CEYHAN PROPANE DEHYDROGENATION - POLYPROPYLENE PRODUCTION PROJECT

LIFE CYCLE ASSESSMENT REPORT

(ANNEX-S)

FEBRUARY 2023

ANKARA

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Ankara, Turkey

Ceyhan Propane Dehydrogenation - Polypropylene Production Project

Life Cycle Assessment Report

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ABBREVIATIONS AND ACRONYMS

AP	Acidification Potential
CCR	Continuous Catalyst Regeneration
EP	Eutrophication Potential
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ODP	Ozone Depletion Potential
PDH	Propane Dehydrogenation
POCP	Photochemical Ozone Creation Potential
PP	Polypropylene
SPV	Special Purpose Vehicle
U&O	Utilities and Off-Site

1 INTRODUCTION

The partnership named Ceyhan Polipropilen Üretim A.Ş. (Ceyhan PP A.Ş. or Project Company) made the investment decision for **“Ceyhan Propane Dehydrogenation – Polypropylene Production Plant Project”** (Ceyhan PDH-PP Project or Project), which is planned to be realized in Ceyhan Petrochemical Industrial Region (CPIR) in district of Adana, province in the south of Turkey at the Mediterranean shore. The members of this partnership are RNS Ceyhan Petrokimya Endüstriyel Yatırım A.Ş. (51%), CYN Petrokimya Endüstri ve Ticaret A.Ş. (15%) and Sonatrach Petroleum Investment Corporation BV (34%).

Since Turkey’s overall demand exceeds the capacity of its existing petrochemical production, imports account for the majority of the country’s petrochemicals supply. With the purpose of reducing import dependence, Ceyhan PDH-PP Project will be realized. The Project will produce polypropylene (472,500 t/y of homo-polymer), which is the second largest portion of the national demand for raw plastics, thus allowing to cover almost 15% of Turkey’s polypropylene requirements.

1.1 PROJECT OVERVIEW

As mentioned, the Project will be located in Adana province. Figure 1.1 shows the Project site location and its boundaries.

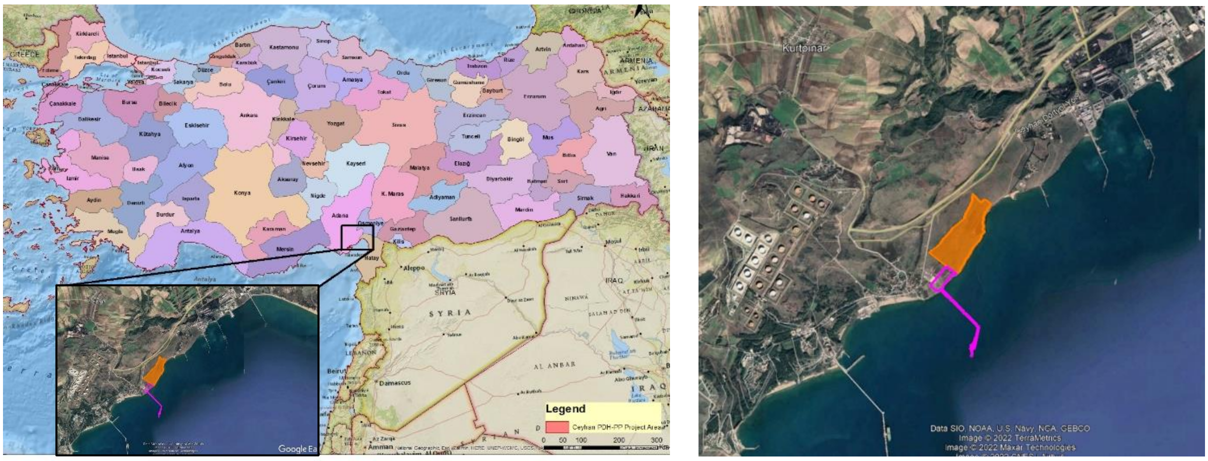

Figure 1.1 - Illustration of the Location of the Project Site, its Boundaries and Jetty

The Project (PDH-PP plants) will be built on 67 hectares of land and will be composed of the following units:

- ✓ PDH Plant and PP Plant;
- ✓ Utilities:
    - Polypropylene (PP) Storage and Regenerative Thermal Oxidation (RTO) Unit;
    - Cooling Tower;
    - Wastewater Treatment;
    - Raw, Drinking and Service Water Storage;
    - Steam, Condensate, Boiler Feed Water and Demineralized Water Production;
    - Tank Farm;
    - Spent Caustic Treatment and Instrument and Plant Air Supply;
    - Fuel Gas Supply and Nitrogen Generation Unit;
- ✓ Ancillary Buildings (administration, laboratory, fire station, control building, etc.).

The 1.2 km long Jetty (Project associated facility) will be composed of: piperack, two unloading arms for unloading propane, one gangway tower with hydraulic package and manifold valve arrangement and two fire monitors. Propane, which will be used as raw material in PDH-PP process, will arrive with propane tankers and then be transported to the site through the Jetty. More information on the Project and associated facilities is provided in Chapter 2 of the ESIA document.

1.2 SCOPE AND ORGANIZATION OF THE DOCUMENT

Scope of this report is the execution of a Life Cycle Assessment (LCA) of the Ceyhan PDH-PP Project. The LCA follows a Cradle-to-Gate approach, thus quantifying all the environmental impacts attributable to the production of the unit of mass of polypropylene, including those related to the extraction, processing and transport of propane and other input materials and energy sources, those related to the processes and auxiliary activities realized in the plant and those related to the end-of-life of waste generated.

LCA is a methodology for identification and evaluation of the environmental impacts of a product. Indeed, it addresses the actual and the potential environmental aspects (e.g.: use of resources and environmental consequences of releases) throughout the product life-cycle: from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (e.g.: cradle to grave).

In particular, the LCA evaluates the impacts using several impact categories depending on the different effects on the environment. These impacts are evaluated by identifying and quantifying data related to:

- ✓ raw materials consumption;
- ✓ energy consumption;
- ✓ waste generation;
- ✓ emissions to air, water and soil.

As shown in Figure 1.2, different boundaries could be considered in LCA analysis. In this document, a Cradle-to-Gate analysis has been carried out, which means that upstream processes in the production chain of a product are studied, until the stage at which the product is ready for commercialization[1].

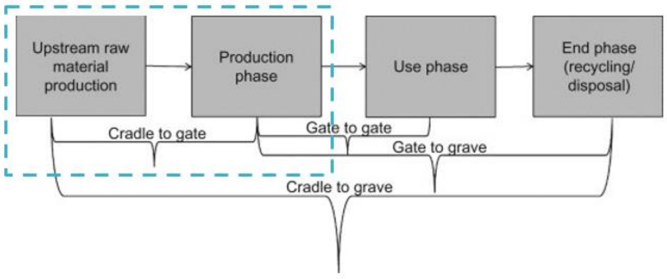

Figure 1.2 - Boundary Selection for Life Cycle Assessments

There are four phases in an LCA study, that will be deepened in the following chapters:

1. the goal and the scope definition phase;
2. the inventory analysis phase;
3. the impact assessment phase;
4. the interpretation phase.

Thanks to the LCA study it is possible to consider all the production processes and the results are especially useful to:

- ✓ describe the overall environment impact of the production process;
- ✓ compare the environmental impacts of different products with the same production process;
- ✓ identify the life cycle steps having higher environmental impacts;
- ✓ support the design of new products or services;
- ✓ develop strategies for enhancing environmental performance.

The report is articulated into the following sections:

- ✓ the present Chapter 1 constitutes the introduction to the report;

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[1] https://www.sciencedirect.com/science/article/pii/B9780127999685000063 Accessed on 26 July 2022

- ✓ Chapter 2 presents the methodological approach applied in the analysis;
- ✓ Chapter 3 delineates the goal and scope of the analysis;
- ✓ Chapter 4 illustrates the life cycle inventory data adopted in the study;
- ✓ Chapter 5 presents and assesses the environmental impacts determined with the analysis;
- ✓ Chapter 6 interprets the results obtained and analyses the breakdown of the calculated environmental impacts among different processes;
- ✓ Chapter 7 draws the conclusions of the assessment.

2 METHODOLOGY

As mentioned, in this study the PDH-PP process has been analysed according to Cradle-to-Gate approach using specialist software Sphera GaBi v.10.6 integrated with Ecoinvent 3.8 database, for which RINA owns regular license.

GaBi is a software, developed by Sphera (previously “Thinkstep” and “PE International”), which allows to easily model process chains, by describing a production technology/product or service through its input and output flows. The selected technology or product can be described by using its structural information and creating parts with material inventories and production processes. Processes and flows already existing in the internal databases can be used, or new items can be defined by the user according to experimental values or literature data. Once the system is defined in terms of involved processes, mass and energy flows, several Impact Assessment Methodologies can be adopted to determine the results.

The standard database provided with GaBi is the Professional database, which has the advantage of being internally consistent and includes more than 5,000 Life Cycle Inventory (LCI) records, based on previous work of PE International. In addition, the Swiss Ecoinvent database is available, which includes thousands of LCI in the fields of agriculture, energy supply, transport, biofuels and biomaterials, chemicals, construction and packaging materials, basic and precious metals, metals processing, ICT and electronics, waste treatment.

2.1 REFERENCE STANDARDS

The international standards which a LCA relies on are part of the ISO 14000 series on “Environmental Management – Life Cycle Assessment” and are specifically ISO 14040:2006 “Principles and framework” and ISO 14044:2006 “Requirements and guidelines”.

The reference guidance at international level for the LCA is the handbook issued by the Joint Research Centre (JRC) of the European Commission “ILCD Handbook – General guide for Life Cycle Assessment – Detailed Guidance”. The document draws a path to follow for an LCA study, as explained in the following chapters of the present document. When dealing with the impact assessment, a second guidance document from JRC has high relevance, the handbook “Recommendations for Life Cycle Impact Assessment in the European Context”.

2.2 PHASES OF THE ANALYSIS

The chart in Figure 2.1 illustrates the key steps of LCA, which will be explained with more details in the following paragraphs.

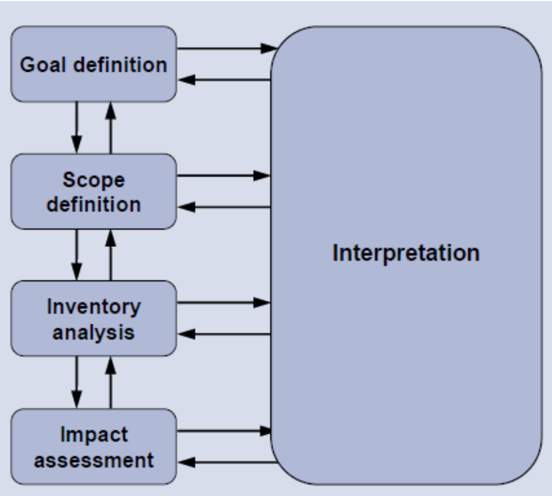

Figure 2.1 - Framework for Life Cycle Assessment (from ISO 14040:2006)

2.2.1 Goal and Scope Definition

The goal and scope definition are the first steps of any life cycle assessment. These phases describe the purposes of the study (e.g.: product development and improvement, strategic planning, public decision making, marketing), the most important choices and assumptions for the analysis and allow to define three main factors:

- ✓ reason for executing the LCA, its foreseen applications and the beneficiaries of the study;
- ✓ definition of the product and its life-cycle;
- ✓ identification of system boundaries.

