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Clean Hydrogen Partnership

Winter School on "Membranes and Membrane Reactors"

AndreaH

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Life Cycle Assessment (LCA) Methodology, Applications and Case Studies

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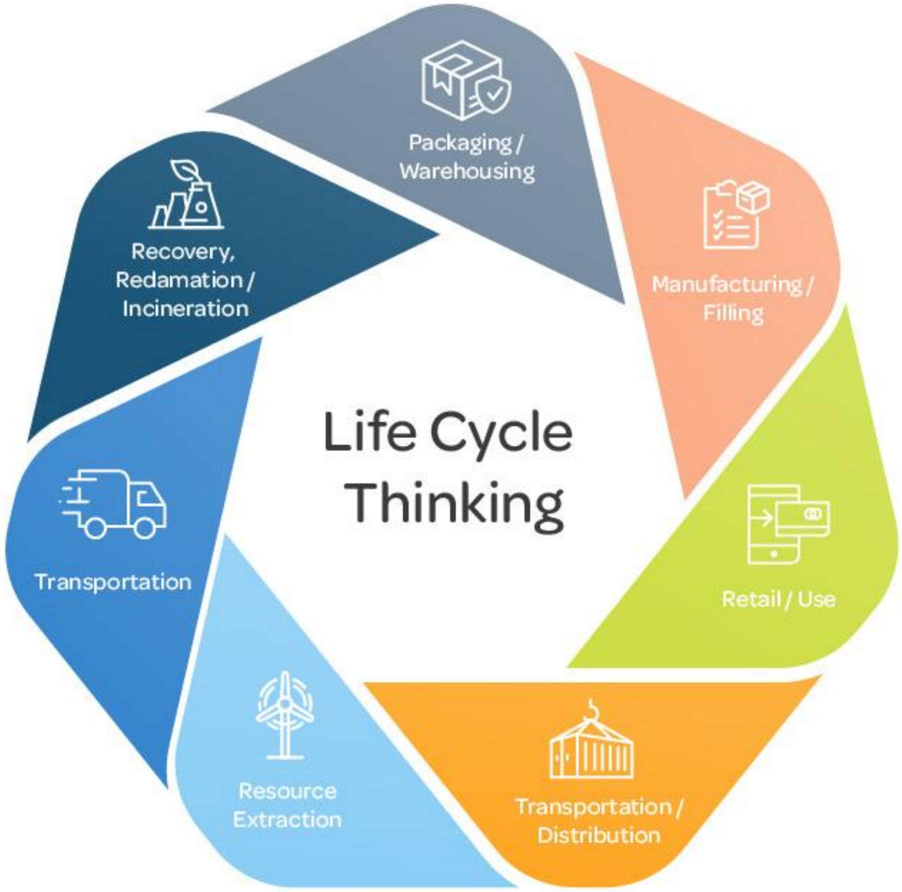
Main concepts: LCA definition and advantages

What is Life Cycle Thinking?

- Life Cycle Thinking is a **way of thinking** that includes the economic, environmental and social consequences of a product or process over its entire life cycle.

- Life Cycle Thinking **helps enterprises understand and improve their environmental performance** and social performance, while maintaining or improving profits.



