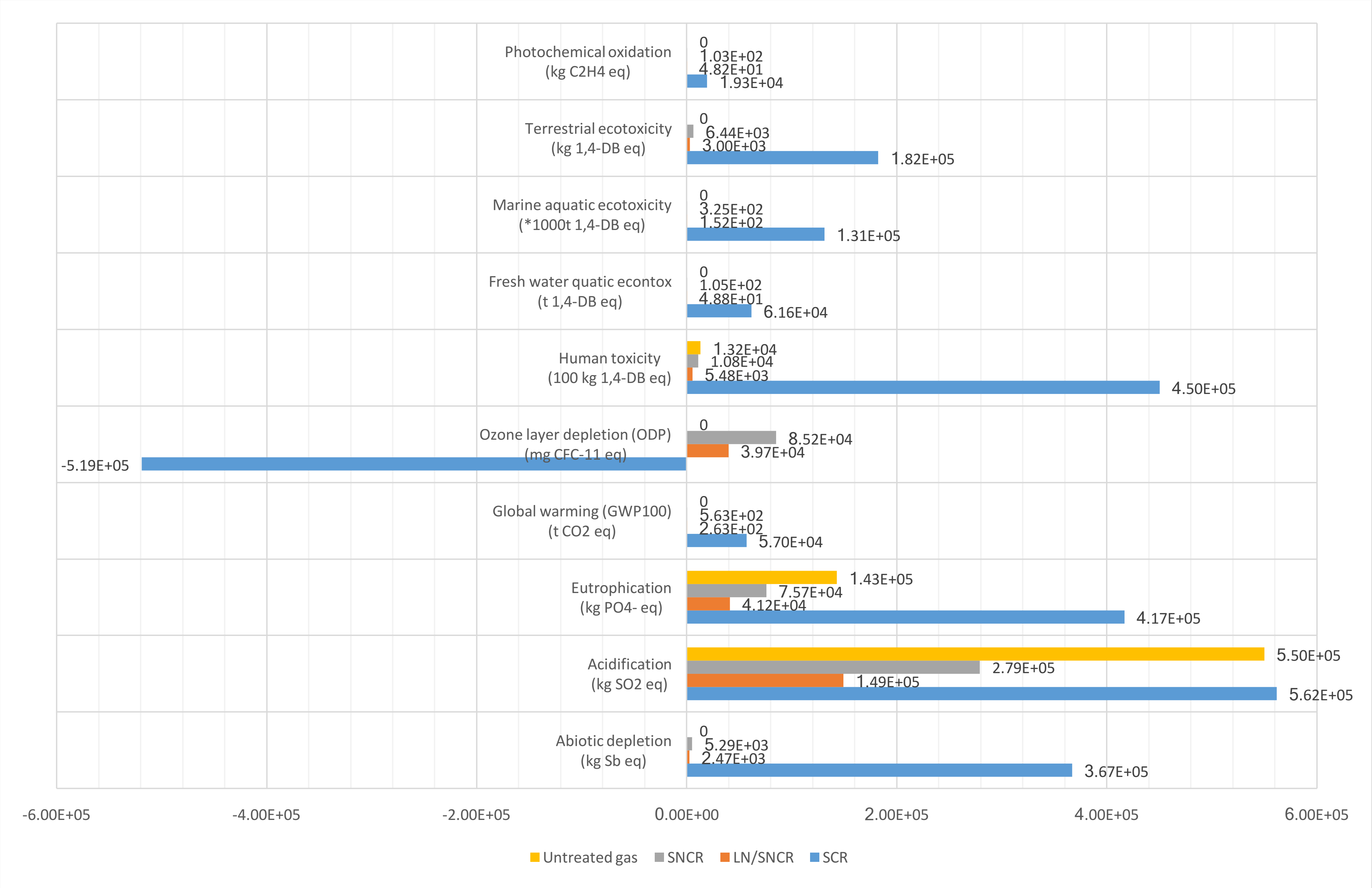


Figure 3.1 Characterization Results of Scenarios compared to untreated gas (CML 2 Baseline 2000)

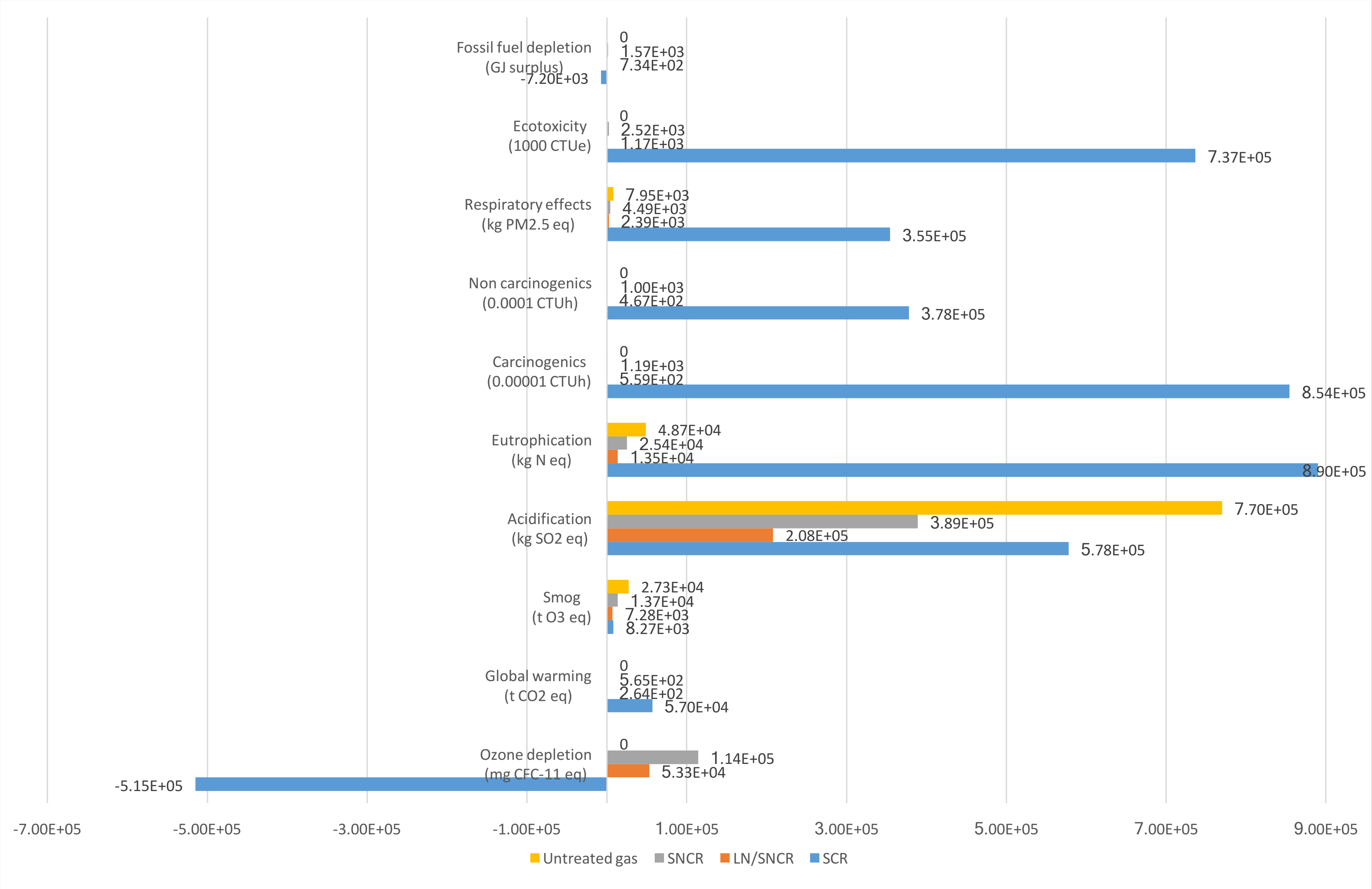
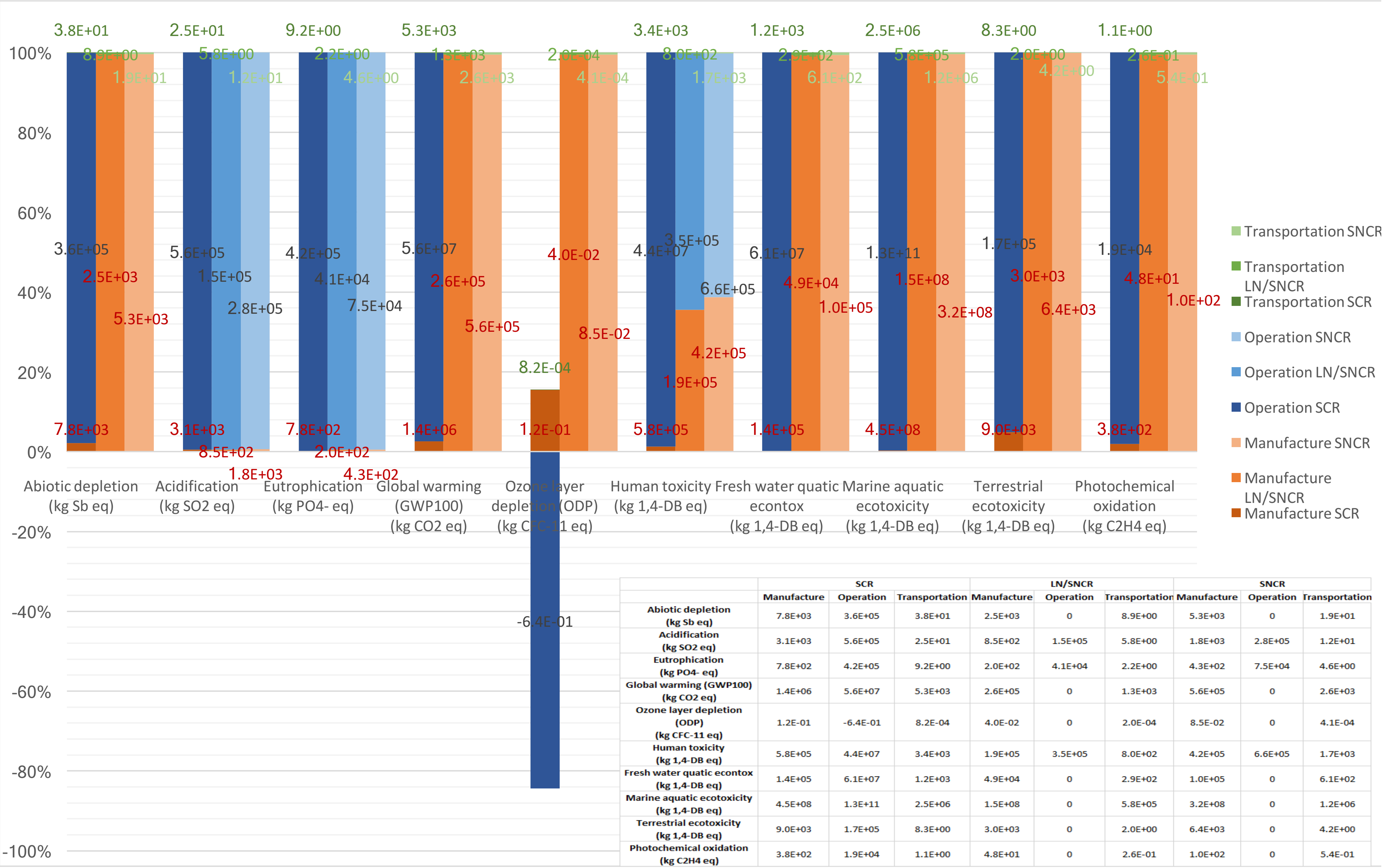
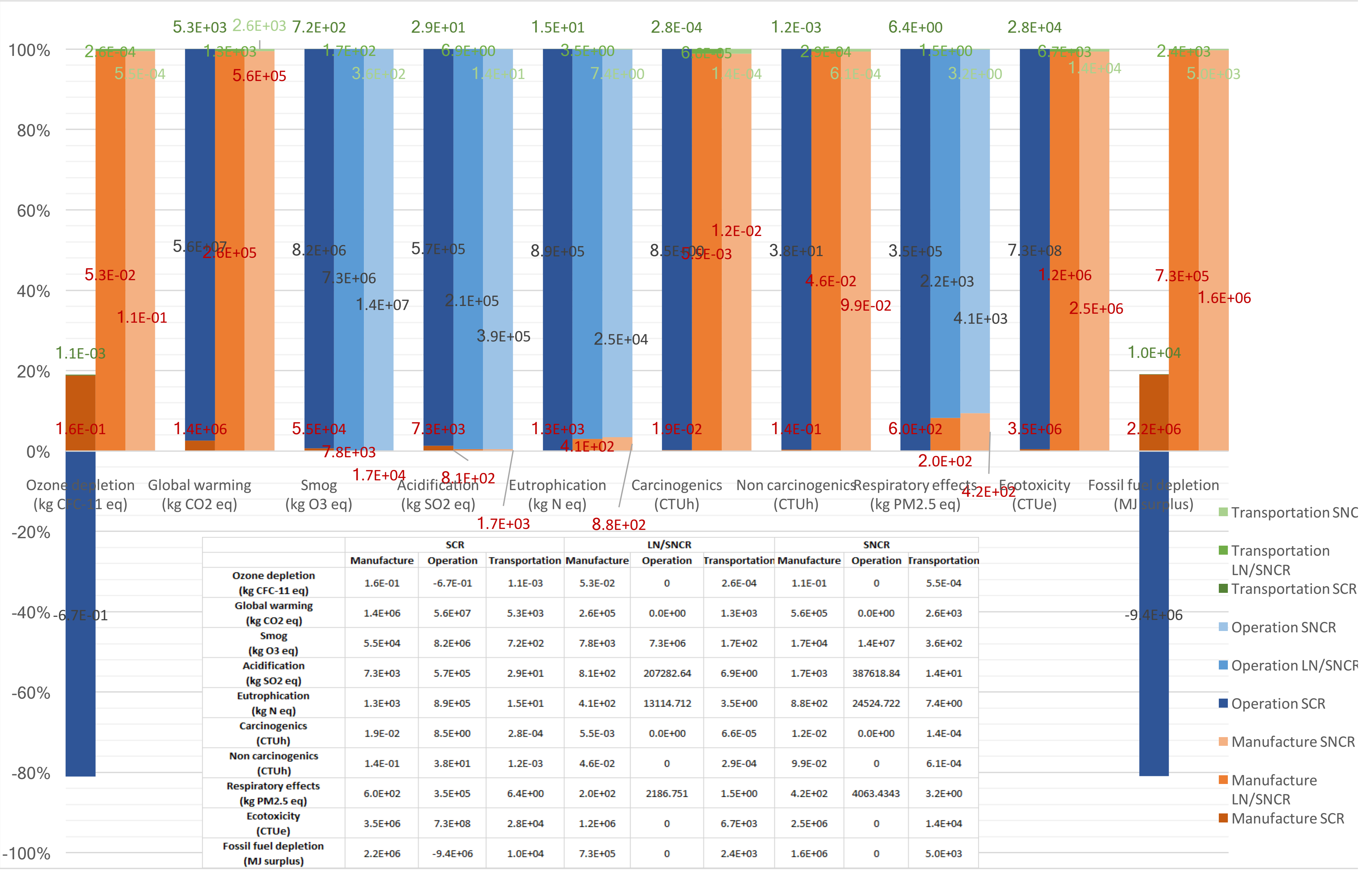