Within the analysed system, it is needed to define processes included in the life cycle and the phases, processes, or data that can be dismissed. All collected data must be referred to a defined functional unit.

2.2.2 Life Cycle Inventory

According to the goal definition and meeting the requirements of the defined scope, during the life cycle inventory (LCI) phase the data collection and modelling of the system (e.g.: product) are carried out. The LCI results are the subsequent life cycle impact assessment (LCIA) phase inputs. These results also provide feedback to the scope phase and initial scope settings often need adjustments.

The inventory is a list of all the flows of input and output materials at all the process units composing the system. In this phase some key-steps can be identified:

1. definition of the flowchart;
2. data gathering;
3. allocation of impacts;
4. data management and software simulation.

As shown in Figure 2.2, the flowchart is a qualitative representation of all the relevant processes involved in life cycle of the analysed system. Its main goal is to provide an overview of the most relevant processes and environmental interventions.

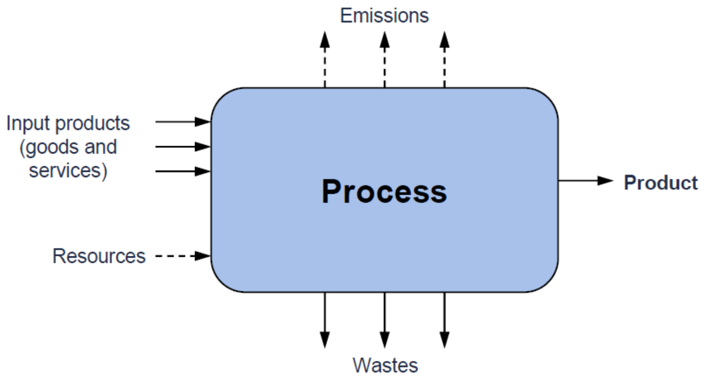

Figure 2.2 - Example of a Flowchart

By defining the inventory, this phase involves the data gathering and the allocation of impacts for:

- ✓ elementary flows (such as resources and emissions but also other interventions with the ecosphere such as land use)
- ✓ product flows (e.g.: goods and services both as “product” of a process and as input/consumables) that link the analysed process with other processes
- ✓ waste flows (both wastewater and solid/liquid wastes) that need to be linked with waste management processes to ensure a complete modelling of the related efforts and environmental impacts

After a correct management of gathered data (e.g.: data transformation into a proper format, specific quantities/sizes calculation, sum and balances of the environmental impacts), simulation with specific software is the next step. The sector specific software contains all the useful databases (e.g.: raw materials, fuels, transport systems, waste management systems) that allow to create the expected balances through proper simulation.

2.2.3 Life Cycle Impact Assessment

Scope of this step is to evaluate the effect of potential environmental impacts, through the interpretation of the results of the inventory analysis. The life cycle impact assessment (LCIA) makes a conversion of every flow identified in the inventory phase into a “impact”. The impact is represented by a set of parameters apt to define the environmental behaviour of a product or of a process. The information provided by the impact is a relative evaluation (i.e.: not an absolute definition), since it is tailored to a “functional unit”.

All inventory data, both input and output, are correlated with environmental impacts. Several categories of impact can be listed, as indicated in the chart in Figure 2.3.

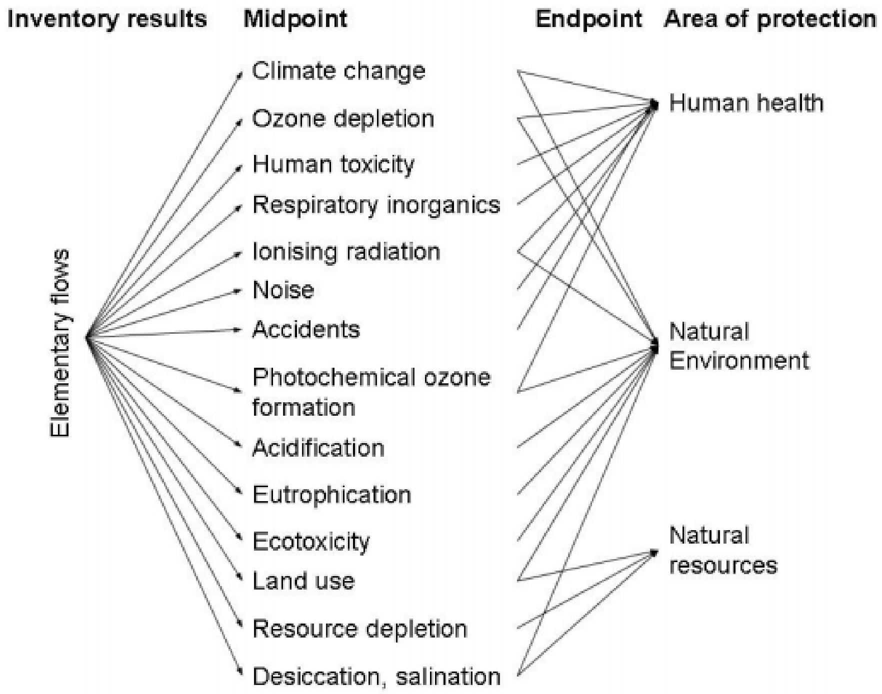

Figure 2.3 - LCIA Process and Indicators

To relate to a common reference the different characterized impact score, it is suggested to normalize the values obtained. Normalization is an optional step under ISO 14044:2006 in LCA analysis, but this way would be useful for an eased interpretation of results, in terms of:

- ✓ to understand the respective importance of each indicator;
- ✓ to provide indications on significance of impacts;
- ✓ to ease the acknowledgment of results.

Indeed, by displaying the normalised LCIA results of the different impact topics next to each other, it can be seen to which impact topics the analysed system contributed relatively more and to which less.

2.2.4 Interpretation of Results

The interpretation phase of an LCA has two main purposes:

- ✓ during the iterative steps of the LCA and for all kind deliverables, the interpretation phase serves to steer the work towards improving the Life Cycle Inventory and review the scope and goal definition and the LCIA;
- ✓ if the iterative steps of the LCA have the resulted in the final LCI model and results, the interpretation phase serves to derive robust conclusions and recommendations.

The interpretation proceeds through three different activities as schematically illustrated in Figure 2.4 and detailed as follow:

- ✓ first, the significant issues (e.g.: the key processes, parameters, assumptions, and elementary flows) are identified;
- ✓ then these issues are evaluated about their sensitivity or influence on the overall results of the LCA;
- ✓ finally, the evaluation results are used in the conclusions formulation and recommendations from the LCS study.

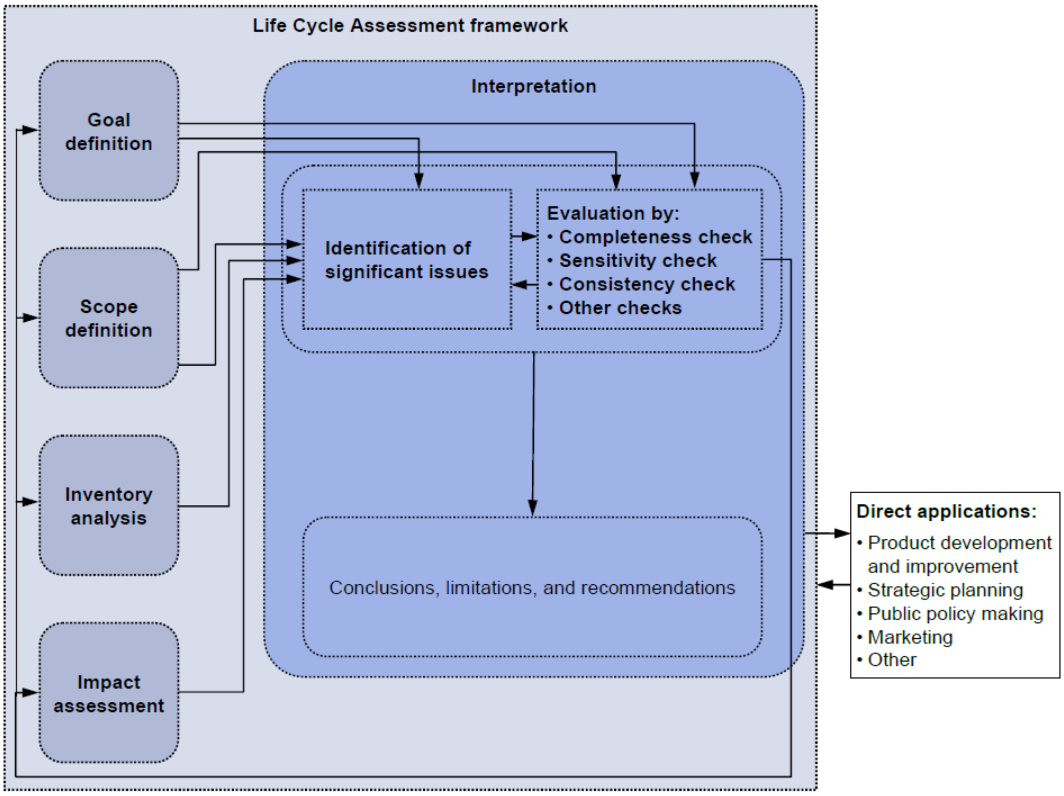

Figure 2.4 - Interpretation Phase Elements and their Relations to Other LCA Phases

3 GOAL AND SCOPE DEFINITION

The purpose of this LCA is to document the LCI data and then evaluate the environmental profile of PDH-PP production process. The intended use of the study results is twofold:

- ✓ to define the current level of resource efficiency and the current strategies for managing resource use;
- ✓ to identify resource efficiency and pollution prevention opportunities through the selection and optimisation of technological assets and design.

The used methodology and its references are defined in ISO 14040:2006 and in ISO 14044:2006.

3.1 DEFINITION OF THE PRODUCT AND ITS LIFE-CYCLE

The PDH-PP plant will process 556,000 t/y of propane to produce 472,500 t/y of polypropylene homo-polymer, considering about 8,000 hours of yearly operation. The whole process is mainly composed by two steps: the propane dehydrogenation (PDH) and the propylene polymerisation (PP).

The first step, in the PDH unit, is the catalytic process (*UoP Honeywell PDH C3-Oleflex™ Process Unit*) to convert liquified propane (raw material) into propylene, while hydrogen is produced as by-product. Apart from the hydrogen cycle between the PDH and PP plant units and requirement in the propylene production process, no hydrogen outlet is expected in the PDH-PP plant. Indeed, in the current design hydrogen will be used as fuel in the production process. The PDH unit has a production capacity of 59,981 t/h of propylene.