Environmental sustainability-Alpha Networks Inc

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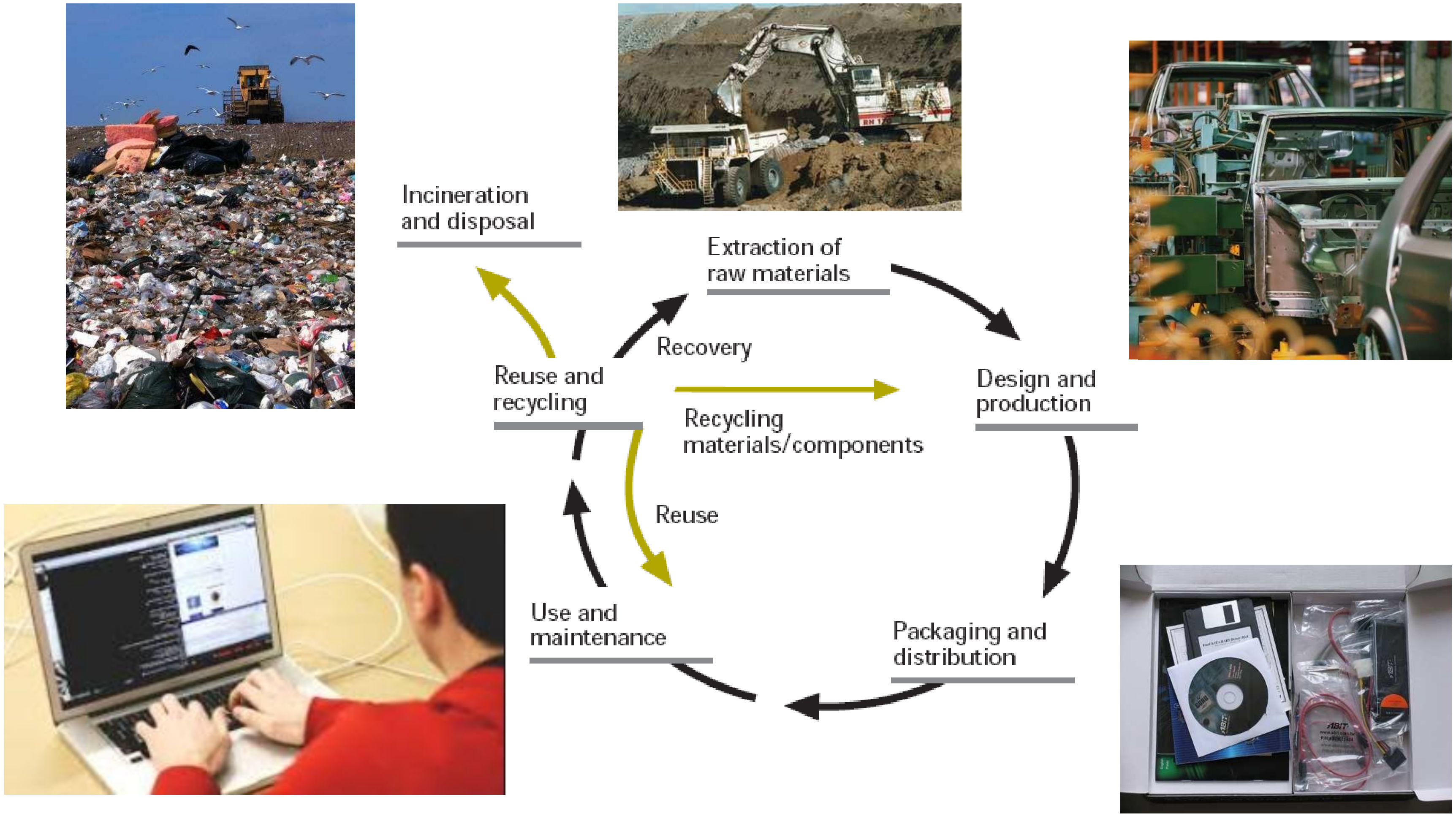
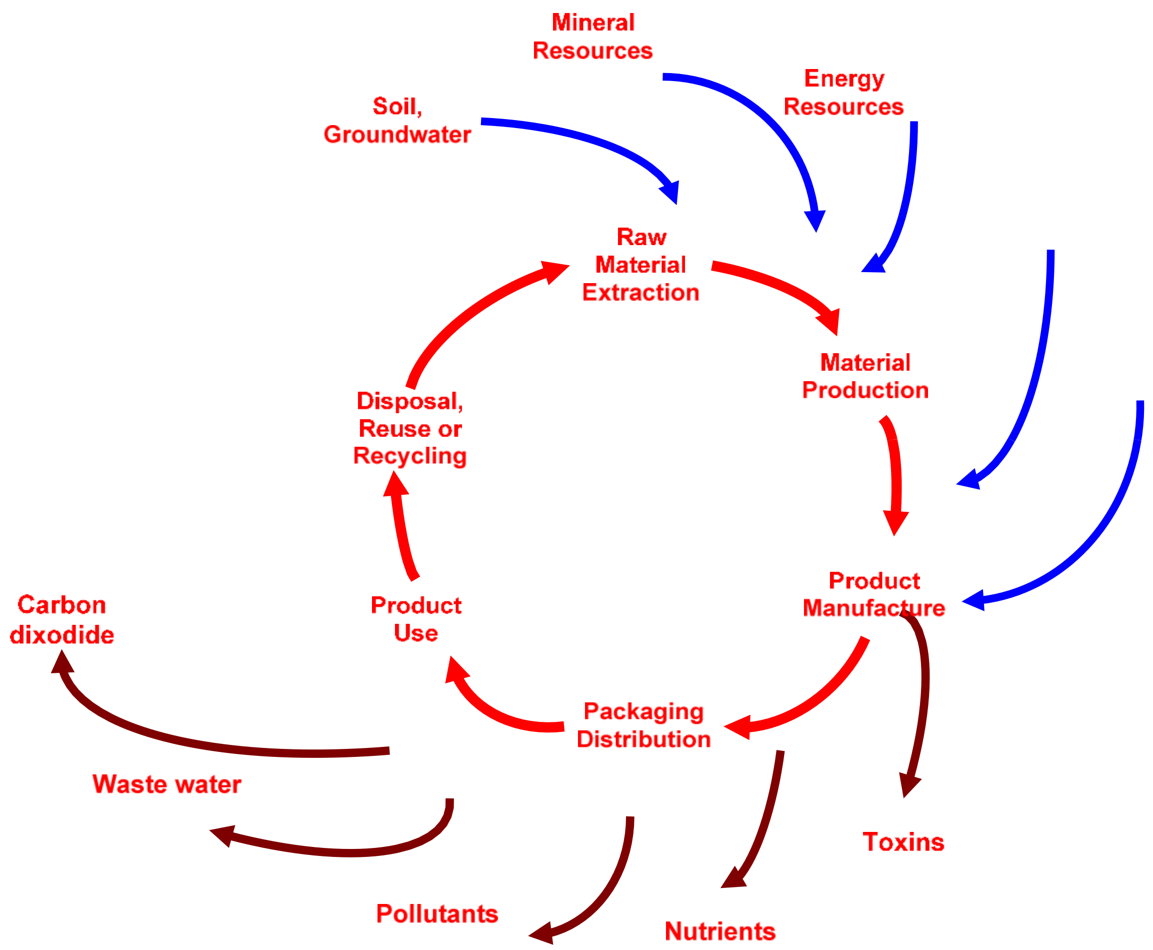
The Life Cycle