Figure 3.2 Characterization Results of Scenarios compared to untreated gas (TRACI)



	SCR			LN/SNCR			SNCR		
	Manufacture	Operation	Transportation	Manufacture	Operation	Transportation	Manufacture	Operation	Transportation
Abiotic depletion (kg Sb eq)	7.8E+03	3.6E+05	3.8E+01	2.5E+03	0	8.9E+00	5.3E+03	0	1.9E+01
Acidification (kg SO2 eq)	3.1E+03	5.6E+05	2.5E+01	8.5E+02	1.5E+05	5.8E+00	1.8E+03	2.8E+05	1.2E+01
Eutrophication (kg PO4- eq)	7.8E+02	4.2E+05	9.2E+00	2.0E+02	4.1E+04	2.2E+00	4.3E+02	7.5E+04	4.6E+00
Global warming (GWP100) (kg CO2 eq)	1.4E+06	5.6E+07	5.3E+03	2.6E+05	0	1.3E+03	5.6E+05	0	2.6E+03
Ozone layer depletion (ODP) (kg CFC-11 eq)	1.2E-01	-6.4E-01	8.2E-04	4.0E-02	0	2.0E-04	8.5E-02	0	4.1E-04
Human toxicity (kg 1,4-DB eq)	5.8E+05	4.4E+07	3.4E+03	1.9E+05	3.5E+05	8.0E+02	4.2E+05	6.6E+05	1.7E+03
Fresh water quatic econtox (kg 1,4-DB eq)	1.4E+05	6.1E+07	1.2E+03	4.9E+04	0	2.9E+02	1.0E+05	0	6.1E+02
Marine aquatic ecotoxicity (kg 1,4-DB eq)	4.5E+08	1.3E+11	2.5E+06	1.5E+08	0	5.8E+05	3.2E+08	0	1.2E+06
Terrestrial ecotoxicity (kg 1,4-DB eq)	9.0E+03	1.7E+05	8.3E+00	3.0E+03	0	2.0E+00	6.4E+03	0	4.2E+00
Photochemical oxidation (kg C2H4 eq)	3.8E+02	1.9E+04	1.1E+00	4.8E+01	0	2.6E-01	1.0E+02	0	5.4E-01

Figure 3.3 Proportion of characterization results in each unit process (CML 2 Baseline 2000)



	SCR			LN/SNCR			SNCR		
	Manufacture	Operation	Transportation	Manufacture	Operation	Transportation	Manufacture	Operation	Transportation
Ozone depletion (kg CFC-11 eq)	1.6E-01	-6.7E-01	1.1E-03	5.3E-02	0	2.6E-04	1.1E-01	0	5.5E-04
Global warming (kg CO2 eq)	1.4E+06	5.6E+07	5.3E+03	2.6E+05	0.0E+00	1.3E+03	5.6E+05	0.0E+00	2.6E+03
Smog (kg O3 eq)	5.5E+04	8.2E+06	7.2E+02	7.8E+03	7.3E+06	1.7E+02	1.7E+04	1.4E+07	3.6E+02
Acidification (kg SO2 eq)	7.3E+03	5.7E+05	2.9E+01	8.1E+02	207282.64	6.9E+00	1.7E+03	387618.84	1.4E+01
Eutrophication (kg N eq)	1.3E+03	8.9E+05	1.5E+01	4.1E+02	13114.712	3.5E+00	8.8E+02	24524.722	7.4E+00
Carcinogenics (CTUh)	1.9E-02	8.5E+00	2.8E-04	5.5E-03	0.0E+00	6.6E-05	1.2E-02	0.0E+00	1.4E-04
Non carcinogenics (CTUh)	1.4E-01	3.8E+01	1.2E-03	4.6E-02	0	2.9E-04	9.9E-02	0	6.1E-04
Respiratory effects (kg PM2.5 eq)	6.0E+02	3.5E+05	6.4E+00	2.0E+02	2186.751	1.5E+00	4.2E+02	4063.4343	3.2E+00
Ecotoxicity (CTUe)	3.5E+06	7.3E+08	2.8E+04	1.2E+06	0	6.7E+03	2.5E+06	0	1.4E+04
Fossil fuel depletion (MJ surplus)	2.2E+06	-9.4E+06	1.0E+04	7.3E+05	0	2.4E+03	1.6E+06	0	5.0E+03

Figure 3.4 Proportion of characterization results in each unit process (TRACI)

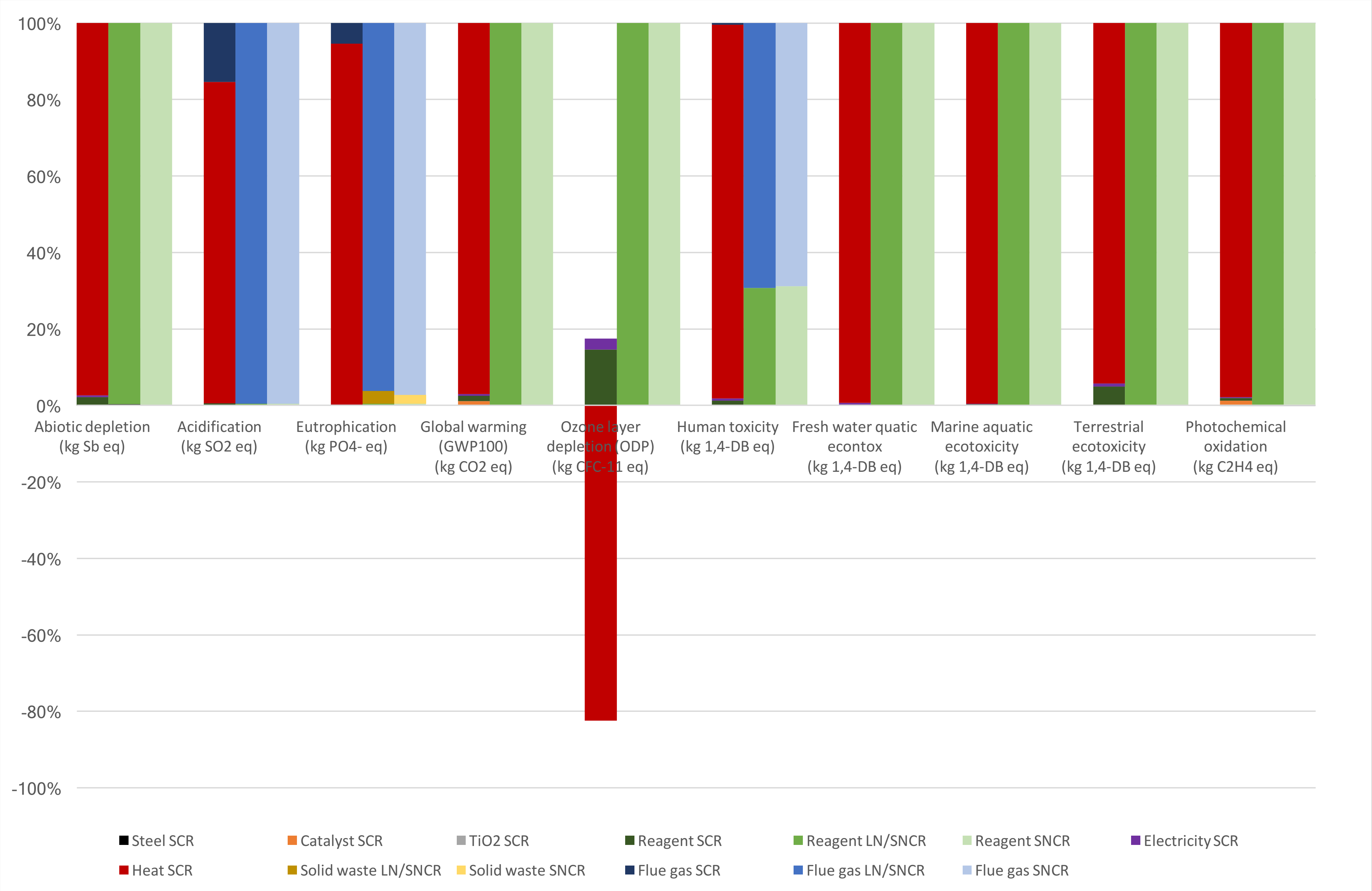


Figure 3.5 Proportion of characterization results in each component (CML 2 Baseline 2000)

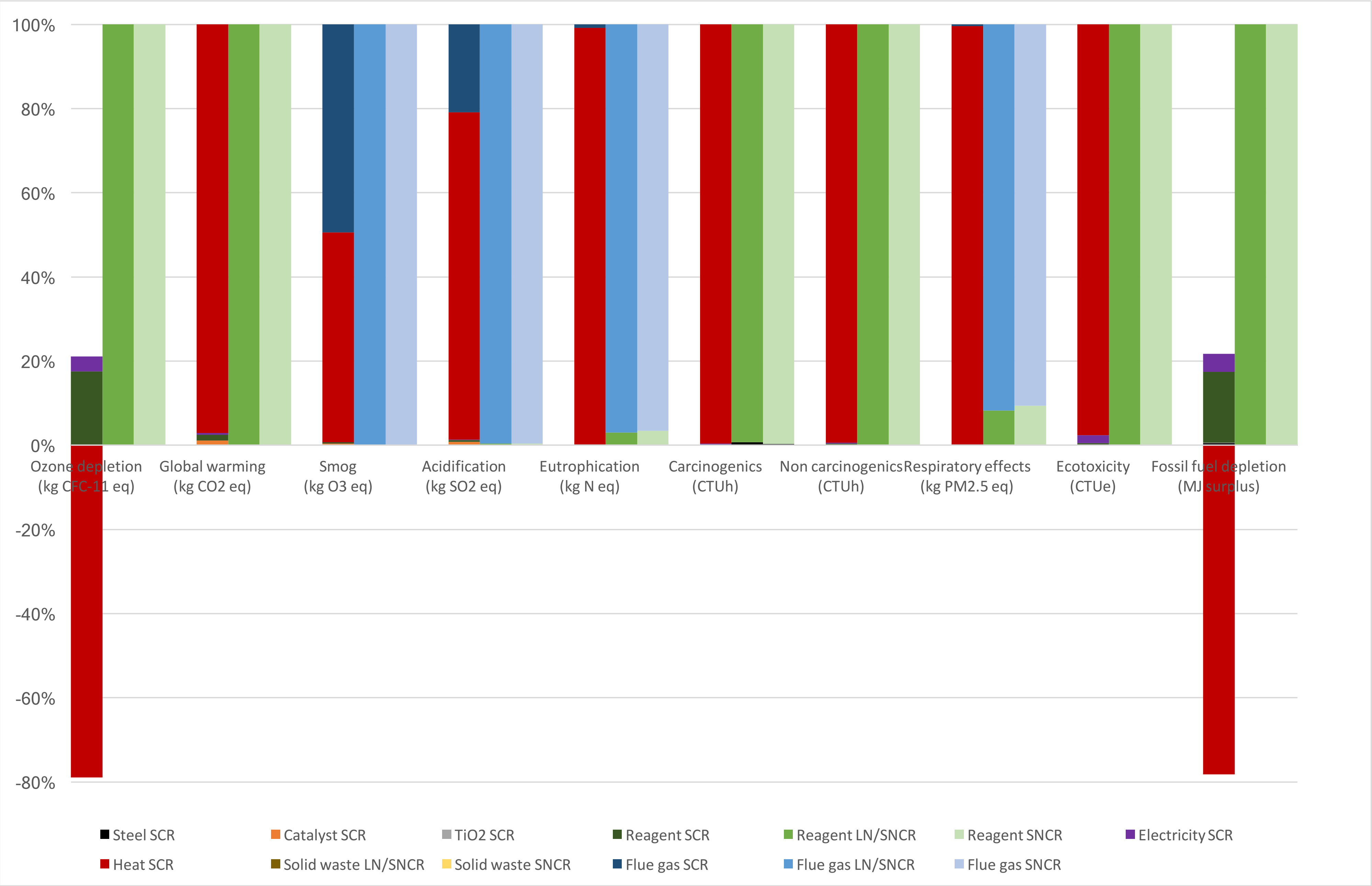


Figure 3.6 Proportion of characterization results in each component (TRACI)