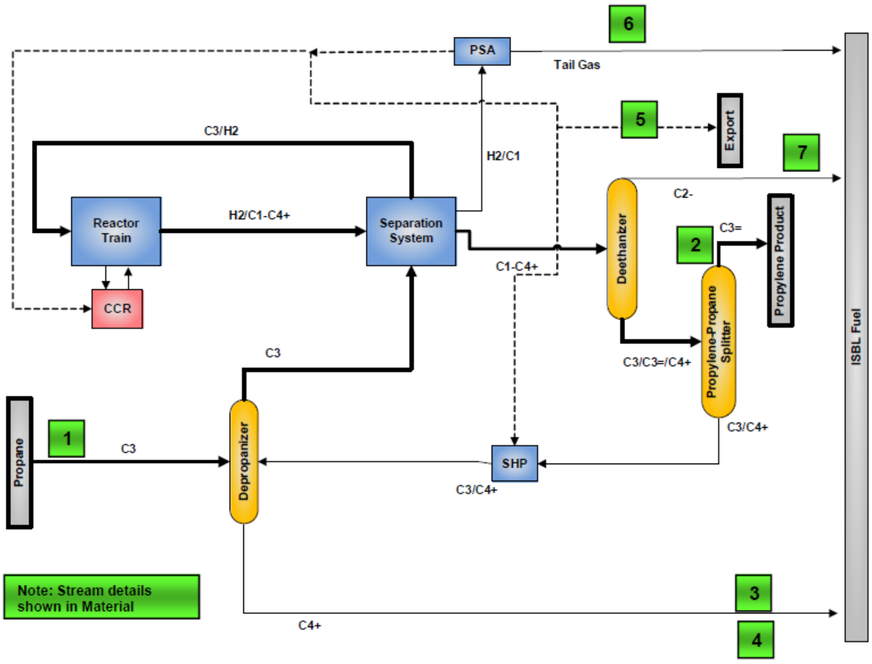

Figure 3.1 - Process Flow (PDH Plant, Oleflex)

As shown in Figure 3.1 the PDH plant contains three main sections: Reactor Section, Fractionation Section and Continuous Catalyst Regeneration (CCR) Section. The Reactor Section consists in four reactors and four fired heaters to provide high temperature conditions required for the endothermic reactions. Following the reactors, the processed gases are cooled, compressed, and treated in order to remove trace impurities. Then, the effluent stream is condensed and pumped to the Fractionation Section, to improves purity of Propane Feed and the stream from the Reactor Section. The impurities that may cause coke formation of degrade catalyst performance are removed using the resin or adsorbents. CCR Section supports the continuous operations of the Oleflex Process, where catalysts are recovered through the continuous incineration of the coke to reactivate, restabilize and recover the selective feature of catalysts used in the process.

Most of the propylene, which is produced in PDH unit, will be sent to the PP Plant and the rest will be send to the intermediate propylene storage tank (as buffer).

Therefore, in the second step, named PP unit, the propylene is polymerized to produce polypropylene. Polypropylene production (*Lyondell Spheripol Process Unit*) is planned to be in homo-polymer form; therefore, ethylene is not planned to be used in production at current state of design. The PP unit has a production capacity of 59,062.5 t/h.

The Spheripol process is a bulky slurry process. The active catalyst slurry mixed with the cold (10°C) propylene stream is fed to Pre-Polymerization Reactor. Cooling water recycling system is used at the Pre-Polymerization Reactor to dissipate the heat generated by exothermic polymerization reaction. After this phase, the main polymerization reaction, that produce homopolymer, takes place in tubular loop reactors. In this process the catalyst, liquid propylene and hydrogen are continuously fed into the loop reactor for molecular weight control. After the homopolymer, the finishing section consists of highly efficient liquid propylene vaporization operations at very high polypropylene concentrations, separation of the unconverted monomers and complete recycling of the monomers to the reactors by Extrusion and Pelletising units.2

Figure 3.2 shows process flow of Spheripol unit including raw & auxiliary materials, utilities used during the process as well as effluents, utilities, recoveries, and products.

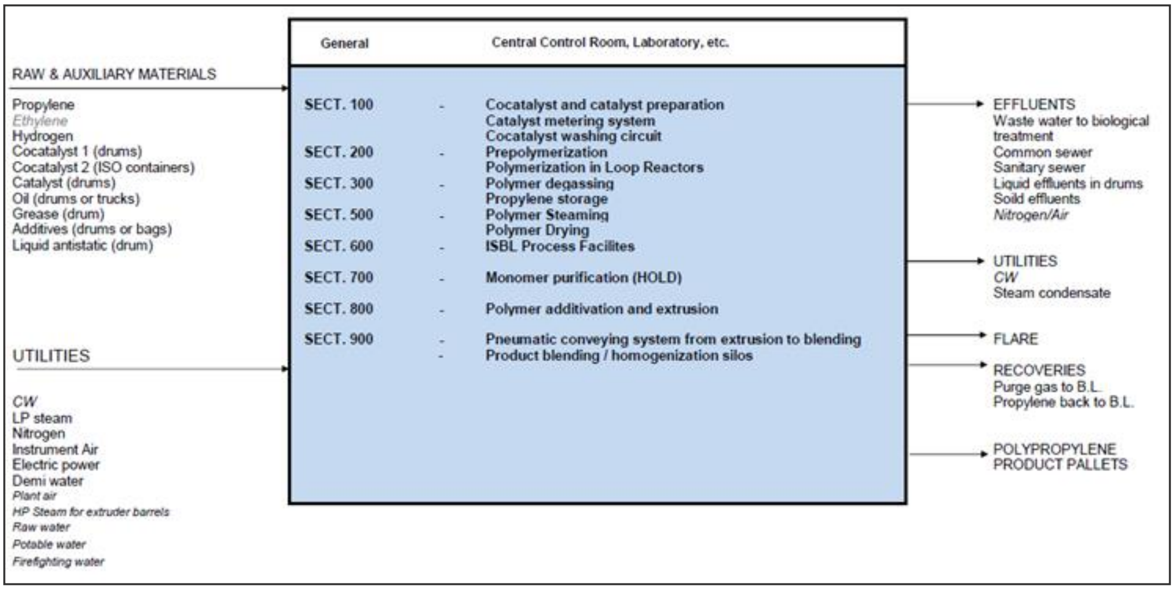

Figure 3.2 - Process Flow (PP plant, Spheripol)

In the PP process also the following units are included: refrigeration unit, low pressure steam condensate recovery, nitrogen compression, mineral oil system and waste oil treatment.

In addition, a fully equipped PP product storage and handling facility will be installed in the Project site. Vent gas from the finishing process is transferred to the regenerative thermal oxidizer (RTO) package that will be installed as part of the PP storage. RTO will aim to convert volatile organic compounds (VOCs) and hazardous air pollutants to carbon dioxide and water vapor through thermal oxidation.

Propane, used as raw material, will be supplied by Sonatrach (one of the SPV members for Ceyhan PDH-PP Project), through their sea tankers from Algeria, twice a month. The distance from Algeria to the Project site is about 3,400 km per transfer. The imported propane will be stored on-site in a storage facility. The storage will be optimized by the Project Company by taking into consideration the ship movements, the capacity of the Jetty and the raw material prices.

The main energy inputs to the Project are electricity and natural gas, which will be supplied from national grid and main supply line, respectively. In order to reduce GHG emissions, the Project company has planned to cover electricity needs with energy from renewable sources, with zero withdrawal of electricity from the national grid.

Natural gas will be supplied by the Management Company. The natural gas import facilities are designed with the appropriate flexibility and operating range to enable any deficit in the fuel gas balance to be met for all operating

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[2] https://www.lyondellbasell.com/globalassets/products-technology/technology/spheripol-brochure.pdf. Accessed on 28 July 2022

scenarios, including start-up and shut-down cases. There will be three utility boilers (two for the constant use and one as backup). Moreover, the Project will include steam and condensate systems, which will be independent and require boiler feed water system, electrical power, chemical, fuel gas and instrument air. Fuel gas will be used in PDH heater, flare, and utility boilers. Therefore, considering the recovered fuel gas, during normal operating conditions of the plant the natural gas demand will be 288.96 Nm^3/h, whereas just for the start-up of the operations the demand will be 11,085 Nm^3/h.

Raw water will be supplied from outside the Project site, it will first be transferred into the raw water pond for subsequent preliminary treatment. Then, the treated water will be distributed to the different project units that use water in different quality and quantities (e.g.: cooling water, drinking water, process water, steam production). For this study the raw water demand is considered to be about 14,400 m^3/day (max 600 m^3/h), as declared in design documents and in a Management Company official letter dated August 12th, 2020.

3.2 BOUNDARIES OF THE ANALYSIS

As mentioned, this LCA report follows a Cradle-to-Gate approach: all raw materials feeds (e.g.: propane, chemicals, catalysts) and utility supplies are considered as input data whereas process wastes and polypropylene ready for commercialization are considered as output data. In Figure 3.3 the system boundaries are identified.

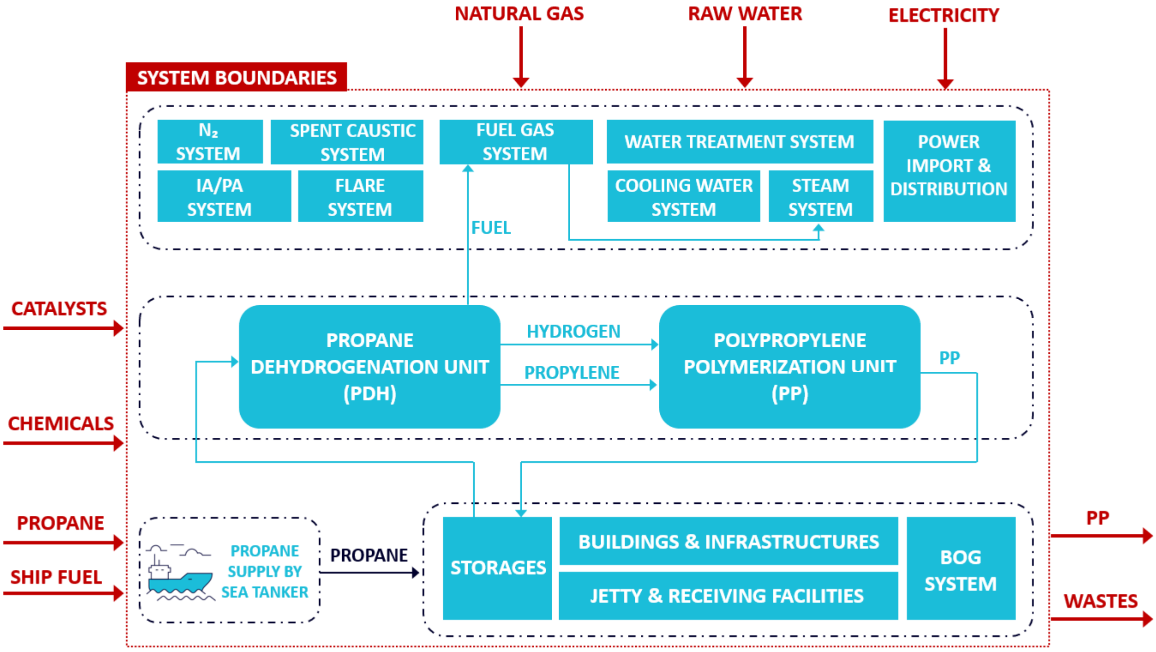

Figure 3.3 – Overall Block Flow Diagram

Geographical borders include Turkey for raw materials production and transport to the Project site. Propane supply will be from Algeria by sea transport. The considered distance for raw materials transport is 3,400 km for sea transport of propane and 100 km for road transport for the other raw materials.

In order to quantify the internal and external flows of materials and energy, the main units of the whole process can be summarized as follows:

- ✓ propane dehydrogenation unit (PDH);
- ✓ polypropylene polymerization (PP);
- ✓ utilities & off-site (U&O).