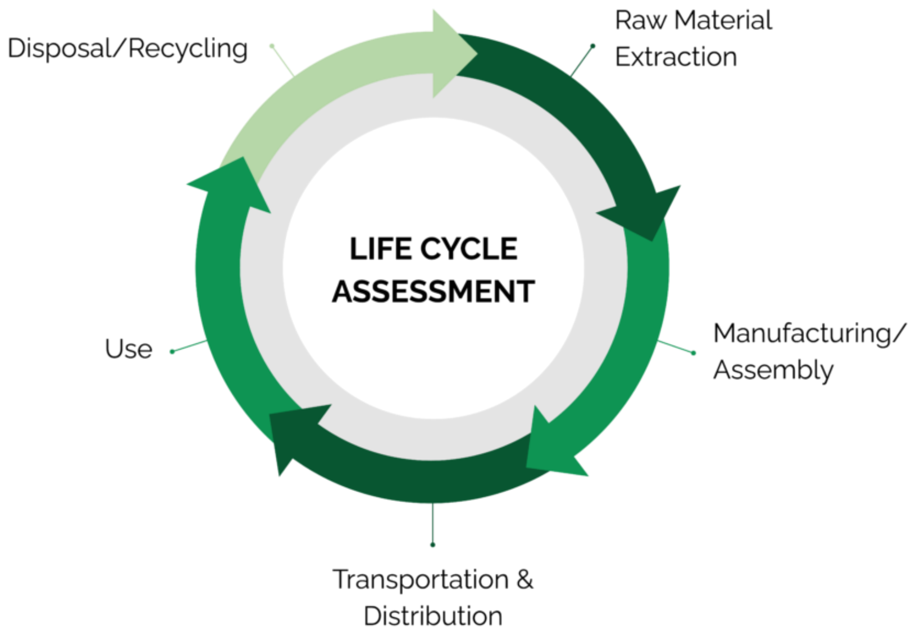


Interaction within life-cycle



What is Life Cycle Assessment (LCA)?

- Life Cycle Assessment (LCA) is a **comprehensive life cycle approach** that **quantifies ecological and human health impacts** of a product or system over its complete life cycle
- LCA uses **credible scientific methods** to model steady-state, global environmental and human health impacts
- LCA helps **decision makers understand the scale** of many environmental and human health impacts of competing products, services, policies or actions



What is LCA - Definitions

What is life cycle?

"Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal"

Life Cycle Assessment

"Compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle"

Source: ISO 14040

Advantages of performing an LCA

Life Cycle Assessment (LCA) offers numerous benefits by providing scientifically-based environmental information that helps in:

Identifying opportunities to improve environmental performance: LCA insights can drive enhancements in product development and environmental communication.

Informing decision-making in policy and business: it supports evidence-based policymaking and strategic planning.

Supporting communication and marketing strategies: marketing teams can use factual data for sustainability communications.

Advantages of performing an LCA

Examples of LCA applications include:

- **Product Designers:** they can explore how design choices affect product sustainability.
- **Policy-Makers:** they can compare environmental impacts to make informed decisions.
- **Sustainability Managers:** they can assess their portfolio to achieve carbon footprint goals.
- **Marketing Teams:** they can utilize factual data for sustainability communications.
- **Purchasing Departments:** they can identify suppliers with the most sustainable products and methods.