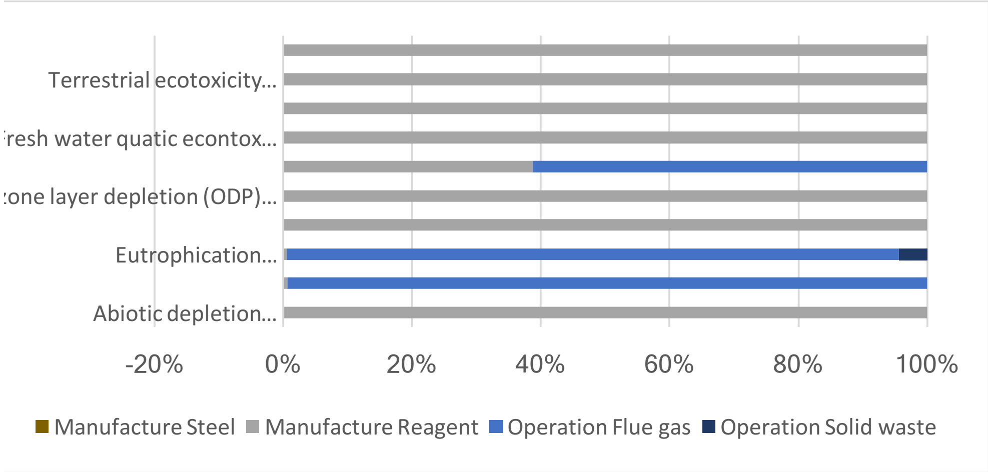


Figure 3.7 Proportion of characterization results for SNCR (CML)

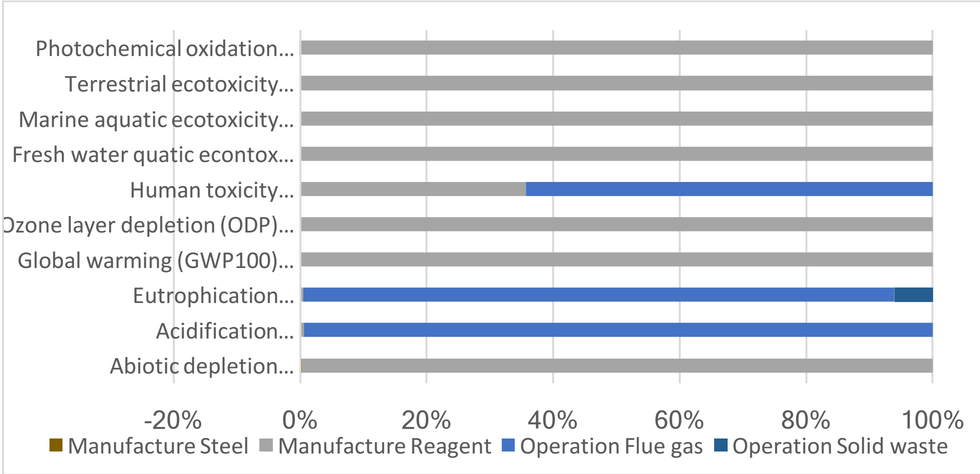
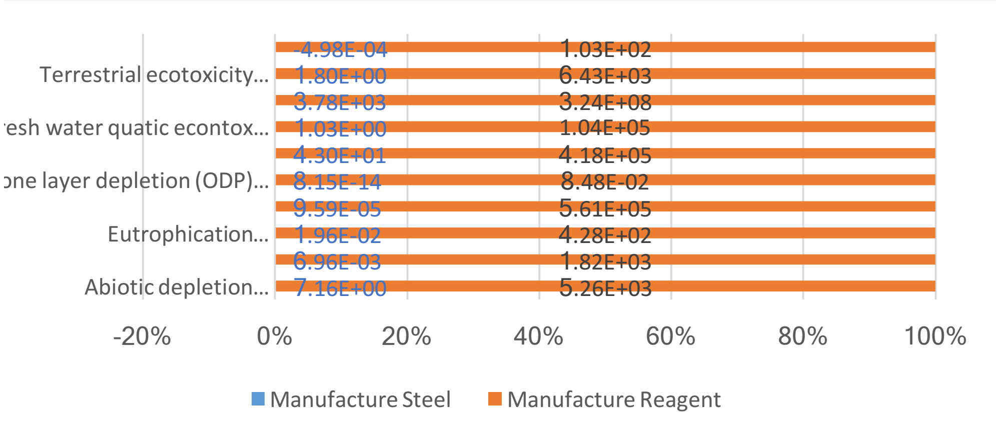


Figure 3.8 Proportion of characterization results for LN/SNCR (CML)



igure 3.9 Proportion of characterization results for SNCR Manufacture (CML)

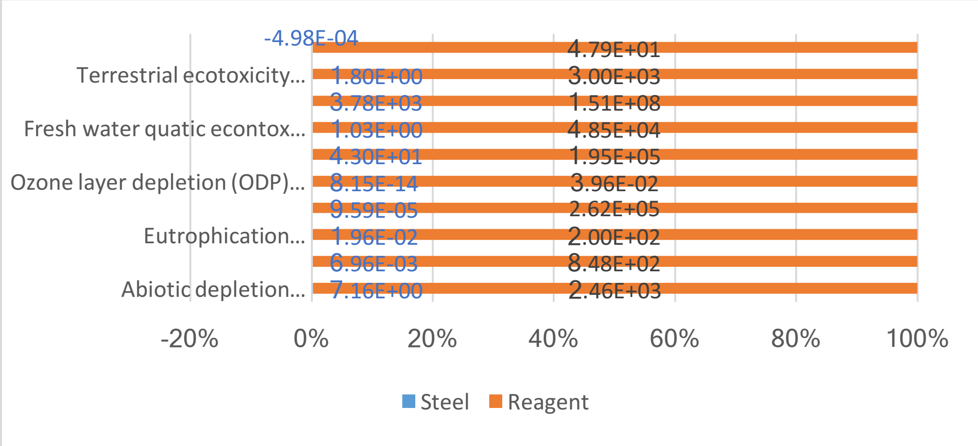


Figure 3.10 Proportion of characterization results for LN/SNCR Manufacture (CML)

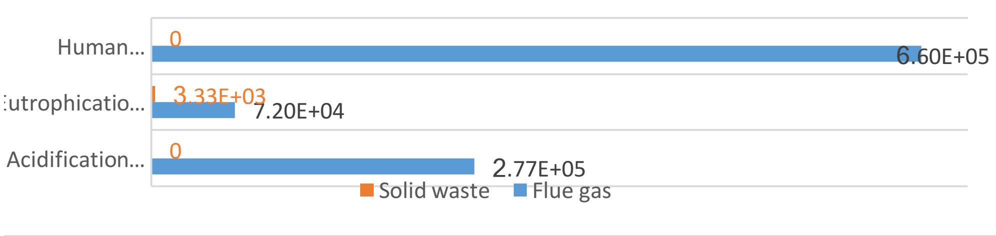


Figure 3.11 Proportion of characterization results for SNCR Operation (CML)

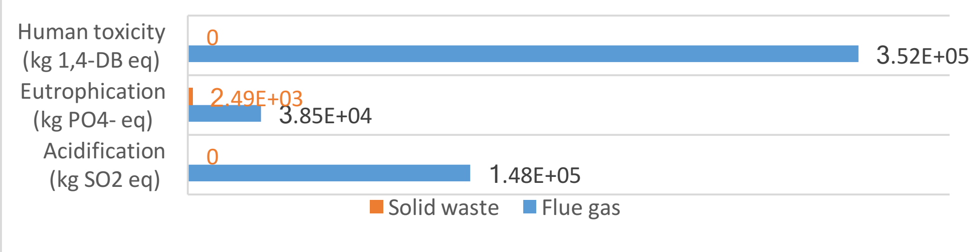


Figure 3.12 Proportion of characterization results for LN/SNCR (CML)

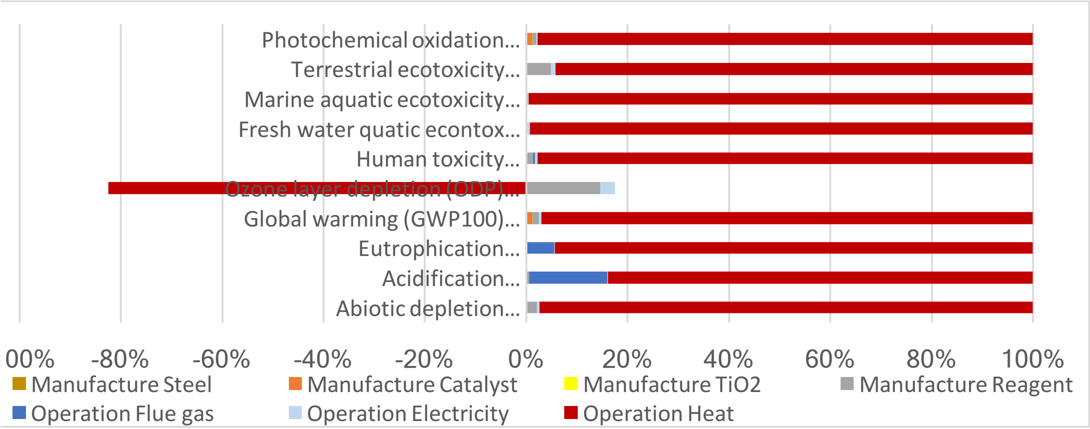


Figure 3.13 Proportion of characterization results for SCR (CML)

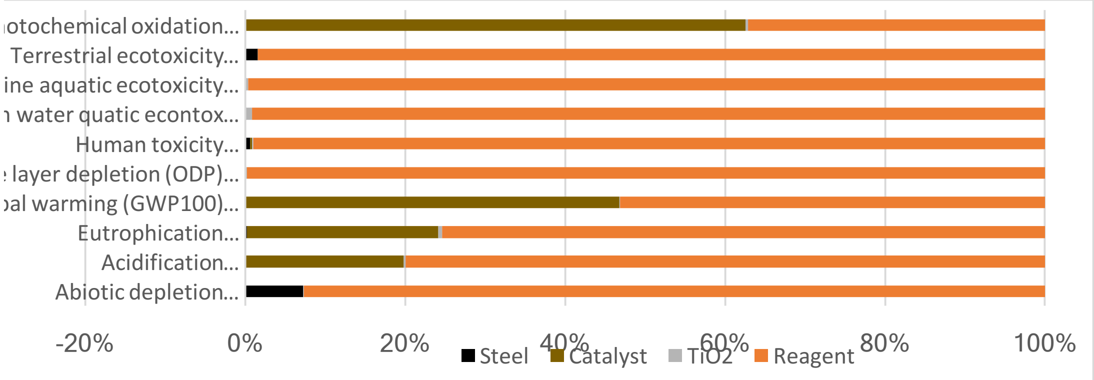
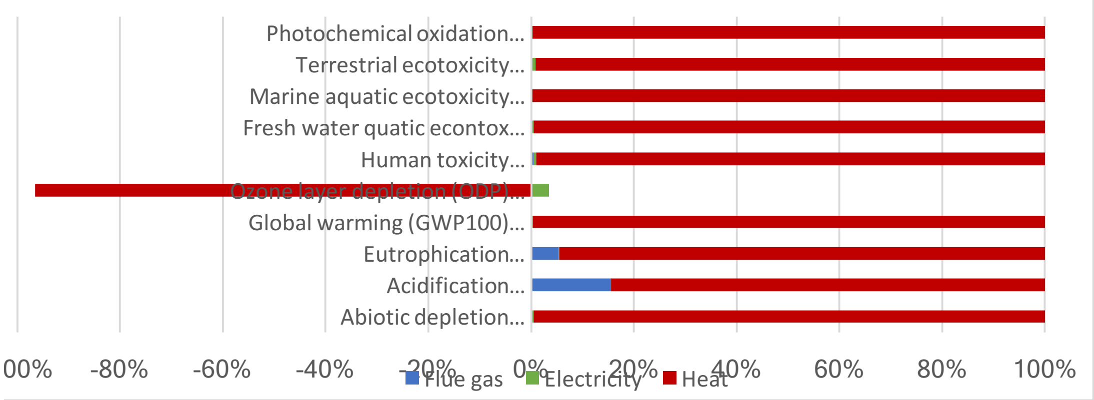


Figure 3.14 Proportion of characterization results for SCR Manufacture (CML)



igure 3.15 Proportion of characterization results for SCR Operation (CML)

Table 3.3 Characterization results for SCR in composition (CML)

	Manufacture				Operation		
	Steel	Catalyst	TiO2	Reagent	Flue gas	Electricity	Heat
Abiotic depletion (kg Sb eq)	5.64E+02	0	9.47E+00	7.22E+03	0	1.85E+03	3.57E+05
Acidification (kg SO2 eq)	5.48E-01	6.17E+02	8.84E+00	2.50E+03	8.69E+04	2.99E+02	4.72E+05
Eutrophication (kg PO4- eq)	1.54E+00	1.86E+02	3.86E+00	5.87E+02	2.24E+04	1.88E+02	3.93E+05
Global warming (GWP100) (kg CO2 eq)	7.55E-03	6.78E+05	1.34E+03	7.70E+05	0	2.37E+05	5.53E+07
Ozone layer depletion (ODP) (kg CFC-11 eq)	6.42E-12	0	2.67E-04	1.16E-01	0	2.36E-02	-6.60E-01
Human toxicity (kg 1,4-DB eq)	3.38E+03	1.52E+03	8.99E+02	5.74E+05	1.98E+05	2.24E+05	4.40E+07
Fresh water aquatic eco-toxicity (kg 1,4-DB eq)	8.11E+01	0	1.15E+03	1.43E+05	0	3.01E+05	6.12E+07
Marine aquatic eco-toxicity (kg 1,4-DB eq)	2.98E+05	0	1.45E+06	4.45E+08	0	1.94E+08	1.30E+11
Terrestrial eco-toxicity (kg 1,4-DB eq)	1.42E+02	0	1.01E+00	8.83E+03	0	1.47E+03	1.72E+05
Photochemical oxidation (kg C2H4 eq)	-3.92E-02	2.38E+02	1.11E+00	1.41E+02	0	3.98E+01	1.89E+04