In line with the selected LCA approach, “Cradle-to-Gate”, all the flows mentioned in the above presented block flow diagram are included in the assessment with all the associated environmental impacts, including their extraction, processing/production, transport to the Project site.

3.3 FUNCTIONAL UNIT

The functional unit is the basis upon which the LCA study is conducted. Since this study is used for the manufacturing process of PDH-PP production, the functional unit is defined in terms of the system output, which is 1 t of homo-polymer.

4 LIFE CYCLE INVENTORY

In this phase of the LCA analysis, all the data regarding the production of the functional unit, i.e. 1 t of PP homopolymer, have been collected from design documents, based on the input and output data of the plant. The key data used for the study are related to:

- ✓ supply of propane as raw material for the PDH unit (considered with all the environmental impacts associated to its extraction, processing/production);
- ✓ fuel consumption for the propane sea transport and all the raw materials delivery;
- ✓ raw water consumption for all the different purposes (considered with all the environmental impacts associated to its extraction, processing/production and transport to the Project site);
- ✓ natural gas demand during the normal operating case of the Project site (considered with all the environmental impacts associated to its extraction, processing/production and transport to the Project site);
- ✓ renewable electricity consumption throughout the Project site (considered with all the environmental impacts associated to its production and transmission/distribution to the Project site);
- ✓ catalysts supply for PDH and PP units (considered with all the environmental impacts associated to the extraction of raw materials and subsequent processing/production and final transport to Project site);
- ✓ chemicals supply for all the different production processes (e.g.: sulfuric acid, caustic soda, solid additives, phosphate, alumina, talc for nucleation, solvents, all considered with all the environmental impacts associated to the extraction of raw materials, their processing/production and final transport to Project site).

To define the processes related to the raw materials production, the use of fuel for each transport mode involved and for the production of energy sources, the EcoInvent database has been used together with the Sphera GaBi software. By identifying the existing processes in the Sphera GaBi software and creating new processes, the technological representativeness of the analysis has also been guaranteed. All the data have been collected and processed according to ISO 14040 and 14044 standards of transparency, accuracy, consistency, and completeness. The datasets selected from the EcoInvent database include all the material and energy consumptions and the emissions to air, water and soil and more in general all the environmental impacts associated to the life-cycle of the material/energy flow they represent.

4.1 INPUT DATA

Input data and their quality are reported in the following Table 4.1, where all the quantities are referred to the selected functional unit of 1 t of PP-homopolymer.

Table 4.1 - LCA Input and Data Quality

Phase	Flow	"Foreground" Data		Data Quality	
		Value	u.m.	"Foreground" Data	"Background" Data
PDH	Propane	1,236	[kg/ton$_{PP}$]	Primary	Ecoinvent
	Raw water	6.613	[m^3 /ton$_{PP}$]	Primary (estimated)	Ecoinvent
	Renewable electricity	0.860	[MWh/ton$_{PP}$]	Primary	Ecoinvent
	Oleflex catalyst	0.026	[kg/ton$_{PP}$]	Primary	Other generic
	Activated Alumina	1.850	[kg/ton$_{PP}$]	Primary	Ecoinvent
	Dimethyl Disulfide	0.462	[kg/ton$_{PP}$]	Primary	Other generic
	Caustic solution 50%	2.160	[kg/ton$_{PP}$]	Primary	Ecoinvent
	Phosphate	0.134	[kg/ton$_{PP}$]	Primary	Ecoinvent
	Chlorine	0.161	[kg/ton$_{PP}$]	Primary	Ecoinvent

Phase	Flow	"Foreground" Data		Data Quality	
		Value	u.m.	"Foreground" Data	"Background" Data
PP	Raw water	2.027	[m^3 /ton$_{PP}$]	Primary (estimated)	Ecoinvent
	Renewable electricity	0.354	[MWh/ton$_{PP}$]	Primary	Ecoinvent
	Catalysts	0.228	[kg/ton$_{PP}$]	Primary	Other generic
	Solid Additives	2.955	[kg/ton$_{PP}$]	Primary	Other generic
	Peroxide	0.205	[kg/ton$_{PP}$]	Primary	Other generic
	Natural gas	8.096	[MJ/ton$_{PP}$]	Primary (estimated)	Ecoinvent
	Talc for nucleation	0.800	[kg/ton$_{PP}$]	Primary	Other generic
	Liquid additives	0.056	[kg/ton$_{PP}$]	Primary	Other generic
U&O	Raw water	2.027	[m^3 /ton$_{PP}$]	Primary (estimated)	Ecoinvent
	Renewable electricity	0.269	[MWh/ton$_{PP}$]	Primary	Ecoinvent
	Natural gas	4.932	[MJ/ton$_{PP}$]	Primary (estimated)	Ecoinvent
	Antiscalant (100%)	0.042	[kg/ton$_{PP}$]	Primary	Other generic
	Sodium bisulfite (30%)	0.169	[kg/ton$_{PP}$]	Primary	Ecoinvent
	Sulfuric Acid	2.292	[kg/ton$_{PP}$]	Primary	Ecoinvent
	Caustic Soda	2.916	[kg/ton$_{PP}$]	Primary	Ecoinvent
	Alum	1.087	[kg/ton$_{PP}$]	Primary	Other generic
	A-Polymer	0.026	[kg/ton$_{PP}$]	Primary	Other generic
	C-Polymer	0.002	[kg/ton$_{PP}$]	Primary	Other generic
	Biocide	0.006	[kg/ton$_{PP}$]	Primary	Other generic
	Scale Inhibitor	0.033	[kg/ton$_{PP}$]	Primary	Other generic
	Corrosion Inhibitor	0.033	[kg/ton$_{PP}$]	Primary	Other generic
	Oxygen Scavenger	0.003	[kg/ton$_{PP}$]	Primary	Other generic
	Neutralizing Amine	0.008	[kg/ton$_{PP}$]	Primary	Other generic
	Phosphate	0.004	[kg/ton$_{PP}$]	Primary	Ecoinvent

This LCA study is based on preliminary data, validated by Project promoters and their technical team. The considered data will be confirmed during the Detailed Engineering and the Construction phase. The obtained results could change significantly in case the real operating conditions will differ from the initial estimates in terms of use of materials, energy sources and waste production.

Excluding the first three processes that have been created from primary data, the processes considered in the analysis are from Ecoinvent 3.8 database (Wernet et al.2016, updated in 2021) and include:

- ✓ PDH (Propane Dehydrogenation);
- ✓ PP (Propylene Polymerisation);
- ✓ U&O (Utilities and Off-site);

- ✓ renewable electricity consumption throughout the Project site ("TR: electricity, production mix photovoltaic, at plant");
- ✓ propane delivery as raw material for the PDH unit ("RER: propane/butane, at refinery");
- ✓ fuel consumption for the propane sea transport and all the raw materials delivery (OCE: "transport, transoceanic tanker");
- ✓ fuel consumption for all the raw materials supply by road transport (RER: "transport, lorry >16t, fleet average");
- ✓ fuel consumption for waste transportation to incinerator (CH: "transport, lorry 3.5-20t, fleet average");
- ✓ raw water consumption for all the different purposes (RER: "tap water, at user");
- ✓ natural gas demand during the normal operating case of the Project site (CH: natural gas, burned in industrial plant >100 kW");
- ✓ dimethyl disulfide consumption for PDH unit ("GLO: chemicals organic, at plant");
- ✓ sodium hydroxide consumption for PDH and U&O units ("RER: sodium hydroxide, 50% in H_2O, production mix, at plant");
- ✓ activated alumina consumption for PDH unit ("RER: aluminium oxide, at plant"):
- ✓ phosphate solution consumption for PDH and U&O units ("MA: phosphate rock, as P_2O_5, beneficiated, dry, at plant");
- ✓ solid and liquid additives consumption for PP unit ("GLO: chemicals inorganic, at plant");
- ✓ peroxide and talc for nucleation consumption for PP unit ("GLO: chemicals inorganic, at plant");
- ✓ chlorine consumption for PDH unit ("RER: chlorine, liquid, production mix, at plant");
- ✓ catalysts supply for PDH and PP units ("GLO: chemicals inorganic, at plant");
- ✓ sulphuric acid consumption for U&O unit ("RER: sulphuric acid, liquid, production mix, at plant");
- ✓ antiscalant, scale inhibitor and corrosion inhibitor consumption for U&O unit ("GLO: solvents, organic, unspecified, at plant");
- ✓ alum, A-Polymer, C-Polymer consumption for U&O unit ("GLO: chemicals inorganic, at plant");
- ✓ biocide, oxygen scavenger, neutralizing amine for U&O unit ("GLO: chemicals organic, at plant");
- ✓ wastewater treatment throughout the Project site ("CH: treatment sewage, to wastewater");
- ✓ solid waste disposal throughout the Project site ("CH: disposal, municipal solid waste, 22.9% of water, to municipal incinerator").

The above list is only presented with the aim of providing indications on the reference sources adopted for the quantification of the environmental impacts associated to the life-cycle of the material/energy flows considered in the analysis. All the listed processes have been used to build the Sphera GaBi block flow diagram presented in Figure 4.1.

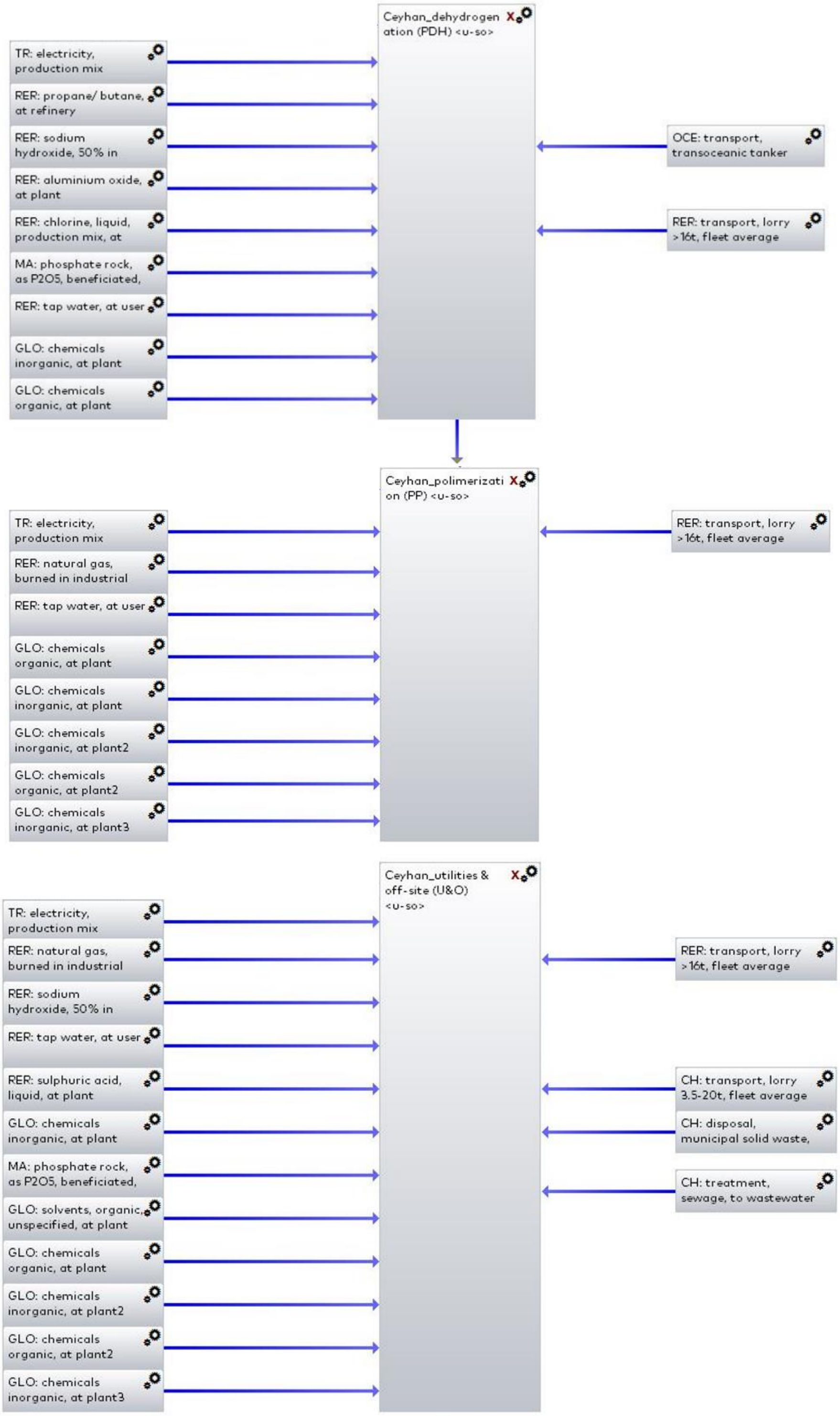

Figure 4.1 – Block Flow Diagram of PDH-PP-U&O Processes Made with Sphera GaBi Software