ISO Framework and LCA Methodology

ISO 14040 - standardised LCA procedure

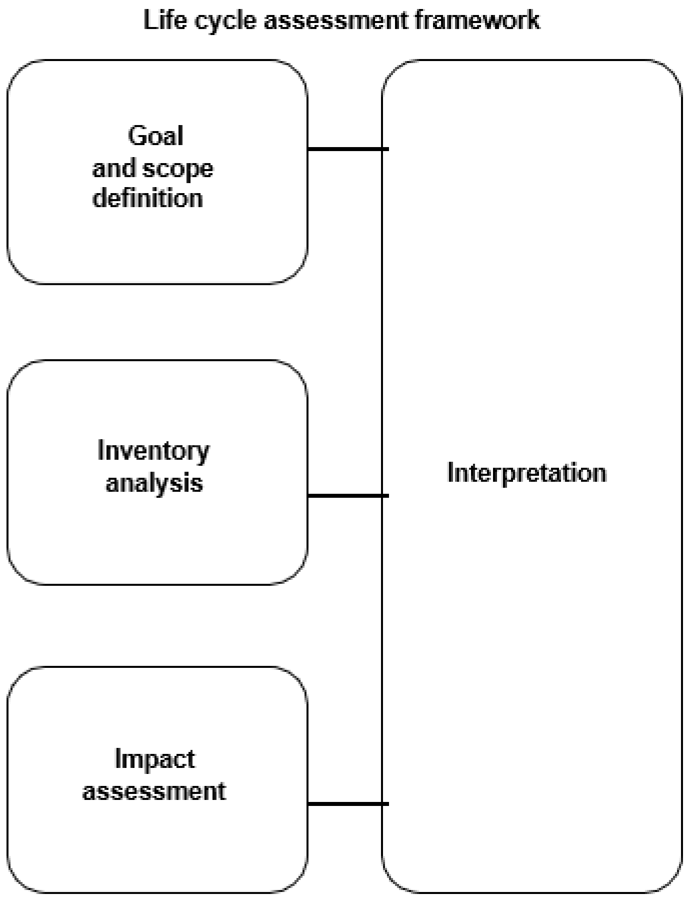
ISO 14040 - standardised LCA procedure
(ISO 14040, created in 1997-2000; revised in 2021)

- Structured framework: four stages
- Rules, requirements and considerations specified
- Specific data and calculation steps not specified
- Much attention for transparency in reporting

ISO International Organization for Standardization

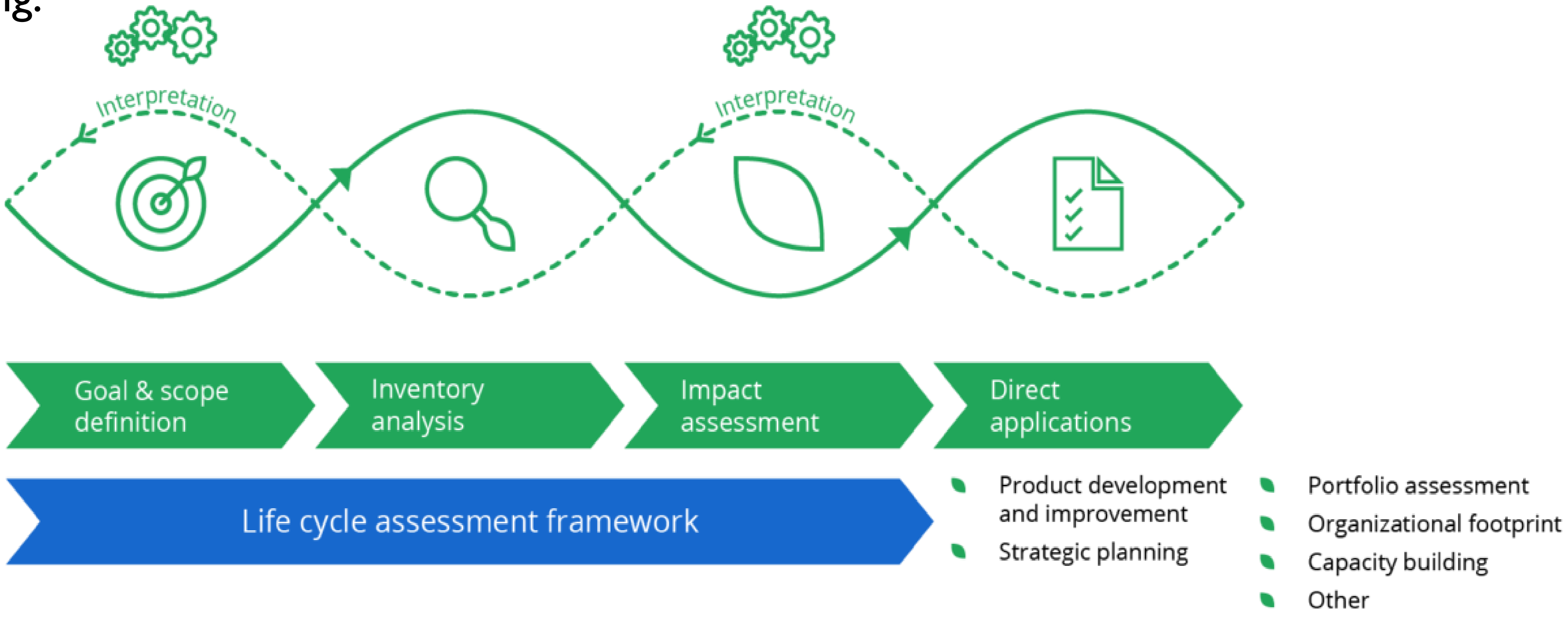
LCA Methodology

LCA is a standardized methodology, ensuring its reliability and transparency. The International Organization for **Standardization (ISO)** provides guidelines for LCA through **ISO 14040** and **14044**. These standards outline the four main phases of an LCA:



LCA Methodology

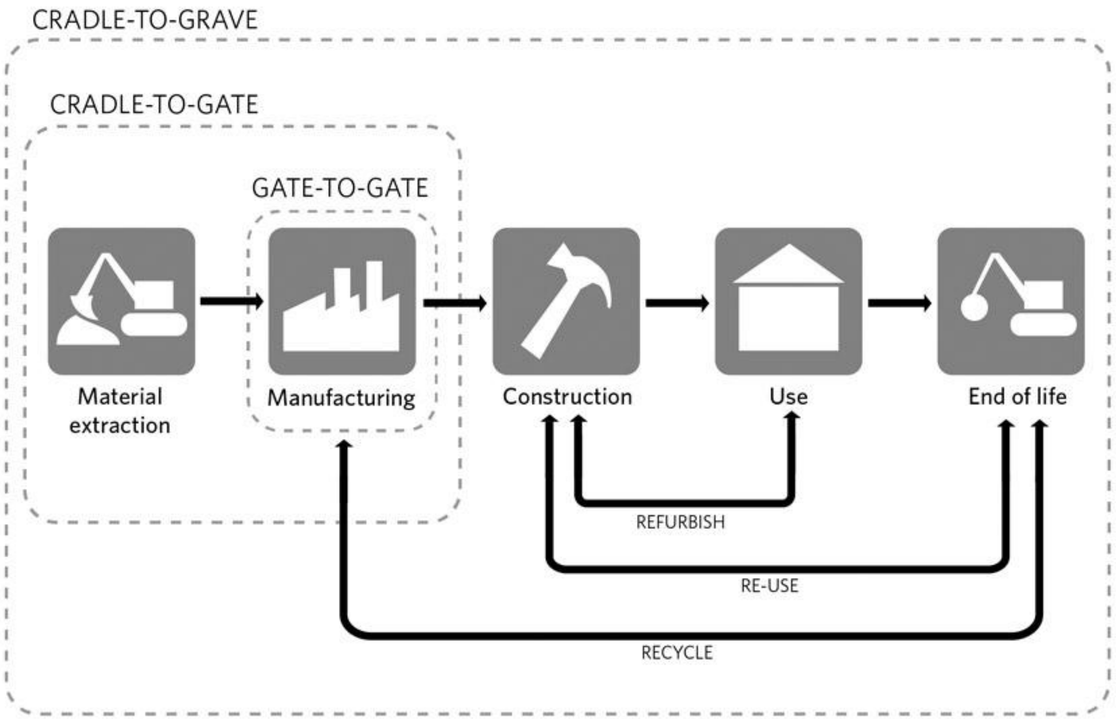
LCA is an iterative methodology, where you refine your analysis as you progress. Additionally, the results of the assessment or your interpretation might prompt you to revise your goal and scope. In this way, each LCA provides valuable business insights and guides future assessments, enhancing learning and decision-making.



LCA Methodology

With LCA, you can assess your product or service's environmental effects at any stage, from beginning to end. There are different scopes for LCA:

- **Cradle to Gate:** from raw materials to the factory gate;
- **Gate to Gate:** focusing solely on the manufacturing processes.
- **Cradle to Grave:** from raw materials to disposal.



Adapted from K. Simonen, Life Cycle Assessment

LCA Methodology

Goal and scope definition

The goal and scope definition is the first and foundational step in LCA, outlining the study's purpose and boundaries to ensure consistency.

An LCA models a product, service, or system life cycle, simplifying complex realities, which can introduce distortions. To minimise these, it's crucial to carefully define the **goal and scope**, which includes subjective choices like the **reason for the LCA, precise product definitions, and system boundaries.**

These **boundaries** determine what is included or excluded from the assessment, such as omitting minor ingredients with minimal impact.

LCA Methodology

Goal and scope definition

What questions is the LCA trying to answer?

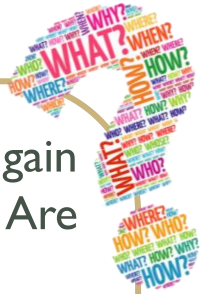
LCA Methodology

Goal definition

The goal definition enables to set the problem, to define the objectives and the scope of the study.