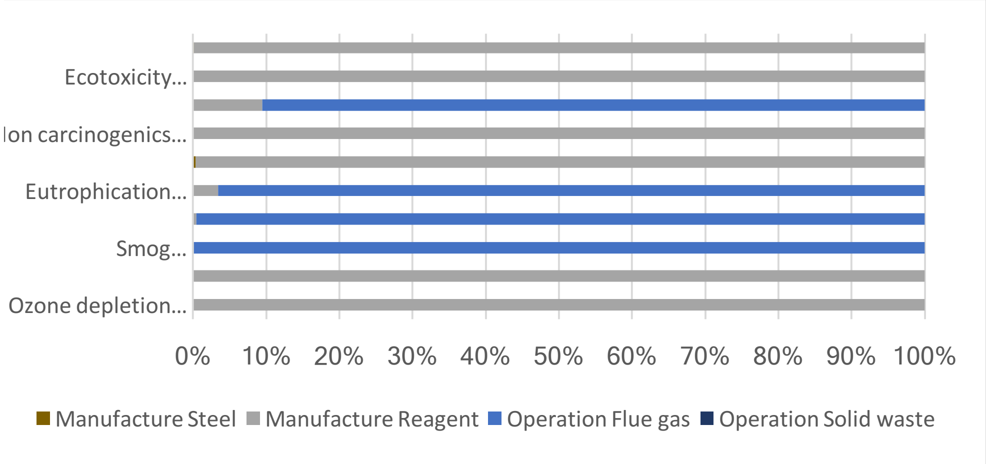


Figure 3.16 Proportion of characterization results for SNCR (TRACI)

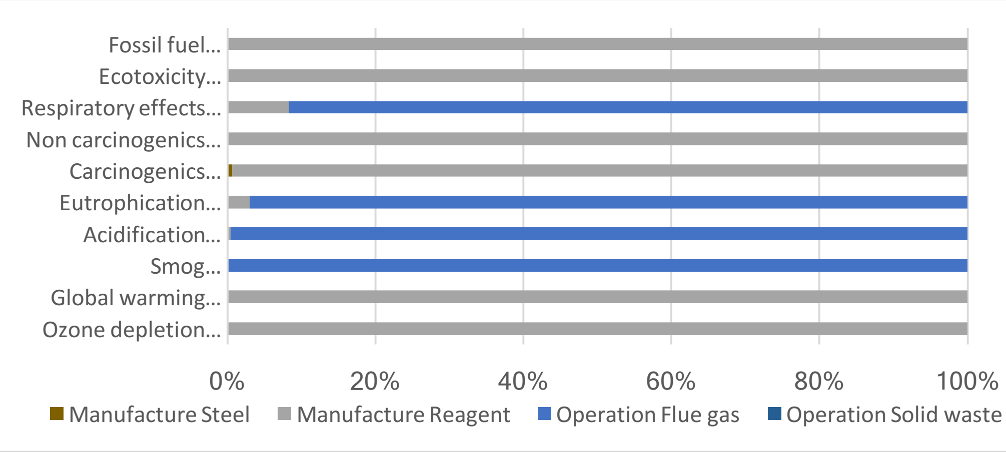
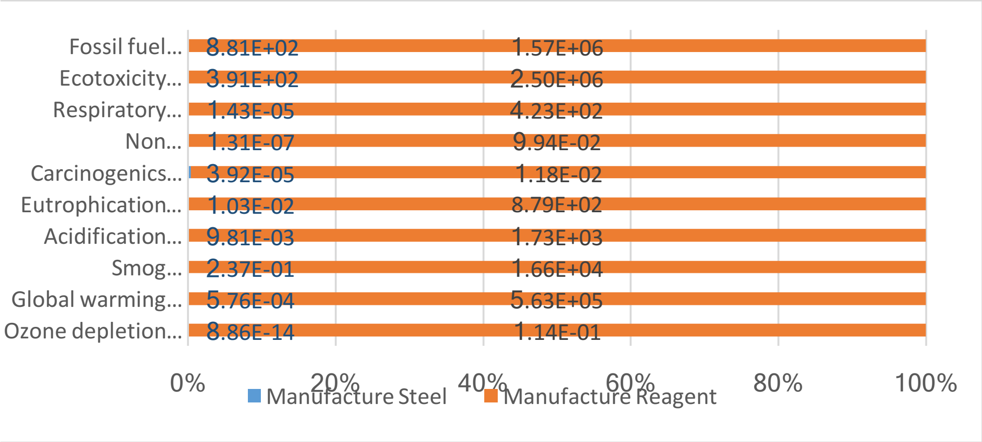


Figure 3.17 Proportion of characterization results for LN/SNCR (TRACI)



gure 3.18 Proportion of characterization results for SNCR Manufacture (TRACI)

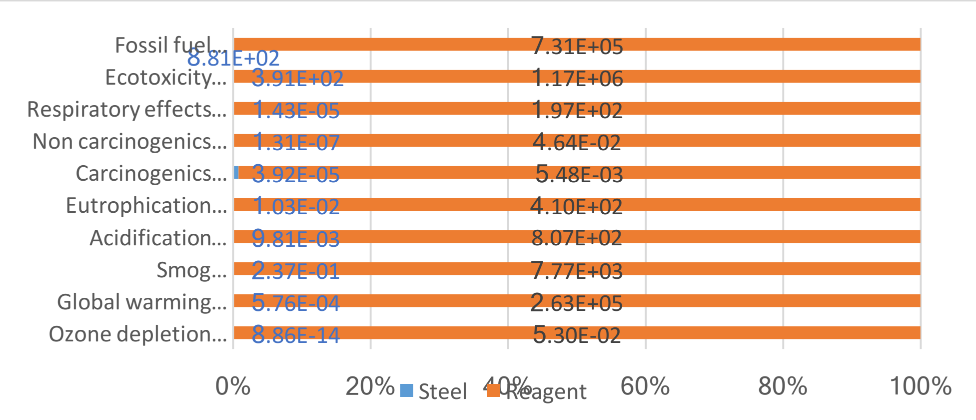


Figure 3.19 Proportion of characterization results for LN/SNCR Manufacture (TRACI)

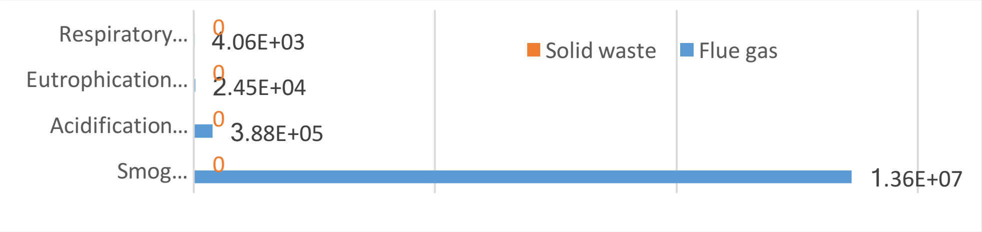


Figure 3.20 Proportion of characterization results for SNCR Operation (TRACI)

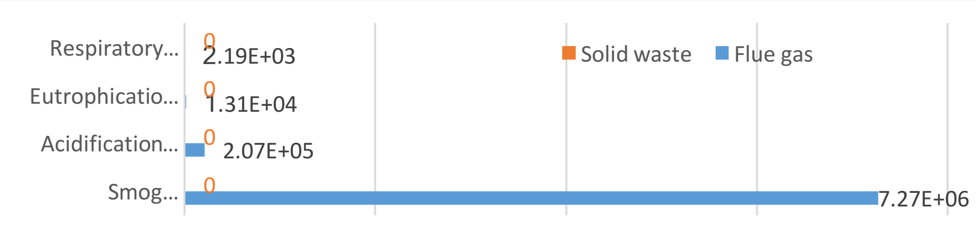


Figure 3.21 Proportion of characterization results for LN/SNCR (TRACI)

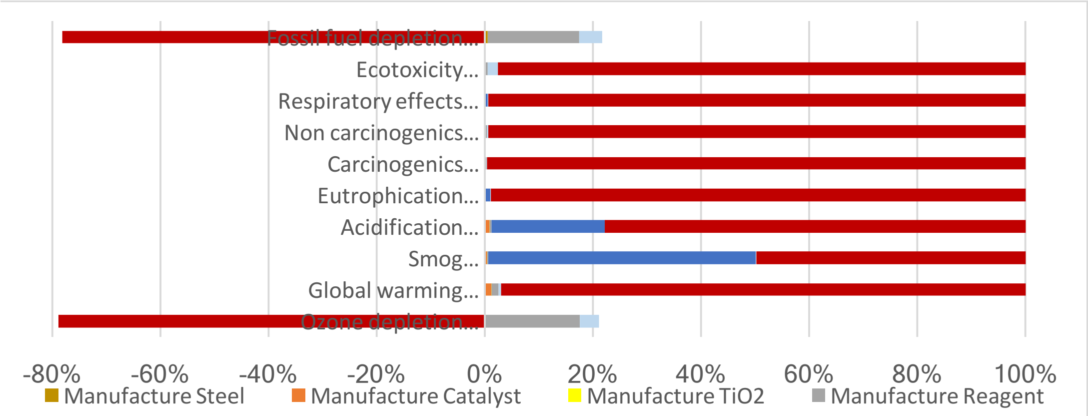
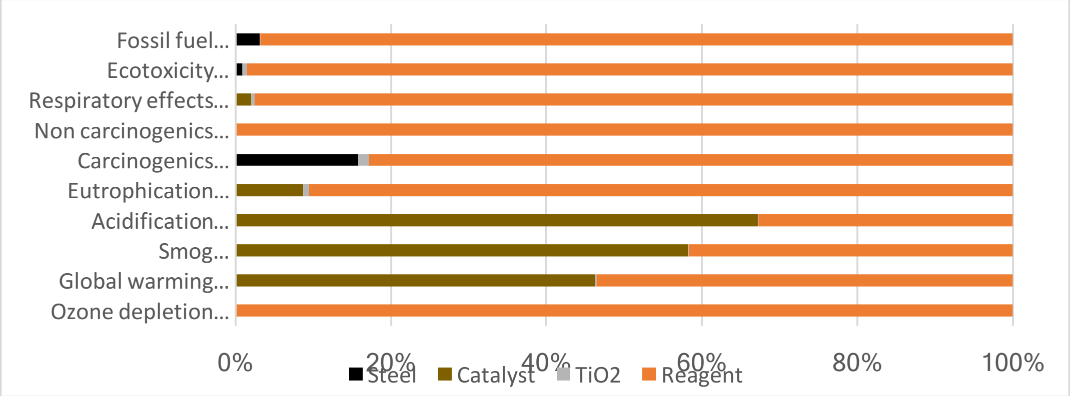
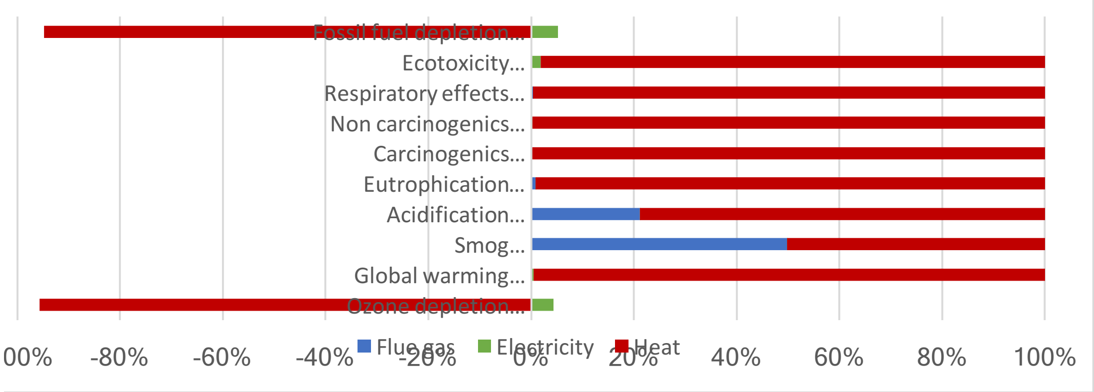


Figure 3.22 Proportion of characterization results for SCR (TRACI)



ure 3.23 Proportion of characterization results for SCR Manufacture (TRACI)



gure 3.24 Proportion of characterization results for SCR Operation (TRACI)

Table 3.4 Characterization results for SCR in composition (TRACI)

	Manufacture				Operation		
	Steel	**Catalyst**	**TiO$_2$**	**Reagent**	**Flue gas**	**Electricity**	**Heat**
Ozone depletion (kg CFC-11 eq)	6.98E-12	0	2.26E-04	1.56E-01	0	3.19E-02	-7.04E-01
Global warming (kg CO2 eq)	4.54E-02	6.67E+05	1.31E+03	7.73E+05	0	2.38E+05	5.53E+07
Smog (kg O3 eq)	1.87E+01	3.19E+04	7.33E+01	2.29E+04	4.09E+06	4.75E+03	4.12E+06
Acidification (kg SO2 eq)	7.73E-01	4.87E+03	8.06E+00	2.37E+03	1.21E+05	3.06E+02	4.50E+05
Eutrophication (kg N eq)	8.08E-01	1.15E+02	9.71E+00	1.21E+03	7.63E+03	3.97E+02	8.81E+05
Carcinogenics (CTUh)	3.08E-03	0	2.69E-04	1.61E-02	0	1.00E-02	8.52E+00
Non carcinogenics (CTUh)	1.03E-05	0	2.11E-04	1.37E-01	0	8.78E-02	3.76E+01
Respiratory effects (kg PM2.5 eq)	1.13E-03	1.19E+01	2.61E+00	5.81E+02	1.37E+03	5.50E+01	3.53E+05
Ecotoxicity (CTUe)	3.08E+04	1.99E+02	1.92E+04	3.44E+06	0	1.37E+07	7.19E+08
Fossil fuel depletion (MJ surplus)	6.94E+04	0	1.35E+03	2.15E+06	0	5.52E+05	-9.99E+06

3.3 Sensitivity analysis

3.3.1 Sensitivity analysis for fuel type

From the characterization results in previous section, heating was found to be the principle component contributing to negative environmental impact in SCR scenario whose characterization value was extremely higher than the other two scenarios in most of environmental categories except ozone layer depletion. The characterization value in previous section was calculated based on the assumption that heating energy was provided by district and industrial heating other than natural gas whose life cycle inventories only provided a general result without indicated specific energy source, thus changing heating energy into different specific source might mitigate the environmental impact caused by SCR. The characterization results for SCR operation with different district or industrial heating energy sources including oil, natural gas, MSW incineration and coal are presented in **Figure 3.25** with CML method and **Figure 3.26** with TRACI method, the results for the general energy other than natural gas which was used for calculation in previous section are also presented as reference. The results demonstrated that:

- CML method, AP and HTP: Coal>Other>Oil>MSW>Natural gas
- CML method, EP: Other>Coal>Oil>MSW>Natural gas
- TRACI method, EP and RE: Other> Coal>Oil>MSW>Natural gas
- TRACI method, Smog: Other>Coal>MSW>Oil>Natural gas
- TRACI method, AP: Coal>Other>Oil>MSW>Natural gas

Based on the characterization results on the impact categories which would be influenced by the direct NO_X emission without any APC measures, MSW and Nautral gas seems two of the heating energy source with best environmental performance. This agreed the information given by [9] that the combustion gas in most of MSWI facility is reheated by the steam from boiler or natural gas. From the LCIA given in this study, although natural gas has larger negative impact on ODP, GWP and resource depletion (ADP for CML and FFD for TRACIS) than MSW incineration, it has a positive impact on impact related to human health (RE, CP and NCP for TRACI) as well as the eco-toxicity, while MSW has negative impact on these human health categories. Thus, in this perspective, natural gas seems the best choice for additional heating energy resource.