4.2 LIFE CYCLE INVENTORY RESULTS

Based on the inventory of all the input/output flows inserted in Sphera GaBi software, it is possible to identify cumulative energy demand and water consumption for the functional unit of 1 t of PP.

4.2.1 Cumulative Energy Demand

The cumulative energy demand includes all renewable and non-renewable energy sources used, during the life-cycle, for: Project production processes, raw materials production and transportation and waste transportation and disposal. This includes in addition to energy consumed within the plant, all the energy sources consumed for the extraction, processing/production and transport to Project site of all the materials and energy sources used in the plant.

The result from software simulation identifies a cumulative energy demand of 77,134.43 MJ/t of PP. This value is composed by:

- ✓ 72,653,21 MJ/t of energy from fossil fuels (petroleum products, natural gas, coal) due to the national energy mix composition used in transport and production processes of the raw materials provided and used in the Project site units
- ✓ 4,481.22 MJ/ton of energy from renewable sources (e.g.: solar, wind, hydropower, geothermal, biomass), due to the renewable energy supplied to the Project through Power Purchase Agreement (PPA) (100% of PDH, PP and U&O consumptions) and to the share of renewables in the national energy mix used in production processes of the raw materials used in the Project site units.

4.2.2 Water Consumption

Freshwater (withdrawn from water source) and water from reservoirs (that is not returned to the source) are included in the consumption of water during the life-cycle. The GaBi simulation value shows that the water consumption for the functional unit of 1 t of PP is of 4.858,06 m^3.

In particular, this value of water consumption includes the use of water in chemical reactions, the incorporation of water into products or waste streams, the loss of water due to evaporation, and the discharge of water to a different watershed, different from which it was withdrawn. The result also includes each step of the life-cycle, including uses related to production of fuels and energy used in that step.

5 LIFE CYCLE IMPACT ASSESSMENT

In this section of the report the data obtained from Sphera GaBi simulation are used to analyse the environmental impacts of the PDH-PP manufacturing process. The LCA follows a Cradle-to-Gate approach, thus quantifying all the environmental impacts attributable to the production of the unit of mass of polypropylene, including those related to the extraction, processing and transport of propane and other input materials and energy sources, those related to the processes and auxiliary activities realized in the plant and those related to the end-of-life of waste generated.

Figure 5.1 summarizes the main impact categories considered in LCIA methodology, whereas the following paragraphs present the environmental impacts belonging to the different impact categories, selected for this LCIA study.

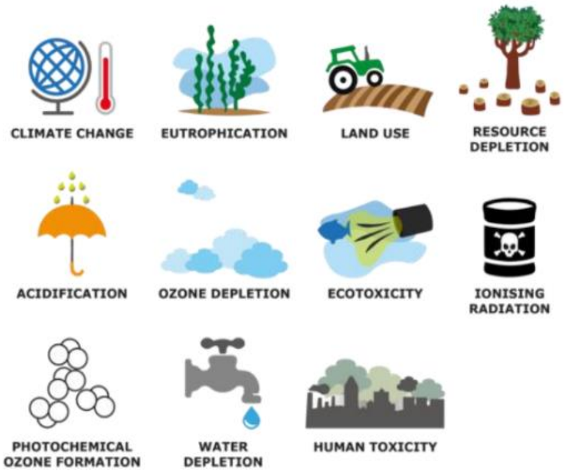

Figure 5.1 – Environmental Impact Categories[3]

5.1 QUANTIFICATION OF ABSOLUTE ENVIRONMENTAL IMPACTS

The impact assessment method considered is CML 2001 (Jan 2016 version), which restricts quantitative modelling to early stages in the cause-effect chain to limit uncertainties[4]. In Table 5.1 the eleven environmental impact indicators determined for 1 t of PP produced according to this lifecycle impact assessment method are reported.

Table 5.1 – Life-Cycle Environmental Impact Indicators (CML 2001 method Jan.2016 Vers.)

Indicator	Value	u.m.
Abiotic Depletion (ADP elements)	0.006	kg Sb eq./ t_{PP}
Abiotic Depletion (ADP fossil)	66,829.619	MJ/ t_{PP}
Acidification Potential (AP)	9.712	kg SO_2 eq. / t_{PP}
Eutrophication Potential (EP)	3.178	kg Phosphate eq. / t_{PP}
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	160.620	kg DCB eq. / t_{PP}
Global Warming Potential (GWP 100 years)	882.607	kg CO_2 eq. / t_{PP}
Human Toxicity Potential (HTP inf.)	453.575	kg DCB eq. / t_{PP}
Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	503,739.349	kg DCB eq. / t_{PP}

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[3] https://eplca.jrc.ec.europa.eu/lifecycleassessment.html Accessed on 2 August 2022

[4] https://gabi.sphera.com/support/gabi/gabi-lcia-documentation/cml-2001/. Accessed on 4 August 2022

Indicator	Value	u.m.
Ozone Layer Depletion Potential (ODP, steady state)	0.001	kg R11 eq. / t_{PP}
Photochemical Ozone Creation Potential (POCP)	0.855	kg Ethene eq. / t_{PP}
Terrestric Ecotoxicity Potential (TETP inf.)	6.053	kg DCB eq.

5.2 QUANTIFICATION OF NORMALIZED ENVIRONMENTAL IMPACTS

With the purpose of presenting life-cycle environmental impacts in a uniform unit of measurement that makes easier the interpretation of results and the comparison of the magnitude of their contributions, normalization has been carried out. All the environmental impacts previously presented in Table 5.1 have been compared to the environmental impacts of a European citizen in one year. The methodology used refers to Ecoinvent process "EU28, year 2000. CML, person equivalent"). The normalized indicators are shown in Table 5.2.

Table 5.2 – Life-Cycle Environmental Impact Indicators (CML 2001 method Jan.2016 Vers.) Normalized per Person-Equivalent/Year

Indicator	Value	u.m.
Abiotic Depletion (ADP elements)	0.45	p-eq/y
Abiotic Depletion (ADP fossil)	0.88	p-eq/y
Acidification Potential (AP)	0.27	p-eq/y
Eutrophication Potential (EP)	0.08	p-eq/y
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	0.36	p-eq/y
Global Warming Potential (GWP 100 years)	0.08	p-eq/y
Human Toxicity Potential (HTP inf.)	0.42	p-eq/y
Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	5.26	p-eq/y
Ozone Layer Depletion Potential (ODP, steady state)	0.03	p-eq/y
Photochemical Ozone Creation Potential (POCP)	0.23	p-eq/y
Terrestric Ecotoxicity Potential (TETP inf.)	0.02	p-eq/y

6 INTERPRETATION OF RESULTS

This LCIA study results allow to understand the environmental impacts of manufacturing process for 1 t of PP-homopolymer. Some of the impact categories, most commonly analysed in PP production studies, have been examined further within the different processes throughout GaBi software.

6.1 BREAKDOWN OF ENVIRONMENTAL IMPACTS AMONG PROCESSES

With the purpose of identifying the most impacting processes/activities, five environmental impact categories have been analysed by examining them through the different phases of the PDH-PP production. This approach is in line with that typically adopted by Product Category Rules documents developed by the International EPD® System and include Global Warming Potential (GWP 100 years), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Layer Depletion Potential (ODP, steady state), Photochemical Ozone Creation Potential (POCP).

In Table 6.1 the environmental impact indicators that have been analysed in the following paragraphs are reported.

Table 6.1 - Life-Cycle Environmental Impact Indicators (CML 2001 method Jan.2016 Vers.)

Indicator	Value	u.m.	Value	u.m.
Global Warming Potential (GWP 100 years)	882.607	kg CO_2 eq./t_{PP}	0.88	p-eq/y
Acidification Potential (AP)	9.712	kg SO_2 eq./t_{PP}	0.27	p-eq/y
Eutrophication Potential (EP)	3.178	kg Phosphate eq./t_{PP}	0.08	p-eq/y
Ozone Layer Depletion Potential (ODP, steady state)	0.001	kg R11 eq./t_{PP}	0.03	p-eq/y
Photochemical Ozone Creation Potential (POCP)	0.855	kg Ethene eq./t_{PP}	0.02	p-eq/y

6.1.1 Global Warming Potential (GWP 100 years)

Greenhouse gases (GHGs) warm the Earth by absorbing energy and slowing the rate at which the energy escapes to space; different GHGs can have different effects on the Earth's warming. The Global Warming Potential (GWP) indicator was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period.[5] The period mostly used for GWPs is 100 years, with the GWP 100 factors are reported by IPCC 2021[6]: fossil carbon dioxide 1 kgCO_2eq/kg, fossil methane 28 kgCO_2eq/kg, nitrous oxide 265 kgCO_2eq/kg, etc.

The Global Warming Potential impact during the Life-Cycle for the production of 1 t of PP-homopolymer is of 882.607 kg CO_2eq. The contribute of emissions for each macro-process is reported in Table 6.2 and in Figure 6.1.

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[5] https://www.epa.gov/ghgemissions/understanding-global-warming-potentials Accessed on 4 August 2022

[6] IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2021.