It addresses:

- ➢ intended application, overall objective
- ➢ reasons for performing the study
- ➢ intended audience
- ➢ final use of the results (e.g.: disclosed to public?)



- *Overall objective* - Is it a way to gain information about an existing product? Are we developing a new product?
- *Target public* – Who will benefit from this information? Is it for internal benchmarking, for consumers or for a governmental body?
- *Actors* - Who are the concerned actors? The different stakehoders and NGOs should be involved from the start of the study within the steering committee.

LCA Methodology

Scope definition

The scope definition lies down the main methodological choices to accomplish the objectives set in the stated goal.

It defines and analyses:

- system function and functional unit
- system boundaries, including temporal/geographical and technological coverage
- allocation procedure
- impact assessment methodology

LCA Methodology

Scope definition: system function and functional unit

LCA is based around comparison of alternative ways to provide a defined set of goods or services.

- It is therefore necessary to define and quantify the **system functions** under study – *i.e.* what utility/service is provided.

Based on the system function, it is possible to define the **functional unit** (FU) common to all scenarios.

The FU is common to all alternatives and is **the basis** for comparison.

LCA Methodology

Scope definition: system boundaries

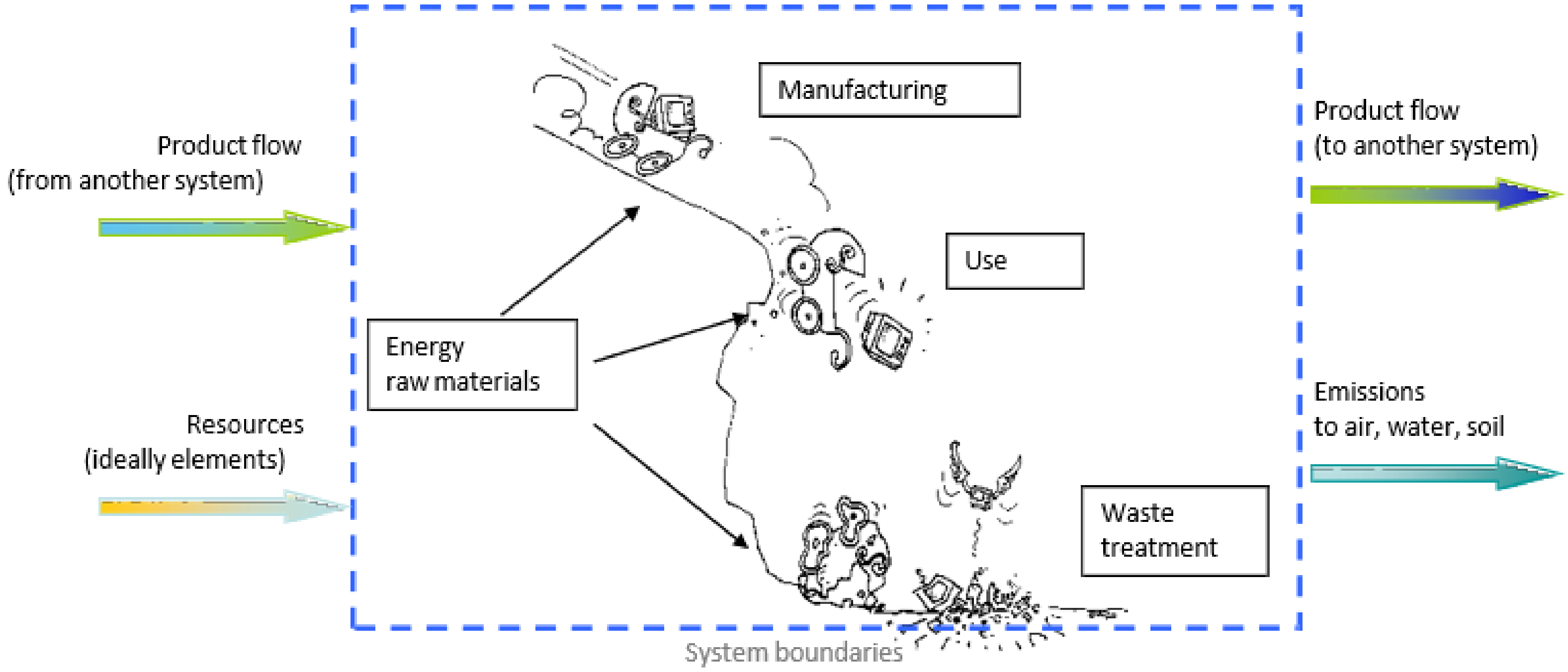
The system boundaries are closely linked to the product system.