Characterization results with different reheating energy resource with detailed components are presented in percentage scale in **Figure 3.27** with CML and in **Figure 3.28** with TRACI. It was shown that the influence from catalyst and reagent production, flue gas emission and electricity to overcome pressure was more obvious when using different reheating energy resource, especially for the flue gas on AP and EP, catalyst on GWP for with methodologies as well as flue gas on smog when using TRACI.

Normalization

The normalized results for SNCR, LN/SNCR and SCR operated with natural compared to untreated gas was presented in **Figure 3.31** with CML methods and **Figure 3.30** with TRACI.. The result for comparing normalized value among scenarios in each categories was similar as for comparing characterized value which was presented in **Figure 3.29**. Concentrating on the impact would be contributed by untreated gas, both characterization and normalization results showed that

- CML methods, AP, EP and HTP: Untreated>SNCR>LN/SNCR>SCR
- TRACI method, AP, EP, RE and Smog: Untreated>SNCR>LN/SNCR>SCR

From the result, SCR showed a positive environmental performance on EP, HTP, RE and eco-toxicity and obvious lower environmental impact than the second best scenario LN/SNCR with about 50% of its characterization and normalization value in these impact category, while the characterization and normalization value of LN/SNCR was about half of that for SNCR which also showed an obvious mitigation on negative environmental performance. However, SCR also has a large negative impact on ADP, GWP, ODP, PO and FFD in which categories with a very low characterization value for SNCR and LN/SNCRThe normalization results for CML was based on the consideration on the world contribution, while the normalization results for TRACI was based on the consideration on the U.S.. The normalization results given by CML showed that the top contribution among the categories and scenario to the world negative environmental impact was

- Untreated gas on AP and EP
- SCR on ADP
- SNCR and LN/SNCR on MEP

The normalization results given by TRACI showed that the top contribution among the categories and scenario to the U.S. negative environmental impact was

- Smog, AP and EP from untreated gas
- SCR on FFD

Therefore, overall SCR seems the scenario with best environmental performance among these three technologies, because it mitigate the most environmental impact categories which would have higher impact when thinking a geographic scope. However, if focus on the resource depletion, LN/SNCR might be a better choice.

3.3.2 Sensitivity analysis for operating temperature and energy recovery

As indicated by [9], the suggested operating temperature for catalyst in many plants is 250℃, while the operating temperature could go down to 180℃ but it is lack of experience. A sensitivity analysis for SCR using natural gas as heating energy resource operating at 180℃, 250℃ and 350℃ are compared to SNCR, LN/SNCR scenario by calculating the normalization value in impact per person per year with TRACI methodology, as shown in Figure 3.33. The results indicated that the negative environmental impact on Smog and AP would not be obviously mitigated, while the positive environmental impact from SCR with natural gas on eco-toxicity, human health and eutrophication would be decreased. However, an obvious mitigation on fossil fuel depletion and global warming with the operating temperature reduction was presented in the normalization results.

Another approach to reduce the consumption of heating energy is reheating the gas entering SCR by gas leaving SCR system. By increasing the heat exchange efficiency, the requirement on additional reheating energy for temperature compensation could be reduced. The reduced temperature was suggested at about 25℃ by [9]. . A sensitivity analysis for SCR using natural gas as heating energy resource with energy recovery equipment at high efficiency is compared to when without energy recovery and SNCR and LN/SNCR scenario by calculating the normalization value in impact per person per year with TRACI methodology, as shown in Figure 3.34. The results was similar as the sensitivity analysis for operating temperature that with higher energy recovery energy would not mitigate the environmental impact on AP and smog, but would decrease the positive environmental impact brought by SCR with natural gas without energy recovery such as eutrophication, eco-toxicity and human health. However, the negative environmental impact on global warming and fossil fuel depletion would be mitigated with the energy recovery.

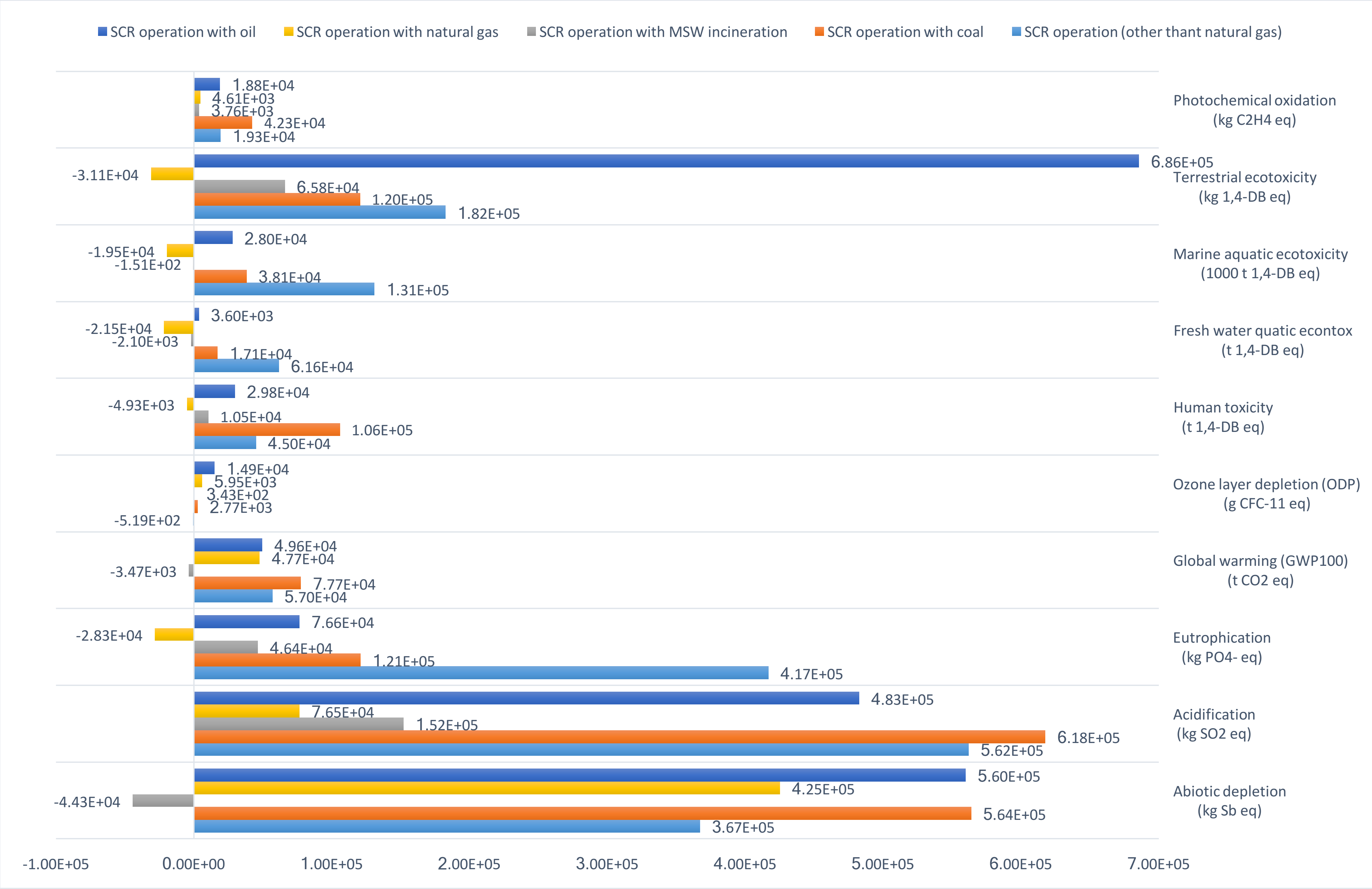


Figure 3.25 Characterization results for SCR operation with different heating energy sources (CML 2 Baseline 2000)

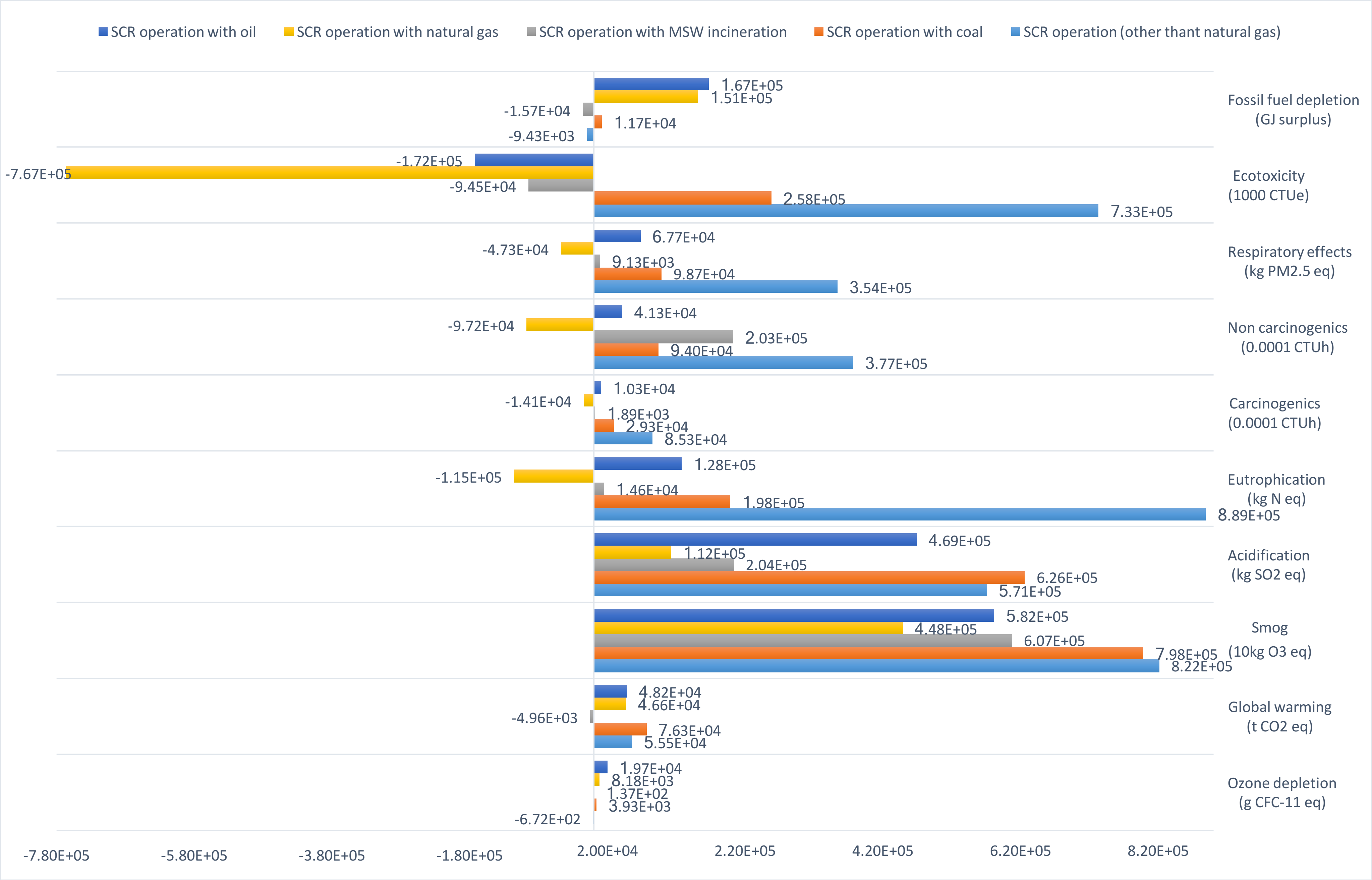


Figure 3.26 Characterization results for SCR operation with different heating energy sources (TRACI)