Table 6.2 – GWP 100 Indicator breakdown among the Life-Cycle macro-processes

Activity	Absolute Contribute (kg CO_2eq)	Relative Contribute (%)
Waste disposal	0.34	0.04%
Chemicals and catalysts supply	20.17	2.28%
Propane sea transport	23.34	2.64%
Propane supply	780.37	88.42%
Water consumption	3.33	0.38%
Electricity consumption (REN)	41.17	4.66%
Natural gas consumption	13.89	1.57%
TOTAL	**882.61**	**100.0%**

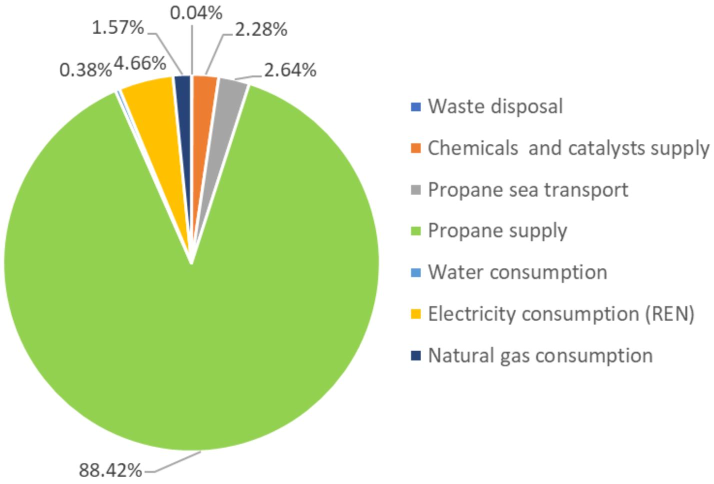

Figure 6.1 – GWP100 Indicator breakdown among the Life-Cycle macro-processes

The most significant contributor to GWP100 impact (88.42%) is the extraction and processing of Propane, used as the main raw material in the Project. Then, the second largest contributor is electricity supply, where thanks to the high share of renewable electricity supply (which therefore accounts only for 4.66 % of CO_2eq emissions), the Non-renewable one impacts for the 0%. The propane sea transport from Algeria accounts for 2.64%. Chemicals and catalysts production and transportation to the Project site accounts for the 2.28% and water consumption for the 0.38%. Due to the fuel gas produced, recovered, and used as system fuel, with the consequent reduction of Natural Gas use, the Natural Gas combustion contribute, in normal operating conditions of the Project, is of 1.57%. The waste disposal contribution is only of 0.04% of the total kgCO_2eq emissions.

With the purpose of identifying the activities that contribute more to the Global Warming Potential impact, in Figure 6.2 and Figure 6.3 and in Table 6.3 the total CO_2eq emissions are divided by PDH, PP and U&O units and their main phases.

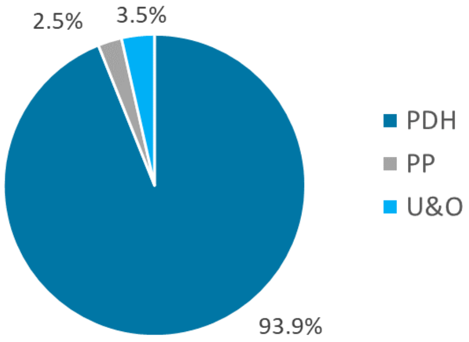

Figure 6.2 – GWP 100 Indicator breakdown among the Life-Cycle units (PDH-PP-U&O)

Table 6.3 – GWP 100 Indicator breakdown among the Life-Cycle units (PDH-PP-U&O)

Activity	Absolute Contribute (kg CO_2eq)	Relative Contribute (%)
Propane supply	780.37	88.42%
Propane sea transport	23.34	2.64%
PDH - Chemicals and catalysts supply	5.87	0.66%
PDH - Electricity consumption (REN)	17.40	1.97%
PDH - Water consumption	2.06	0.23%
PP - Chemicals and catalysts supply	8.11	0.92%
PP - Natural gas consumption	0.56	0.06%
PP - Water consumption	0.63	0.07%
PP - Electricity consumption (REN)	13.20	1.50%
U&O - Chemicals supply	6.19	0.70%
U&O - Natural gas consumption	13.34	1.51%
U&O - Water consumption	0.63	0.07%
U&O - Electricity consumption (REN)	10.57	1.20%
Waste disposal	0.34	0.04%
TOTAL	**882.61**	**100.0%**

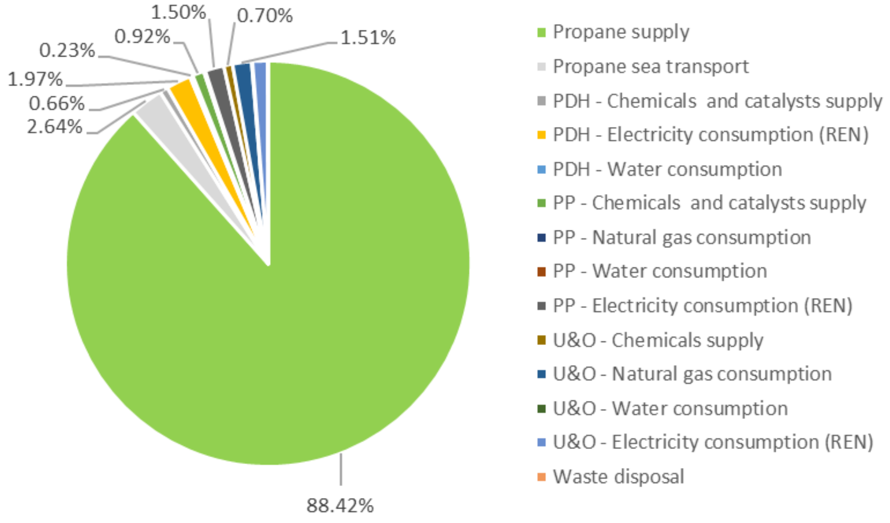

Figure 6.3 – GWP100 Indicator breakdown among the Life-Cycle units (PDH-PP-U&O)

As mentioned before, the activities having the highest impact on the GWP impact category are part of the PDH unit and include Propane supply (88.42%), electricity consumption (from renewable sources) of PDH (1.97%), PP (1.50%) and U&O (1.20%) units. The sea transport of propane from Algeria accounts for 2.64% of total GHG emissions.

6.1.2 Acidification Potential (AP)

Acidification estimates the potential of emissions to contribute to the development and deposit of acid rain on soil and water which can seriously affect plant and animal life and damage infrastructure. The acidification impacts are mainly primarily caused by fossil fuel combustion emissions, particularly Sulphur Dioxide (SO_2) and Nitrogen Oxides (NO_x). Emissions from burning fossil fuel to generate grid electricity, are a significant contributor to acidification effects for the system. Also, emissions from the extraction and processing of natural gas impact the AP category.

The Acidification Potential impact during the Life-Cycle for 1 t of PP-homopolymer is of 9.712 kg SO_2 eq. The contribute of emissions for each macro-process is reported in Table 6.4 and Figure 6.4.

Table 6.4 - Acidification Potential Indicator breakdown among the Life-Cycle macro-processes

Activity	Absolute Contribute (kg SO_2eq)	Relative Contribute (%)
Waste disposal	0.0004	0.004%
Chemicals and catalysts supply	0.1377	1.418%
Propane sea transport	0.5746	5.916%
Propane supply	8.7729	90.333%
Water consumption	0.0159	0.164%
Electricity consumption (REN)	0.1997	2.056%
Natural gas consumption	0.0106	0.110%
TOTAL	**9.7118**	**100.0%**

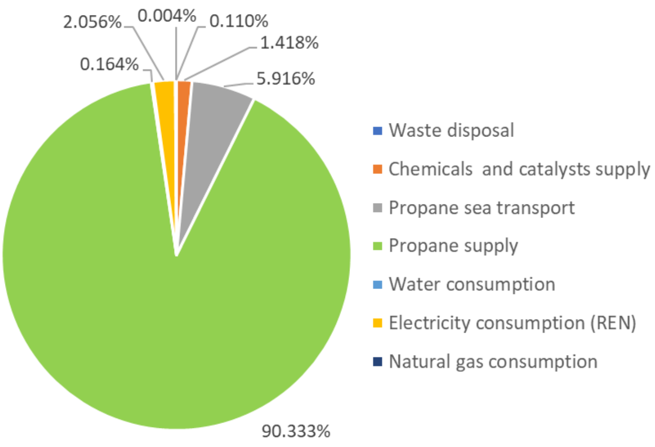

Figure 6.4 - Acidification Potential Indicator breakdown among the Life-Cycle macro-processes

A significant contributor to AP impact (90.3%) is the extraction and processing of Propane, used as the main raw material in the Project. Thanks to the high share of renewable electricity supply (which accounts only for 2.0% of SO_2eq emissions), the Non-renewable one impacts for 0%. The propane sea transport from Algeria accounts for 5.9%. Chemicals and catalysts production and transportation to the Project site account for 1.4% and water consumption for 0.16%. Due to the fuel gas produced, recovered, and used as system fuel, with the consequent reduction of Natural Gas use, the Natural Gas combustion contribute, in normal operating conditions of the Project, is of 0.1%. The waste disposal contribution is of 0.004% of the total $kgSO_2eq$ emissions.

With the purpose of identifying the activities that contribute more to the Acidification Potential impact, in Figure 6.5, Figure 6.6 and Table 6.6 the total SO_2eq emissions are divided by PDH, PP and U&O units and their main phases.

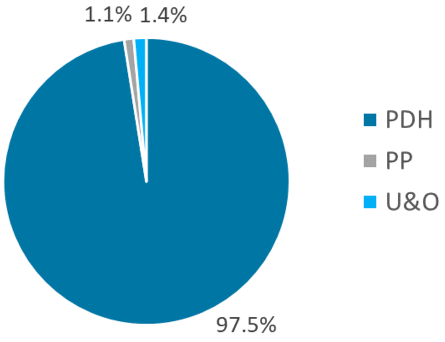

Figure 6.5 - Acidification Potential Indicator breakdown among the Life-Cycle units (PDH-PP-U&O)

Table 6.5 - Acidification Potential Indicator breakdown among the Life-Cycle units (PDH-PP-U&O)

Activity	Absolute Contribute (kg SO_2eq)	Relative Contribute (%)
Propane supply	8.7729	90.333%
Propane sea transport	0.5746	5.916%
PDH - Chemicals and catalysts supply	0.0272	0.280%
PDH - Electricity consumption (REN)	0.0844	0.869%
PDH - Water consumption	0.0099	0.102%

Activity	Absolute Contribute (kg SO_2eq)	Relative Contribute (%)
PP - Chemicals and catalysts supply	0.0375	0.386%
PP - Natural gas consumption	0.0004	0.004%
PP - Water consumption	0.0030	0.031%
PP - Electricity consumption (REN)	0.0641	0.660%
U&O - Chemicals supply	0.0730	0.751%
U&O - Natural gas consumption	0.0102	0.105%
U&O - Water consumption	0.0030	0.031%
U&O - Electricity consumption (REN)	0.0512	0.528%
Waste disposal	0.0004	0.004%
TOTAL	**9.7118**	**100.0%**

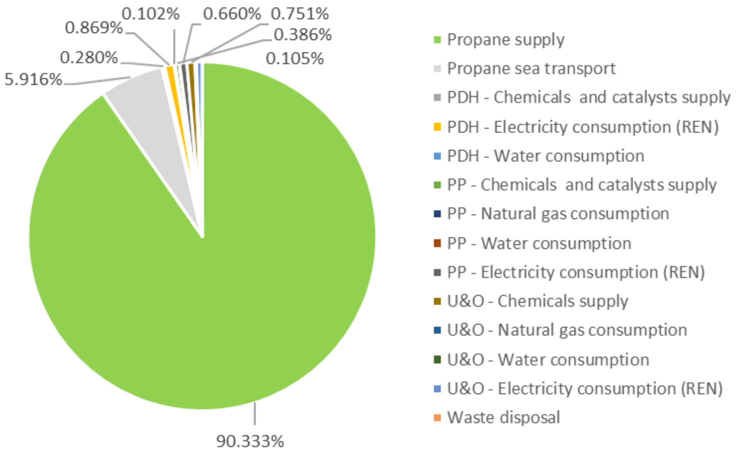

Figure 6.6 - Acidification Potential Indicator breakdown among the Life-Cycle units (PDH-PP-U&O)

The activities that have the highest impacts on the AP category are included in PDH unit and include Propane supply (90.3%) and its sea transport (5.9%).