In the ISO 14041 standard, the product system has the following definitions:

- *"A product system is a collection of unit processes connected by flows of intermediate products which perform one or more defined functions. A product system* ***description includes unit processes, elementary flows and product flows across the system boundaries and intermediate product flows*** *within the system.”*
- *“The essential property of a product system is characterized by its function and cannot be defined solely in terms of the final products.“*

LCA Methodology

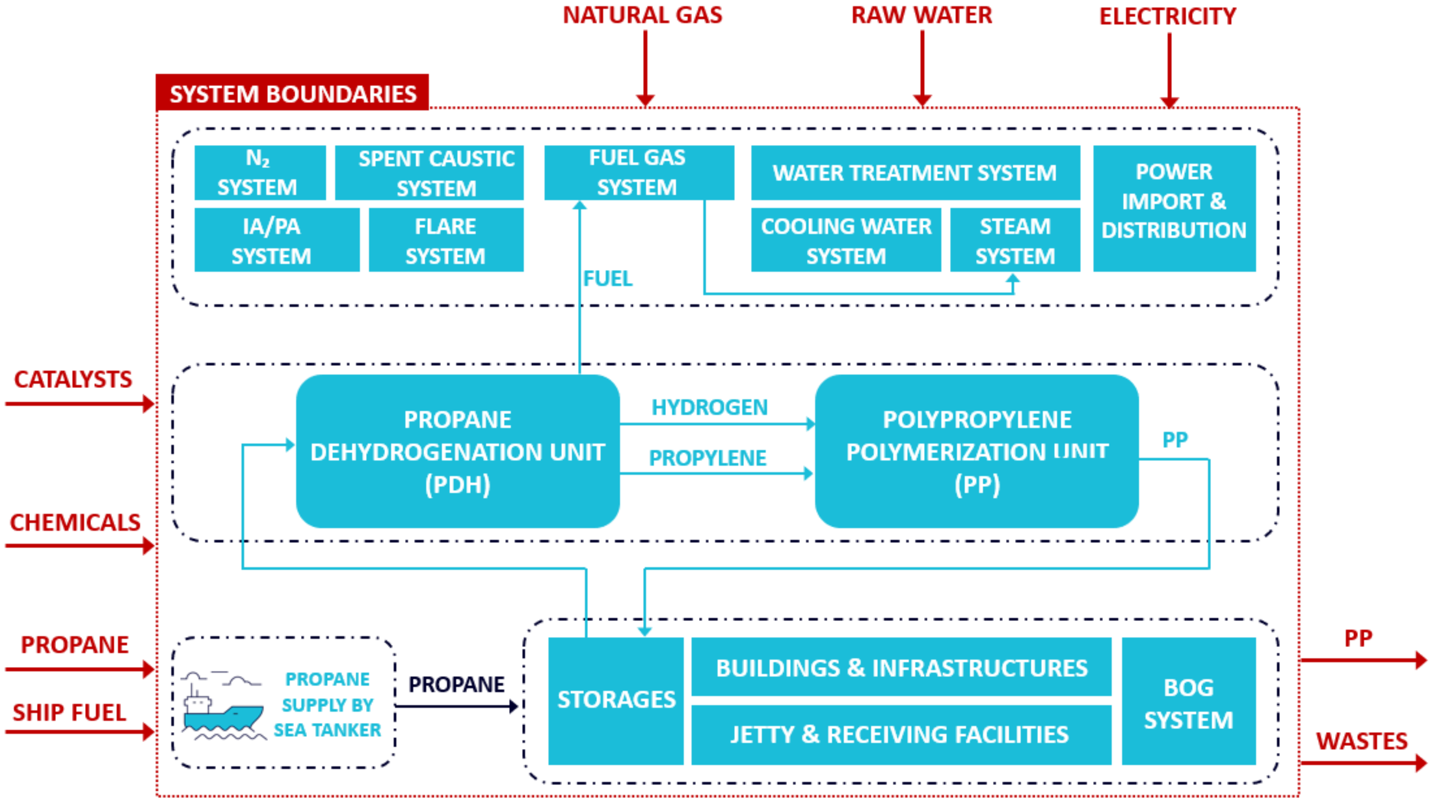
Scope definition: system boundaries



LCA Methodology

Scope definition: system boundaries - process tree

- Draw process tree to describe unit processes, system interconnections and show system boundaries
- Process trees can also identify the expected level of aggregation in systems.