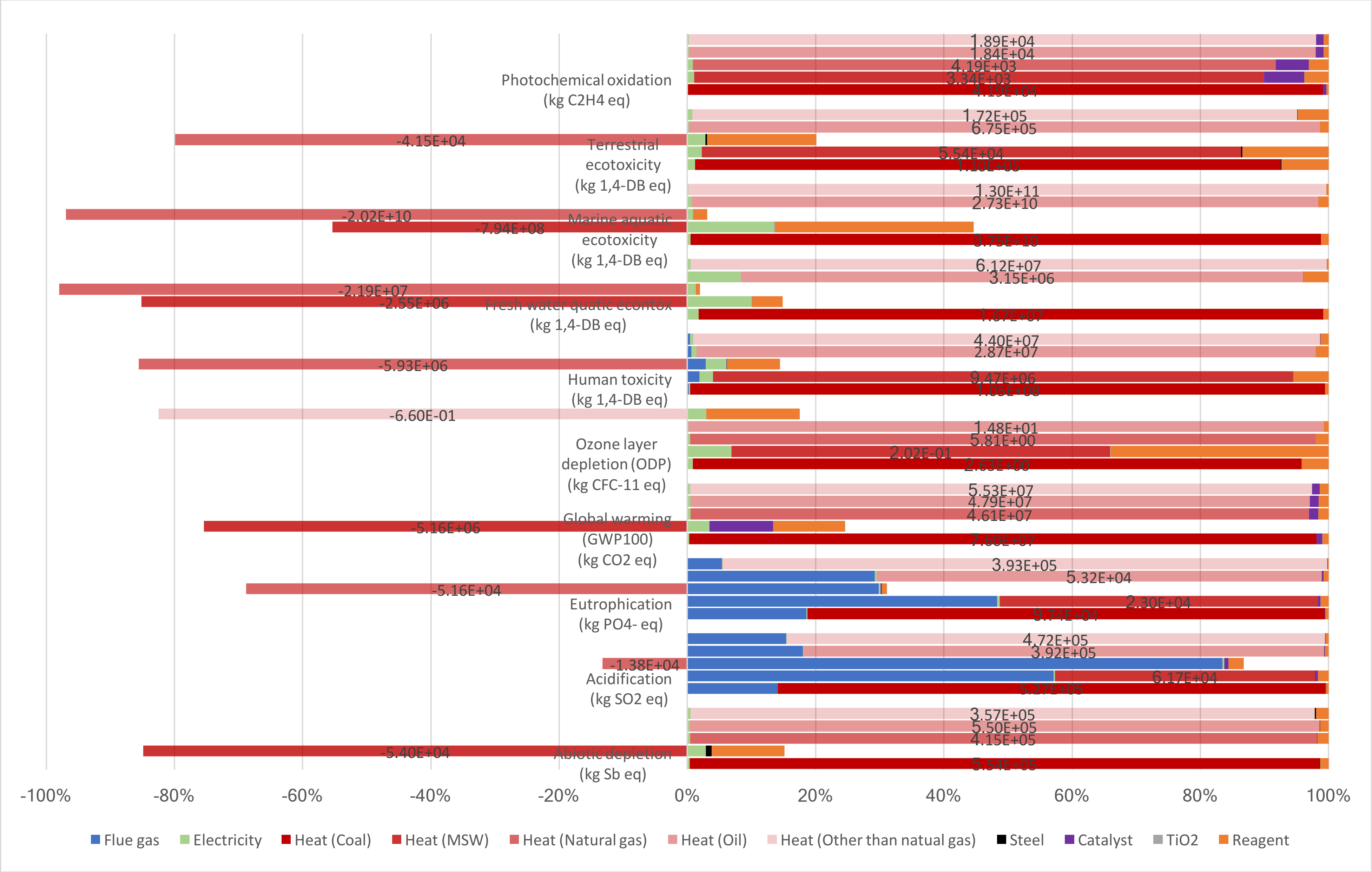


Figure 3.27 Characterization results for SCR operation with different heating energy sources in a percentage view detailed in component (CML)

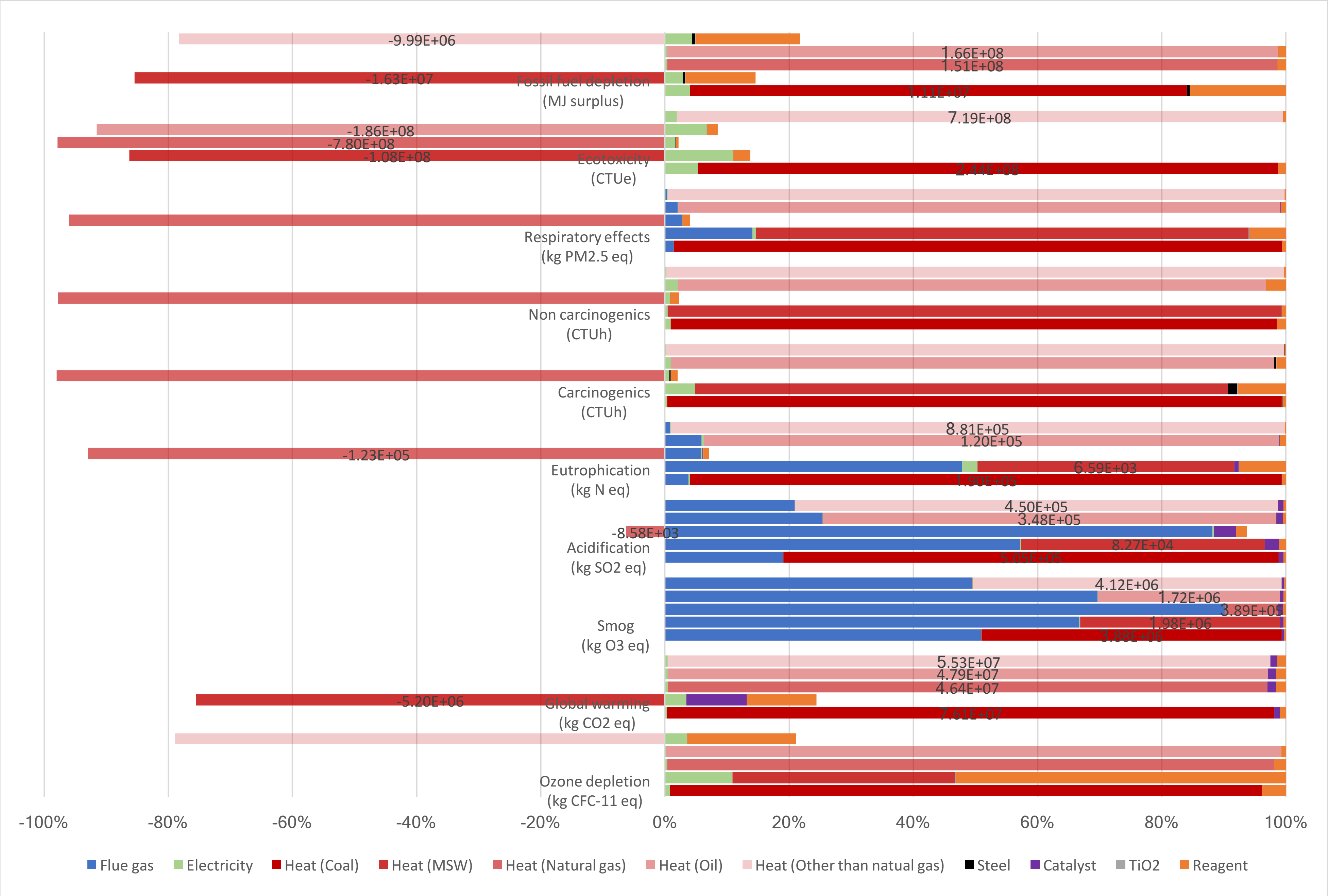


Figure 3.28 Characterization results for SCR operation with different heating energy sources in a percentage view detailed in component (TRACI)

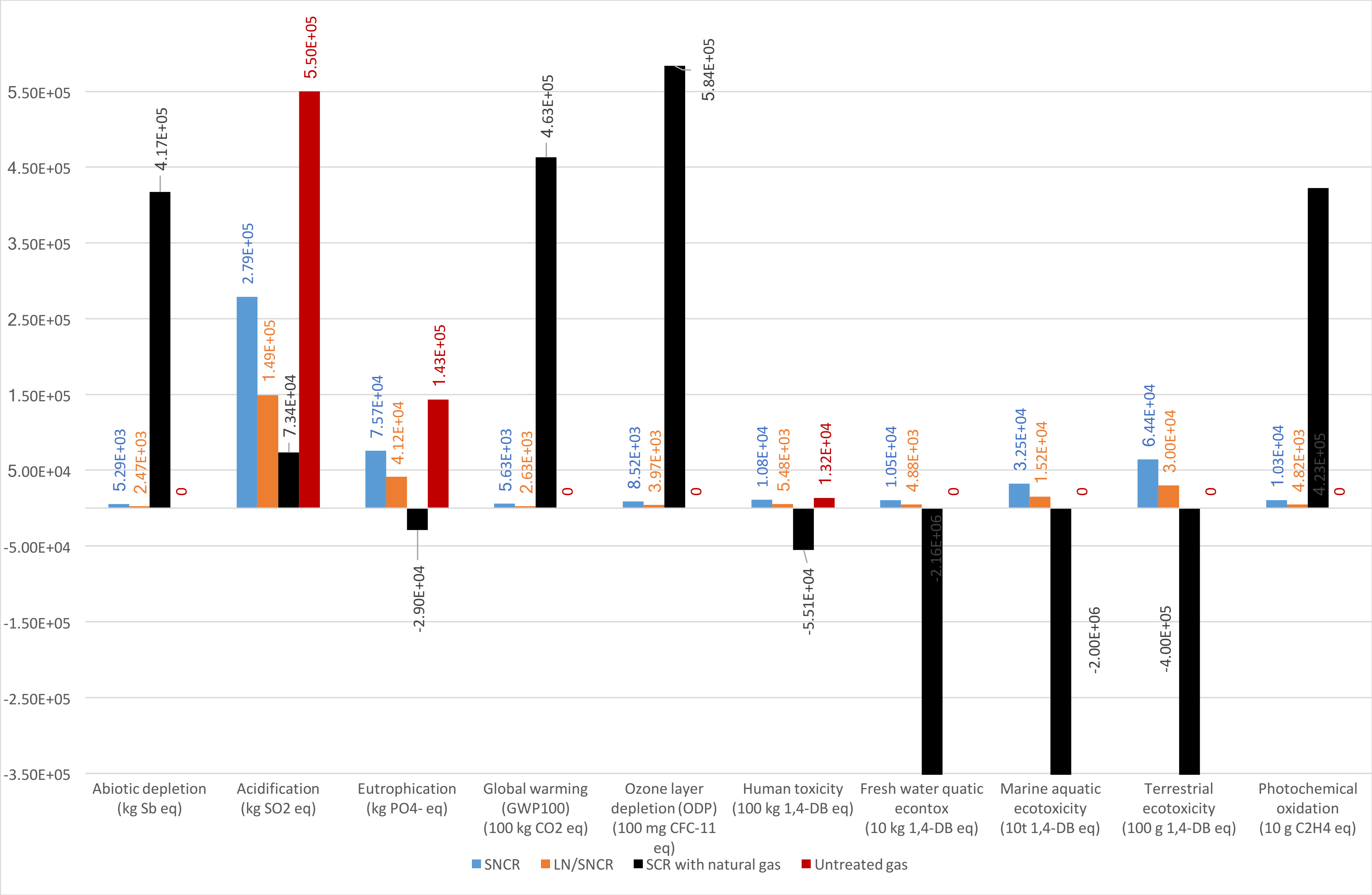


Figure 3.29 Characterization results for SNCR, LN/SNCR, SCR with natural gas and untreated gas (CML)

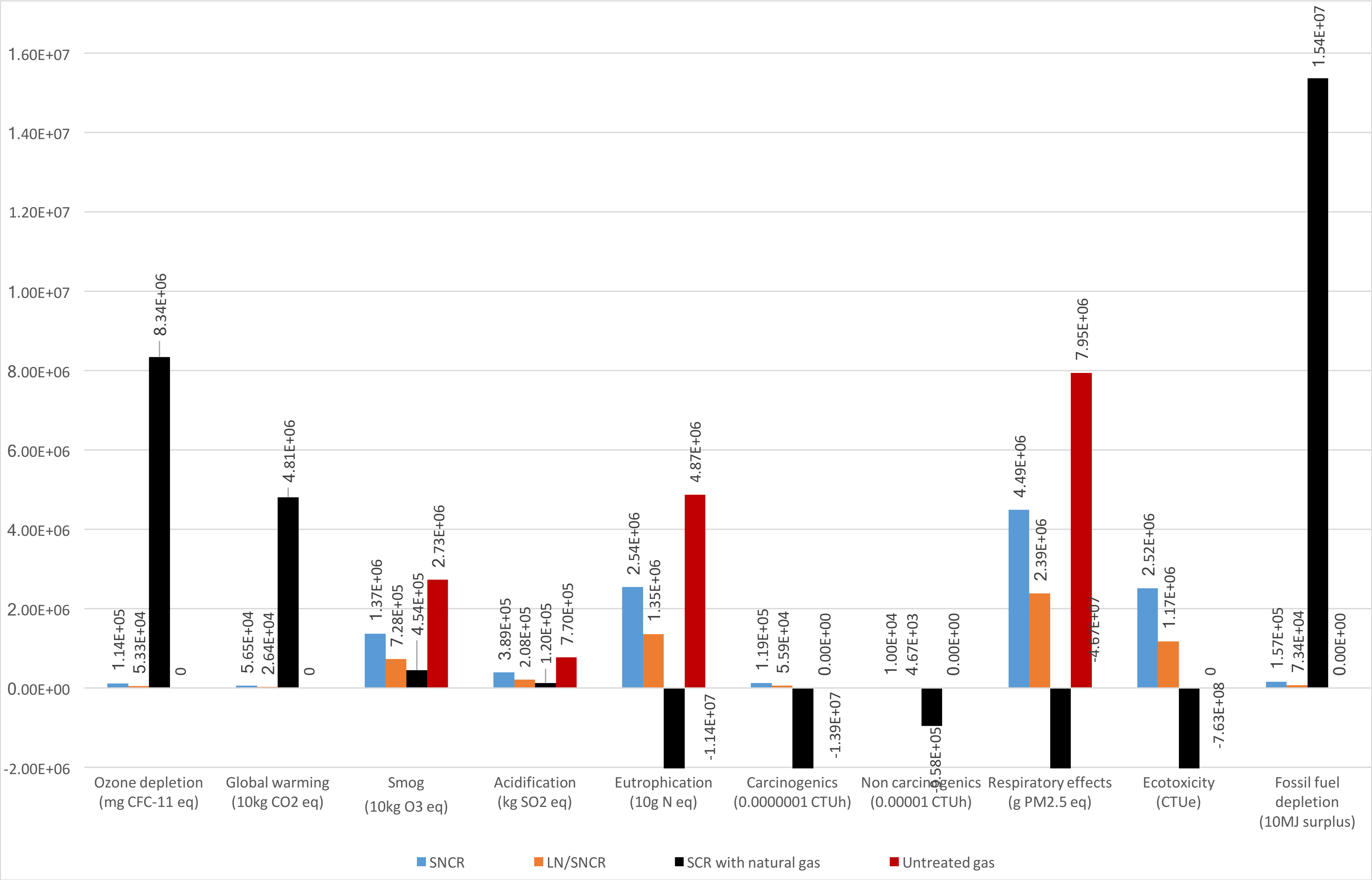


Figure 3.30 Characterization results for SNCR, LN/SNCR, SCR with natural gas and untreated gas (TRACI)