6.1.3 Eutrophication Potential (EP)

Eutrophication occurs when excess nutrients (nitrates, phosphates) are introduced to surface water causing the rapid growth of aquatic plants. Excess releases of these substances may provide undesired effects on the waterways.[7] The characterization factors for eutrophication are the product of a nutrient factor and a transport factor.[8] The nutrient factor is based on the amount of plant growth caused by each pollutant, while the transport factor accounts for the probability that the pollutant will reach a body of water. Atmospheric emissions of nitrogen oxides (NO_x) as well as waterborne emissions of nitrogen, phosphorus, ammonia, biochemical oxygen demand (BOD), and chemical oxygen demand (COD) are the main contributors to eutrophication impacts, converted in Kg Phosphate equivalent.

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[7] Bare, J. C. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 - User's Manual; EPA/600/R-12/554 2012.

[8] Bare JC, Norris GA, Pennington DW, McKone T. (2003). TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, Journal of Industrial Ecology, 6(3–4): 49–78

The Eutrophication Potential impact during the Life-Cycle for 1 t of PP-homopolymer is of 3.1783 kg Phosphate eq. The contribute of emissions for each macro-process is reported in Table 6.7 and Figure 6.7.

Table 6.6 - Eutrophication Potential Indicator breakdown among the Life-Cycle macro-processes

Activity	Absolute Contribute (kg Phosphate$_{eq}$)	Relative Contribute (%)
Waste disposal	0.0014	0.045%
Chemicals and catalysts supply	0.0451	1.420%
Propane sea transport	0.1629	5.125%
Propane supply	2.8232	88.828%
Water consumption	0.0095	0.299%
Electricity consumption (REN)	0.1343	4.225%
Natural gas consumption	0.0019	0.059%
TOTAL	**4.1783**	**100.0%**

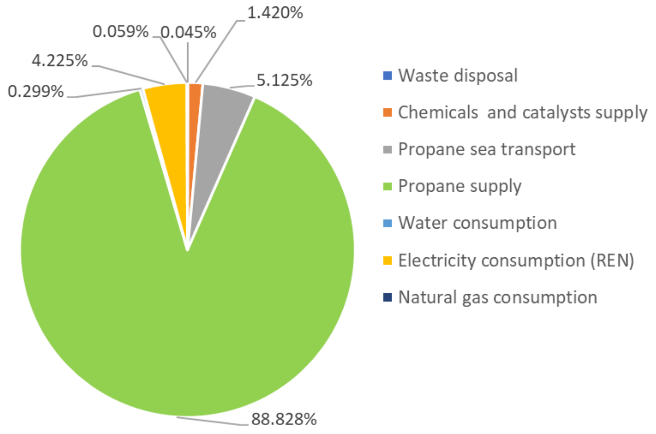

Figure 6.7 - Eutrophication Potential Indicator breakdown among the Life-Cycle macro-processes

A significant contributor to EP impact (88.8%) is the extraction and processing of Propane, used as the main raw material in the Project. Thanks to the high share of renewable electricity supply (which accounts only for 4.2%), the Non-renewable one impacts for 0%. The propane sea transport from Algeria accounts for 5.1%. Chemicals and catalysts production and transportation to the Project site accounts for the 1.4% and water consumption for the 0.3%. Due to the fuel gas produced, recovered, and used as system fuel, with the consequent reduction of Natural Gas use, the Natural Gas combustion contribute, in normal operating conditions of the Project, is of 0.06%. The waste disposal contribution is of 0.04%.

With the purpose of identifying the activities that contribute more to the Eutrophication Potential impact, in Figure 6.8, Figure 6.9 and Table 6.8 the total Phosphate$_{eq}$ emissions are divided by PDH, PP and U&O units and their main phases.

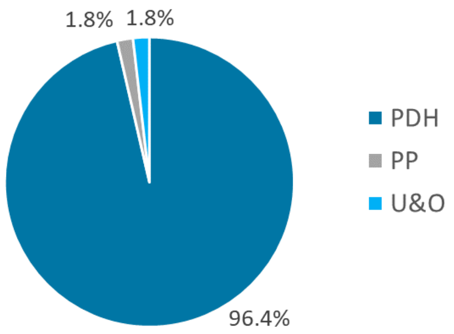

Figure 6.8 - Eutrophication Potential Indicator breakdown among the Life-Cycle units (PDH-PP-U&O)

Table 6.7 - Eutrophication Potential Indicator breakdown among the Life-Cycle units (PDH-PP-U&O)

Activity	Absolute Contribute (Kg Phosphate$_{eq}$)	Relative Contribute (%)
Propane supply	2.8232	88.8279%
Propane sea transport	0.1629	5.1245%
PDH - Chemicals and catalysts supply	0.0150	0.4732%
PDH - Electricity consumption (REN)	0.0568	1.7859%
PDH - Water consumption	0.0059	0.1853%
PP - Chemicals and catalysts supply	0.0116	0.3664%
PP - Natural gas consumption	0.0001	0.0024%
PP - Water consumption	0.0018	0.0569%
PP - Electricity consumption (REN)	0.0431	1.3555%
U&O - Chemicals supply	0.0184	0.5804%
U&O - Natural gas consumption	0.0018	0.0566%
U&O - Water consumption	0.0018	0.0569%
U&O - Electricity consumption (REN)	0.0344	1.0836%
Waste disposal	0.0014	0.0445%
TOTAL	**3.1783**	**100.0%**

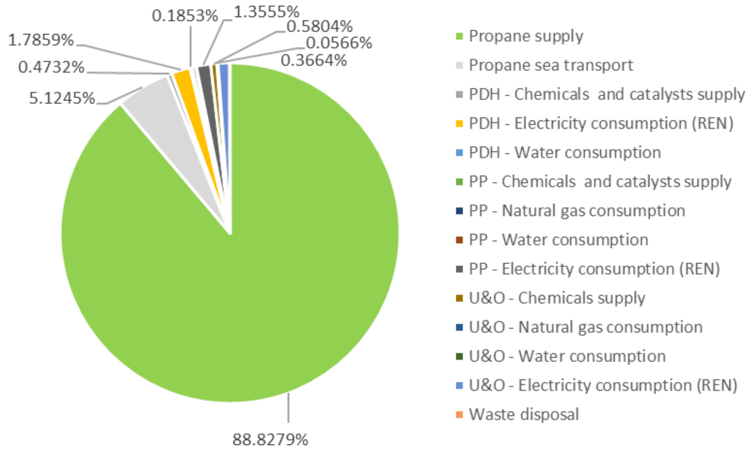

Figure 6.9 - Eutrophication Potential Indicator breakdown among the Life-Cycle units (PDH-PP-U&O)

The activities that have the main impact to the EP category are included in PDH unit and include Propane supply (88.8%) and its sea transport (5.1%) and electricity consumption (from renewable sources) of PDH systems (1.78%).

6.1.4 Ozone Layer Depletion Potential (ODP, steady state)

The reduction of protective ozone in the stratosphere caused by emissions of ozone-depleting substance (e.g. CFCs and halons) is known as Ozone Layer Depletion (ODP). The ozone depletion impact category characterizes the potential to destroy ozone based on a chemical's reactivity and lifetime. Effects related to ozone depletion can include skin cancer, cataracts, material damage, immune system suppression, crop damage, and other plant and animal effects.

The Ozone Layer Depletion Potential impact during the Life-Cycle for 1 t of PP-homopolymer is of 0.6209 t R11 eq. The contribute of emissions for each macro-process is reported in Table 6.9.

Table 6.8 - Ozone Layer Depletion Potential Indicator breakdown among the Life-Cycle macro-processes

Activity	Absolute Contribute (t R11eq)	Relative Contribute (%)
Waste disposal	0.000004	0.001%
Chemicals and catalysts supply	0.003705	0.597%
Propane sea transport	0.002646	0.426%
Propane supply	0.604339	97.327%
Water consumption	0.000172	0.028%
Electricity consumption (REN)	0.008088	1.303%
Natural gas consumption	0.001983	0.319%
Waste disposal	0.000004	0.001%
TOTAL	**0.620938**	**100.0%**

The most significant contributor to ODP impact (97.3%) is the extraction and processing of Propane, used as the main raw material in the Project. Renewable electricity supply impacts for 1.3% of $R\text{-}11_{eq}$ emissions. The other macro-processes impacts are very low (<1%); for this reason, the pie-chart is not reported in this study.

As shown in Figure 6.10 the PDH activities emissions represent almost all R11eq emissions (98.4%); Table 6.10 reports the emissions for each phase of PDH-PP-U&O units.

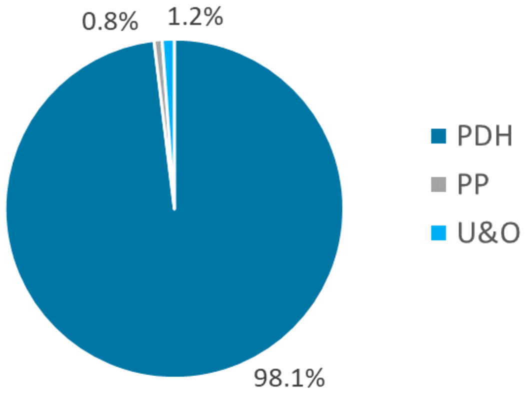

Figure 6.10 - Ozone Layer Depletion Potential Indicator breakdown among the Life-Cycle units (PDH-PP-U&O)

Table 6.9 - Ozone Layer Depletion Potential Indicator breakdown among the Life-Cycle units (PDH-PP-U&O)

Activity	Absolute Contribute (t R11eq)	Relative Contribute (%)
Propane supply	0.604339	97.327%
Propane sea transport	0.002646	0.426%
PDH - Chemicals and catalysts supply	0.000792	0.127%
PDH - Electricity consumption (REN)	0.003420	0.551%
PDH - Water consumption	0.000107	0.017%
PP - Chemicals and catalysts supply	0.000794	0.128%
PP - Natural gas consumption	0.000079	0.013%
PP - Water consumption	0.000033	0.005%
PP - Electricity consumption (REN)	0.002592	0.417%
U&O - Chemicals supply	0.002120	0.341%
U&O - Natural gas consumption	0.001904	0.307%
U&O - Water consumption	0.000033	0.005%
U&O - Electricity consumption (REN)	0.002076	0.334%
Waste disposal	0.000004	0.001%
TOTAL	**0.620938**	**100.0%**

6.1.5 Photochemical Ozone Creation Potential (POCP)

The Photochemical Ozone Creation Potential (POCP) impact category characterizes the potential of airborne emissions to cause photochemical smog. The creation of photochemical smog occurs when sunlight reacts with NO_x and volatile organic compounds (VOCs), resulting in tropospheric (ground-level) ozone and particulate matter. Endpoints of such smog creation can include increased human mortality, asthma, and deleterious effects on plant growth. Smog formation impact are generally dominated by emissions associated with fuel combustion, so that impacts are higher for life cycle stages and components that have higher process fuel and transportation fuel requirements. [9] The following analysis are reported in terms of kg of Ethene$_{eq}$ emissions.

The Photochemical Ozone Creation Potential Impact during the Life-Cycle for the production of 1 t of PP-homopolymer is of 0.85494 kg Ethene-eq. The contribute of emissions for each macro-process is reported in Table 6.11 and Figure 6.11

Table 6.10 - Photochemical Ozone Creation Potential Indicator breakdown among the Life-Cycle macro-processes

Activity	Absolute Contribute (kg Ethene$_{eq}$)	Relative Contribute (%)
Waste disposal	0.00003	0.003%
Chemicals and catalysts supply	0.00979	1.145%
Propane sea transport	0.02782	3.253%
Propane supply	0.79259	92.707%
Water consumption	0.00135	0.158%
Electricity consumption (REN)	0.02167	2.535%
Natural gas consumption	0.00169	0.197%
TOTAL	**0.85494**	**100.0%**

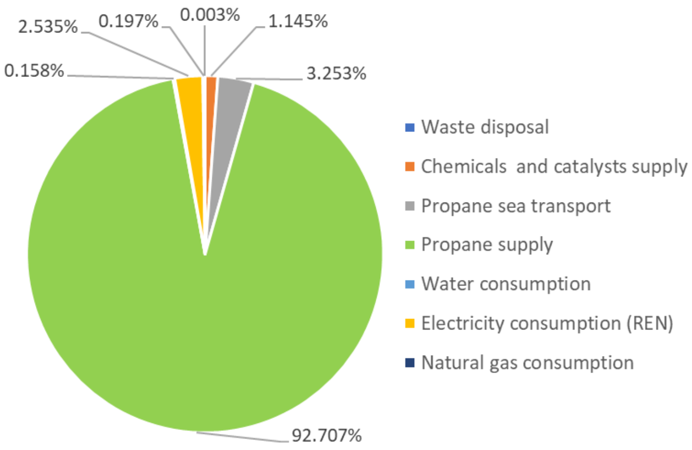

Figure 6.11 - Photochemical Ozone Creation Potential Indicator breakdown among the Life-Cycle macro-processes

The most significant contributor to POCP impact (92.7%) is the extraction and processing of Propane, used as the main raw material in the Project. The renewable electricity supply accounts for 2.5% of impacts. The propane sea transport from Algeria accounts for 3.2%. Chemicals and catalysts production and transportation to the Project site accounts for the 1.145% and water consumption for 0.15%. Due to the fuel gas produced, recovered, and used as system fuel, with the consequent reduction of Natural Gas use, the Natural Gas combustion contribute, in normal operating conditions of the Project, is of 0.2%. The waste disposal contribution is of 0.003%.

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[9] Bare, J. C. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 - User's Manual; EPA/600/R-12/554 2012.

With the purpose of identify the activities that contribute more to the Photochemical Ozone Creation Potential impact, in Figure 6.12, Figure 6.13 and Table 6.12 the total Ethene$_{eq}$ emissions are divided by PDH, PP and U&O units and their main phases.

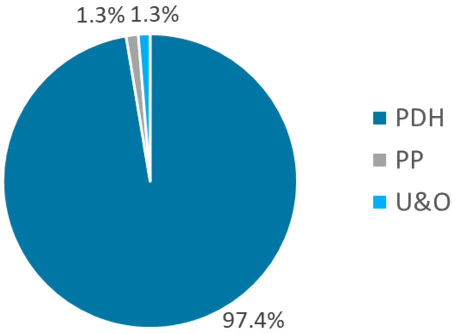

Figure 6.12 - Photochemical Ozone Creation Potential Indicator breakdown among the Life-Cycle units (PDH-PP-U&O)

Table 6.11 - Photochemical Ozone Creation Potential Indicator breakdown among the Life-Cycle units (PDH-PP-U&O)

Activity	Absolute Contribute (Kg Ethene$_{eq}$)	Relative Contribute (%)
Propane supply	0.79259	92.707%
Propane sea transport	0.02782	3.253%
PDH - Chemicals and catalysts supply	0.00208	0.244%
PDH - Electricity consumption (REN)	0.00916	1.071%
PDH - Water consumption	0.00084	0.098%
PP - Chemicals and catalysts supply	0.00413	0.483%
PP - Natural gas consumption	0.00007	0.008%
PP - Water consumption	0.00026	0.030%
PP - Electricity consumption (REN)	0.00695	0.813%
U&O - Chemicals supply	0.00358	0.419%
U&O - Natural gas consumption	0.00162	0.190%
U&O - Water consumption	0.00026	0.030%
U&O - Electricity consumption (REN)	0.00557	0.651%
Waste disposal	0.00003	0.003%
TOTAL	**0.85494**	**100.0%**

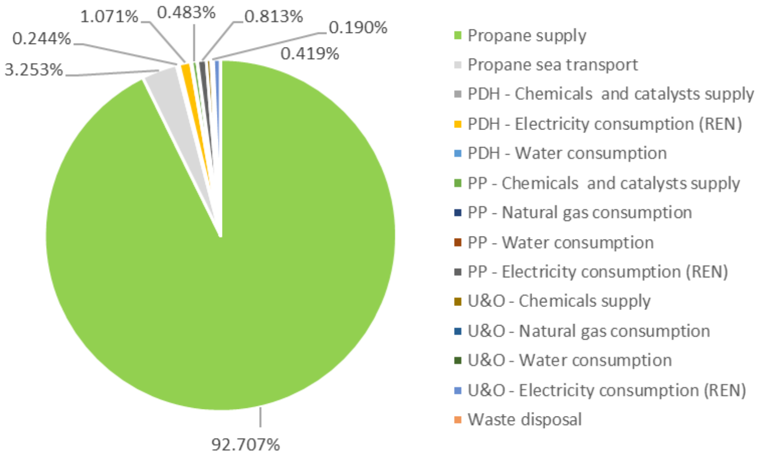

Figure 6.13 - Photochemical Ozone Creation Potential Indicator breakdown among the Life-Cycle units (PDH-PP-U&O)

The activities that have the main impact on the POCP category are included in PDH unit, such as Propane supply (92.7%) and its sea transport (3.2%) and electricity consumption (from renewable sources) of PDH systems (1.07%).

6.2 RECOMMENDATIONS FOR FUTURE IMPROVEMENTS

Based on the analysis carried out it emerges that for all the impact categories under analysis, the main sources of environmental impacts in the life-cycle are the production of propane, the electricity consumption in the plant and the transport of propane from Algeria to the Project site. More limited impacts are attributed to the supply of chemicals and the use of natural gas in the plant, whereas all other processes have almost negligible impacts.

Considering this breakdown of environmental impacts, the following main recommendations for the reduction of life-cycle impacts can be proposed to the Project promoters:

- ✓ the adoption of green procurement criteria for providers of transport services (sea and road transport), which ensures, even with no changes in the distance between the production and the use of raw materials, the reduction of environmental impacts for transport; this is especially important for ships used for sea transport of propane from Algeria to the Project site, whose environmental impacts could be reduced by using ships having a lower energy consumption per unit of cargo transported and distance travelled, e.g. if using LNG or biodiesel as fuel;
- ✓ the selection of suppliers of chemical substances located as close as possible to the plant, thus reducing environmental impacts associated to the transport by truck to the site;
- ✓ the continuous monitoring of the level of energy efficiency of the plant aimed at identifying potential operation and maintenance actions able to guarantee a reduction of energy consumption;
- ✓ the evaluation of the potential electrification of some processes carried out in the plant, in order to replace energy inputs with potential alternatives characterized by a lower environmental impact, given the 100% renewable electricity used in the plant;
- ✓ the evaluation of the potential replacement of fossil-based raw materials with bio-based inputs; this could be applicable for instance to natural gas used in the plant that could be replaced with biogas, if available in the area and compatible with technical and economic constraints, but also, in the future, to fossil propane that might be replaced with innovative alternative materials characterized by lower life-cycle environmental impacts.

Moreover, in order to improve the quality of the Life Cycle Assessment study, it is suggested to carry out a new study after a few years of operation of the plant, in order to quantify the environmental impacts based on real plant operational data instead of data taken from ex-ante design documents.

7 CONCLUSIONS

The present report presents the Life Cycle Assessment (LCA) carried out in line with ISO 14040-14044 for the Ceyhan PDH-PP Project, a polypropylene production plant to be realized in Adana province, Turkey.

LCA is a methodology for identification and evaluation of the environmental impacts of a product, which addresses the actual and the potential environmental impacts (e.g.: use of resources and environmental consequences of releases) throughout the product life-cycle: from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (e.g.: cradle to grave).

In this specific case, a Cradle-to-Gate analysis was carried out, which means that upstream processes in the production chain of a product are studied, until the stage at which the product is ready for commercialization.

The data required for the analysis were collected from the design documents made available by the Project promoters and a block flow diagram of the life-cycle was elaborated, considering the breakdown of the polypropylene production process among propane dehydrogenation, polimerization and utilities & off-site.

The input data were processed using the Sphera GaBi LCA software together with the EcoInvent LCI database, and the environmental impacts in the life-cycle were quantified according to the CML 2001 (vers. Jan.2016) impact assessment method, calculating eleven indicators that represent different effects on the environment of the processes analyzed. All the impacts were quantified with reference to the selected functional unit (1 ton of polypropylene monomer) and were presented both in absolute terms and in a normalized form, with reference to the average environmental impacts of an European citizen in one year.

In order to identify the most impacting processes/activities, five impact categories have been analysed more in-depth, by examining their breakdown among the different phases of the PDH-PP production. These categories include: Global Warming Potential (GWP 100 years), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Layer Depletion Potential (ODP, steady state), Photochemical Ozone Creation Potential (POCP).

The analysis carried out highlighted that for all the impact categories under analysis, the main sources of environmental impacts in the life-cycle are the production of propane, the electricity consumption in the plant and the transport of propane from Algeria to the Project site. More limited impacts are attributed to the supply of chemicals and the use of natural gas in the plant, whereas all other processes have almost negligible impacts. Based on these outcomes, a set of potential opportunities for future improvements have been identified.

Since the plant is planned to be realized in line with the best available technologies for the sector and is fed with electricity produced from renewable energy sources, the potential improvements identified through the present LCA study are mainly related (in addition to the actions aimed at maintaining high the level of resource efficiency of the plant) to the reduction of environmental impacts associated with input materials used, and to the study of innovative solutions for the reduction of process-related environmental impact. In the former category, actions related to green procurement are included, which encompass the selection of sea and road transport companies ensuring lower energy consumption per unit of cargo transported, as well as the selection of raw materials suppliers located at a lower distance from the plant, to minimize the environmental impacts associated with transport modes. On the other hand, among innovative solutions, it is recommended to evaluate the possibility to replace fossil raw materials with bio-based ones as well as to check the possibility of electrifying as much as possible the processes realized in the plant, to further reduce their environmental impacts thanks to the use of electricity produced from renewables.

To conclude, since the present LCA study was prepared based on design data, it is recommended to carry out a new study after a few years of operation of the plant, in order to evaluate the actual environmental impacts based on real operational data of the plant, thus being able to identify potential further improvement actions.

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