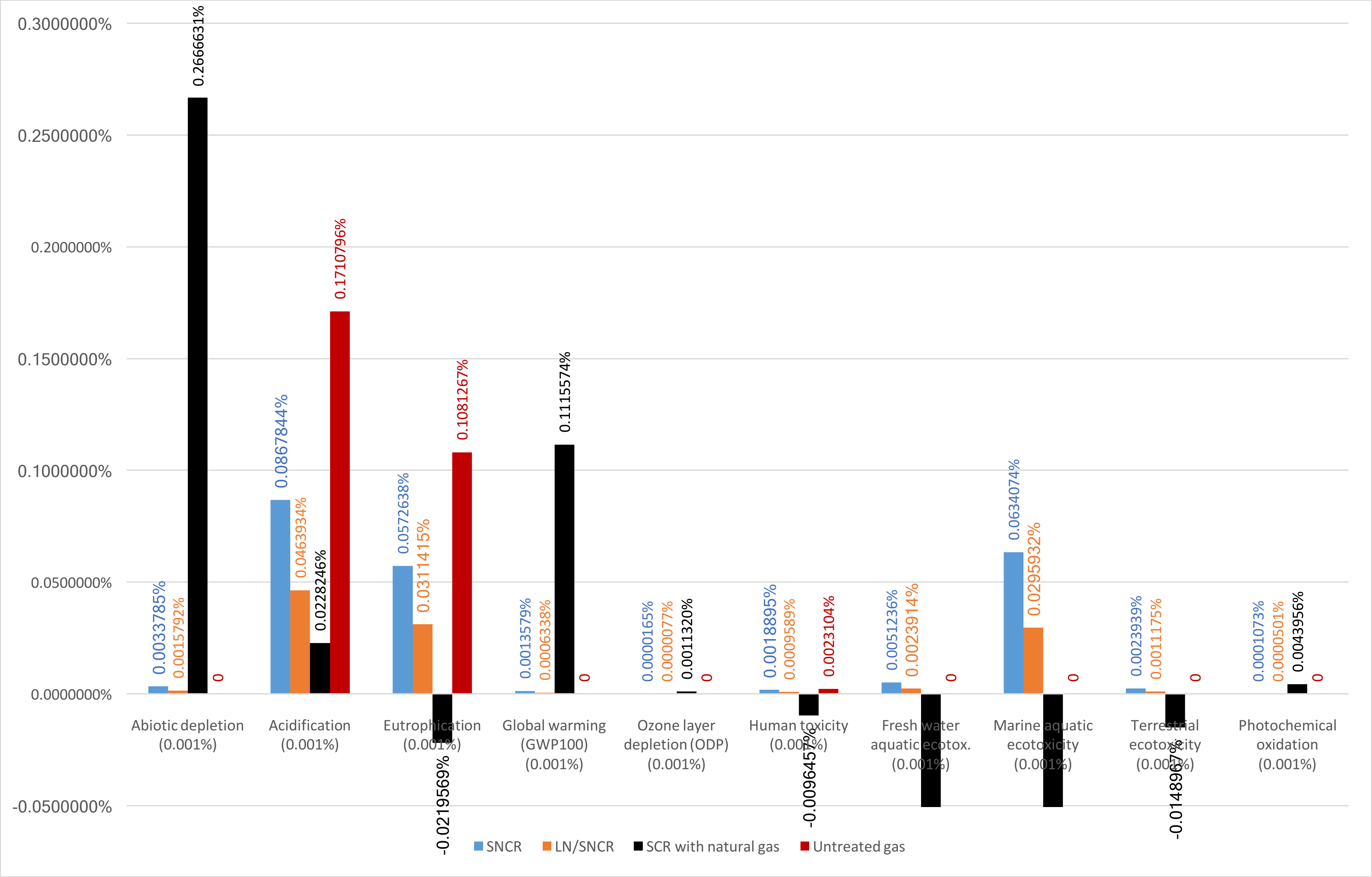


Figure 3.31 Normalization results for scenarios with SCR in natural gas for heating and compared to untreated gas (CML)

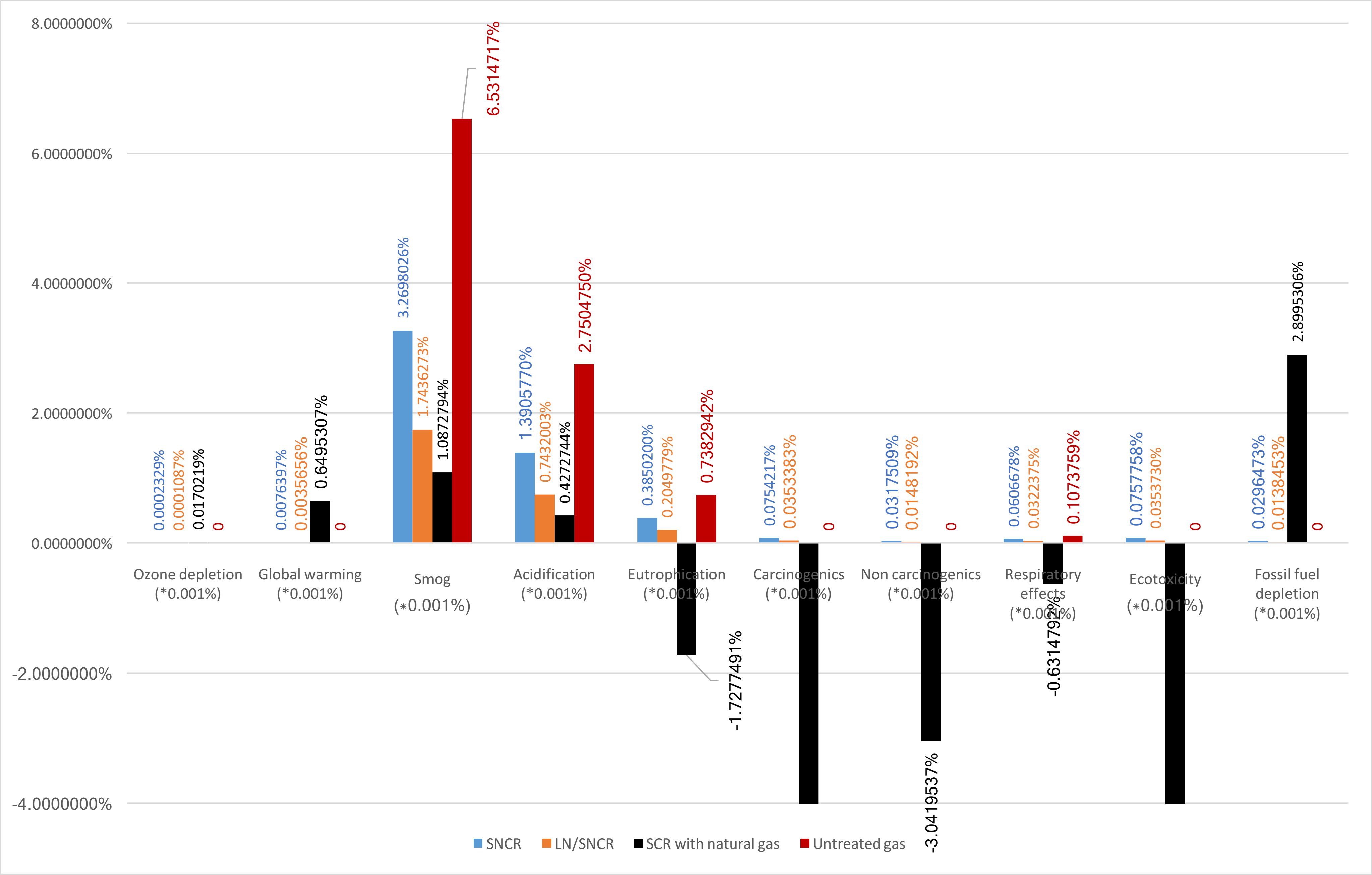


Figure 3.32 Normalization results for scenarios with SCR in natural gas for heating and compared to untreated gas (TRACI)

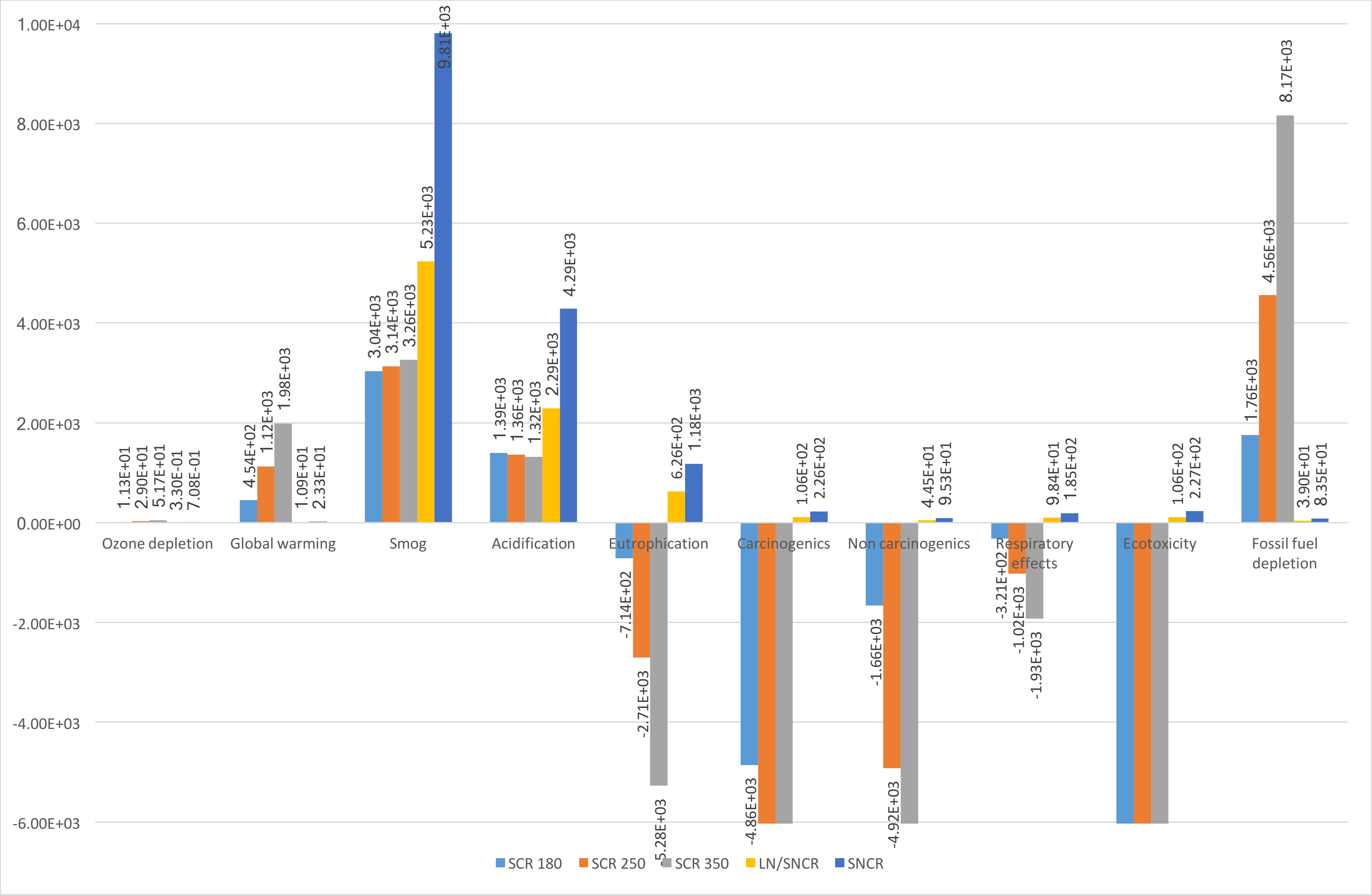


Figure 3.33 Normalization result for SCR operating with different operating temperature (TRACI)

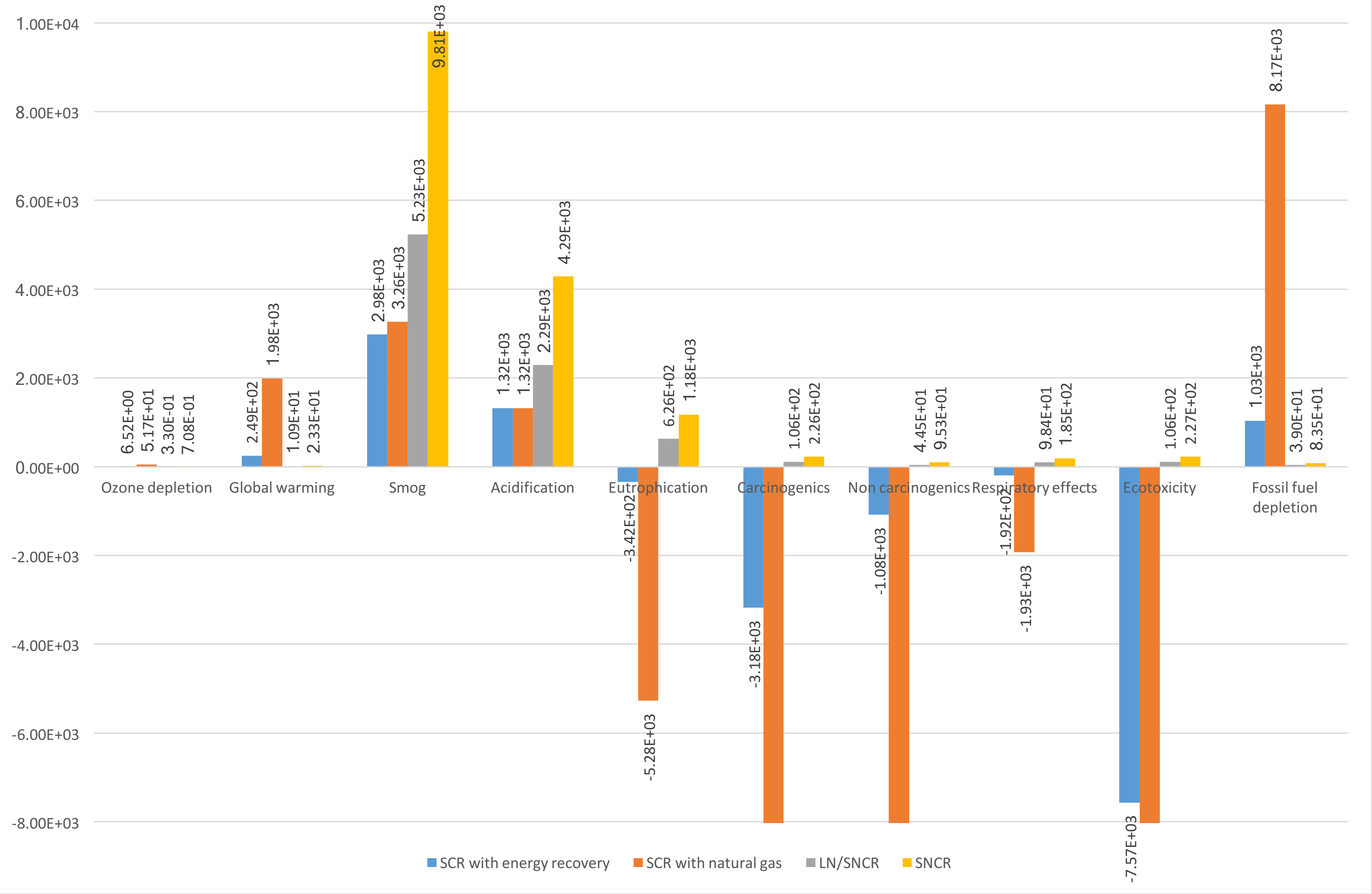


Figure 3.34 Normalization result for SCR operating with energy recovery

4 Discussion

Two Midpoint methods for life cycle impact assessment were used: CML 2 Baseline 2000/World, 1995 and TRACI 2.1. They have four common impact categories, acidification, eutrophication, ozone depletion and global warming. The characterization and normalization were listed in following Table 4.1 to Table 4.4.Results given in characterization were close, while there was a big difference between normalization results this might because the considered geographic scope for analysis were different. However, the difference on normalization value still indicate the same best performance scenarios.

CML has more impact categories on aquatic and ecosystem toxicity, while TRACI provides more categories related to human health (such as smog, carcinogenics and respiratory effects). Although the combination for these two methodologies lead to a more comprehensive and detailed assessment in different environmental impact categories, TRACI seems would give a more accurate results in this study. In this study, the impact assessment was focused on NO_X and the byproduct generated during denitrification. The largest direct emission was NO_X, while a small amount of ammonia slip which could be regarded as neglected would be discharged in fly ash which would be disposed in soil. Theoretically, NO_X would have an impact on acidification, eutrophication and production of chemical smog. However, the CML methodology could not give the indication on impact categories related to photochemical smog, while TRACI did. In addition, the main direct discharge in this study was to air, so the impact would be more related to human health by respiratory rather than aquatic which was the strength for CML. Although the solid waste would not present any impact on eutrophication by TRACI 2.1 while CML did, the eutrophication impact caused by solid waste was so small compared to other component that its impact could be regarded as negligible. Moreover, indicated by [29], eutrophication, as one of the main environmental impact caused by NO_X emission, its fate modelling was excluded in CML 2 baseline 2000 methodologies, while the TRACI well modeled toxicity and eutrophication adapted to US conditions. As some categories such as eutrophication and acidification are more related in local scale, TRACI methodology has a more accurate estimation on the impact in these type of categories. Also, the database for TRACI is much latest than CML 2 did, so the estimation given would be more close to the current situation.

Focused on acidification and eutrophication impact, the NO_X reduction technologies in the orders from largest to smallest negative environmental impact based on the results presented in **Figure 3.1** was SCR, untreated gas, SNCR and LN/SNCR. This results was not match the results given by Liang et al (as shown in **Figure 4.1**) which indicated SCR technologies had the best environmental performance on acidification and nutrient enrichment. This might because the scenario for Liang et al was for coal power plant whose flue gas would have high temperature at the inlet of SCR system that could reach the operating temperature for catalyst to meet the removal efficiency without gas reheating which was the main component contributed to the result of acidification for environmental impact. After change the heating source to natural gas and MSW incineration, the results presented the **Figure 3.29** approved the results indicated by the Liang et al. This also indicated the significance of heating energy for SCR operation to environment. In addition, the results given by **Figure 3.25** and **Figure 3.26** indicate natural gas and MSW incineration would have better environmental performance than other reheating energy resource, which is most widely used in waste to energy facilities [9]. From sensitivity analysis as shown in Figure 3.33 and Figure 3.34, the negative environmental impact on global warming and fossil fuel could be obviously mitigated by reduce the catalyst operating temperature and increase the heat exchange efficiency. However, even operating with the lowest temperature in sensitivity analysis, the negative impact on these two categories were still much higher than SNCR and SCR. This approved that the high energy consumption made the SCR difficult to comply with R1 criterion required by EU Waste Framework Directive introduced by Gohlke et al, while the R1 efficiency was shown in **Figure 4.2**.

Although the results given in this study in some extent approve the results provided by peer research, some further improvement could be made in future research:

- Consider the electricity consumption in SNCR and LN/SNCR
- Evaluate the results by weighting: As each scenario had different influence on different environmental categories, the weighting for environmental categories would indicated which categories was more important to focus on. With weighted results, the best scenario for NO_X reduction would be more convincible.

- Change the operating temperature for SCR based on catalyst type: As the lack of life cycle inventories for catalyst manufacture, the inventory used in this study was from Liang et al. which requires the operating temperature used was close to the one used in Liang et al. However, this would cause one-sided results for SCR. To have a more comprehensive perspective on the possible environmental impact performance, the life cycle inventories for different kinds of catalyst manufacture was important.
- Sensitivity analysis for NO_X removal efficiency: As the environmental impact for SNCR and LN/SNCR highly depends on ammonia production and flue gas emission, change the NSR with the change of removal efficiency into several scenarios to find the theoretical removal efficiency with best environmental performance
- Use the industrial data for NSR and ammonia slip, because the efficiency and ammonia slip varied with temperature and initial NO_X formation
- Sensitivity analysis on LN/SNCR to find the best combination of efficiency on LN and SNCR on environmental performance
- Use the average data from industry considering the catalyst aging, pressure drop in air preheater and ammonia injection system to build a life cycle impact assessment in a more practical perspective
- Analyze the characterization value based on the cost and compare the cost to decrease per kg of characterization value to find determine the technologies has best environmental performance in an economic perspective

Table 4.1 Characterization result from CML methodology

Impact category	**Unit**	**SNCR**	**SCR (natural gas)**	**SCR operation**	**Untreated gas**
Acidification	kg SO2 eq	2.79E+05	1.49E+05	7.34E+04	5.50E+05
Eutrophication	kg PO4--- eq	7.57E+04	4.12E+04	-2.90E+04	1.43E+05
Global warming	kg CO2 eq	5.63E+05	2.63E+05	4.63E+07	0
Ozone layer depletion	kg CFC-11 eq	8.52E-02	3.97E-02	5.84E+00	0

Table 4.2 Characterization result from TRACI methodology

Impact category	**Unit**	**SNCR**	**SCR (natural gas)**	**SCR operation**	**Untreated gas**
Acidification	kg SO2 eq	3.89E+05	2.08E+05	1.20E+05	7.70E+05
Eutrophication	kg N eq	2.54E+04	1.35E+04	-1.14E+05	4.87E+04
Global warming	kg CO2 eq	5.65E+05	2.64E+05	4.81E+07	0
Ozone layer depletion	kg CFC-11 eq	1.14E-01	5.33E-02	8.34E+00	0

Table 4.3 Normalization result from CML methodology

Impact category	SNCR	LN/SNCR	SCR (natural gas)	Untreated gas
Acidification	8.68E-07	4.64E-07	2.28E-07	1.71E-06
Eutrophication	5.73E-07	3.11E-07	-2.20E-07	1.08E-06
Ozone depletion	1.65E-10	7.71E-11	1.13E-08	0
Global warming	1.36E-08	6.34E-09	1.12E-06	0

Table 4.4 Normalization result from TRACI methodology

Impact category	SNCR	LN/SNCR	SCR (natural gas)	Untreated gas
Acidification	9.97E-06	5.33E-06	2.62E-06	1.96E-05
Eutrophication	1.15E-05	6.24E-06	-4.40E-06	2.17E-05
Ozone depletion	1.15E-02	5.37E-03	9.45E-01	0
Global warming	1.15E-14	5.37E-15	7.89E-13	0

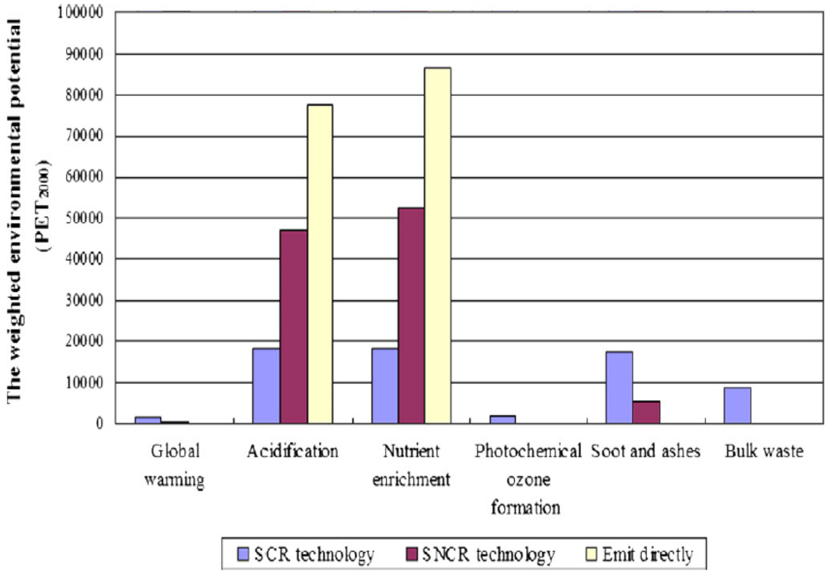


Figure 4.1 The weighted environmental potentials of scenarios given by Liang et al [24]

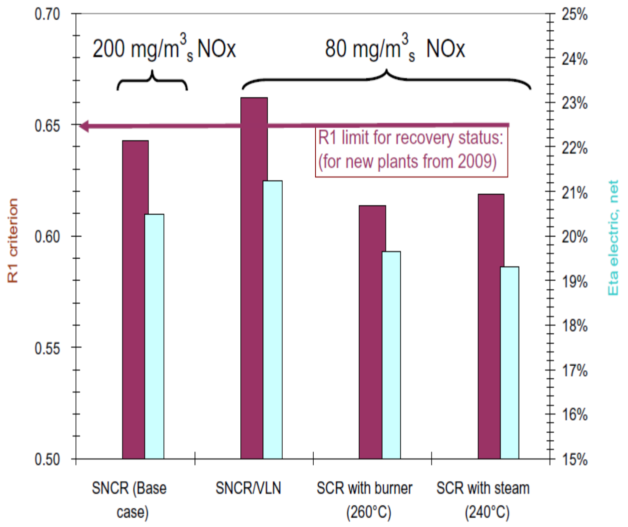


Figure 4.2 Influence of NO_X reduction system on efficiency [2]

5 Conclusions

A critical study has been conducted with the aim to compare the environmental performance of SNCR, LN/SNCR and SCR by using life cycle analysis.

It was assumed that the initial feedstock produces 300ppm NO_X@7% O_2. Three scenarios were assessed, with regard to the reduction potential of each system.

- 150ppmdv NO_X@7% O_2 by Selective Non-Catalytic Reduction (SNCR) only
- 80ppmdv NO_X@7% O_2 by Low NO_X technologies followed by SNCR (LN/SNCR)
- 45ppmdv NO_X@7% O_2 by tail end Selective Catalytic Reduction (SCR) only

The main conclusions can be summarized as follow:

- LN/SNCR has shown the best environmental performance amongst the three technologies
- For SNCR and LN/SNCR, the reagent production and the flue gas emission to ambient air after the APC system are the two main categories that influence acidification, eutrophication, smog, human toxicity and respiratory effect. Reagent production is the main contribution on eco-toxicity, resource depletion and other categories of human health.
- Reheating of the flue gas is the major contribution to the environment for the SCR system, especially for human health, acidification, eutrophication, resource depletion and eco-toxicity.
- Fuel selection has a significant impact in the overall environmental performance of the SCR system. Natural gas would provide SCR with the best environmental performance followed by MSW incineration in second place.
- Compared to SNCR and LN/SNCR, SCR with natural gas as reheating energy has the best performance on mitigating the negative environmental impact on acidification, eutrophication and human health initiated by the initial high concentration of NOX, as well as a positive environmental performance on eco-toxicity. Operating on a lower temperatures or recovering waste heat from the gas stream leaving the SCR would significantly mitigate and improve the negative environmental impact on global warming and resource depletion

but with not affect the smog and acidification categories. Also, the positive environmental impact on eutrophication, human health and eco-toxicity would be decreased.

- Adjusting the operating conditions in SCR, particularly reducing the operating temperature or recovering waste heat, would reduce the negative impact from resource depletion and global warming. However, the mitigated negative environmental impact is still higher than SNCR and LN/SNCR. Even reducing to the lowest possible operating temperature, SCR still results in a more negative environmental impact on resource depletion and global warming

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