LCA Methodology

Inventory analysis

In the second step, inventory analysis of extractions and emissions, you examine all environmental inputs (like raw materials and energy) and outputs (such as pollutants and waste) associated with a product or service. This process provides a comprehensive **life cycle inventory (LCI),** focusing on collecting and accurately modelling relevant data through these **inputs and outputs.**

In this phase is necessary to:

- describe the system in terms of interconnected unit operations
- collect data on environmental exchanges from each unit process
- sum the environmental exchanges across the whole product system

LCA Methodology

Inventory analysis

- The **boundaries mark what is included in the product system and what is excluded**
- Each product/material/service should be followed until it has been translated into elementary flows (emissions, natural resource extractions, land use, …)

UPSTREAM

- upstream: TV → transformer → copper wire → copper → copper ore
- upstream: TV → electricity → high-voltage electricity → coal

DOWNSTREAM

- downstream: TV → electronic equipment waste → removal of precious and recyclable materials → landfill

LCA Methodology

Impact assessment

In the life cycle impact assessment (LCIA), you evaluate the potential environmental impacts identified in the inventory analysis. This step helps you understand sustainability challenges and make informed business decisions. **You classify and translate environmental impacts into themes such as global warming and human health.** A key decision is whether to present results as a single sustainability score or in detailed categories (e.g., CO_2 emissions and land use) based on your audience's needs and ability to understand the results.

- **ISO: This LCA phase is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system, as specified in the goal and scope.**
  - International Standard ISO 14044
  - Technical Report ISO/TR 14047
- **This is the third phase of a LCA**
  - LCIA

LCA Methodology

Impact assessment: impact categories and category indicators

Impact category

ISO 14040 definition:
class representing environmental issues of concern to which LCI results may be assigned

Examples:

- climate change
- acidification

Category indicators

ISO 14040 definition: quantifiable representation of an impact category

Examples:

- infrared radiative forcing
- proton release

LCA Methodology

Impact assessment: characterisation models and factors

Characterisation model

Non-ISO definition:

mathematical model of the impact of elementary flows with respect to a particular category indicator

Examples:

- IPCC model for climate change
- RAINS model for acidifying substances

Provides the basis for a characterisation factor

Characterisation factor

ISO 14040 definition:

a factor derived from a characterization model which is applied to convert the assigned LCI results to the common unit of the category indicator

Examples:

- Global warming potential (GWP)
- Acidification potential (AP)

LCA Methodology

Impact assessment: the principle of characterisation

impact category

- CO_2 and CH_4 both contribute to climate change.

characterization factor

- Global Warming Potential (GWP) is a measure for climate change in terms of radiative forcing of a mass-unit of greenhouse gas.

category indicator

- Example calculation:
  - **5** kg CO_2 — GWP = 1
  - **3** kg CH_4 — GWP = 21
  - 1 x **5** + 21 x **3** = 65
  - 68 kg CO_2-eq

category indicator result

According to most recent IPCC updates, this value can reach 36

LCA Methodology

Impact assessment: the principle of characterisation

Simple conversion and aggregation:

$$IndicatorResult_{cat} = \Sigma_{subs} CharFact_{,cat,subs} \times InventoryResult_{,subs}$$

68 kg CO2-eq (IndicatorResult)

CO_2, CH_4 (subs)

1, 21 (CharFact) → *IPCC climate model*

Climate change (cat) → *Infrared radiative forcing*

5, 3 (InventoryResult)

LCA Methodology

Impact assessment: Example Impact categories, characterisation models, factors & units

Impact category	Indicator	Characterisation model	Characterisation factor	Equivalency unit
Abiotic depletion	Abiotic depletion	Guinee & Heijungs 95	Abiotic depletion potential	kg Sb eq.
Climate change	Infrared radiative forcing	Intergovernmental Panel on Climate Change	Global warming potential	kg CO_2 eq.
Stratospheric ozone depletion	Stratospheric ozone breakdown	World Meteorological Organization model	Stratospheric ozone layer depletion potential	kg CFC-11eq.
Human toxicity	Predicted daily intake, Accepted daily intake	EUSES, California Toxicology Model	Human toxicity potential	kg 1,4-DCB eq.
Ecological toxicity	PEC, PNEC	EUSES, California Toxicology Model	AETP, TETP, etc.	kg 1,4-DCB eq.
Photo-oxidant smog formation	Tropospheric ozone production	UN-ECE trajectory model	Photo-oxidant chemical potential	kg C_2H_6 eq.
Acidification	Acidification	Regional Acidification Information & Simulation	Acidification potential	kg SO_2 eq.

LCA Methodology

Interpretation

The interpretation phase concludes the assessment by reviewing and substantiating the conclusions. ISO 14044 outlines several checks to ensure the data and procedures used to support your conclusions. This thorough review allows you to confidently share your results and improvement decisions with the world, minimising the risk of any surprises.

Practical examples and Case Studies

ANDREAH Project
LCA – Cradle to grave

AndreaH

ANDREAH Project - Introduction

The ANDREAH project is an innovative initiative aimed at transforming the European energy and transport sectors by addressing the reliance on fossil fuels and enhancing energy security. With over 57% of the EU's energy coming from imports, ANDREAH seeks to mitigate climate change and reduce air pollution through advanced ammonia decomposition technologies that produce ultra-pure hydrogen (H_2) from ammonia (NH_3).

Motivation and Challenges

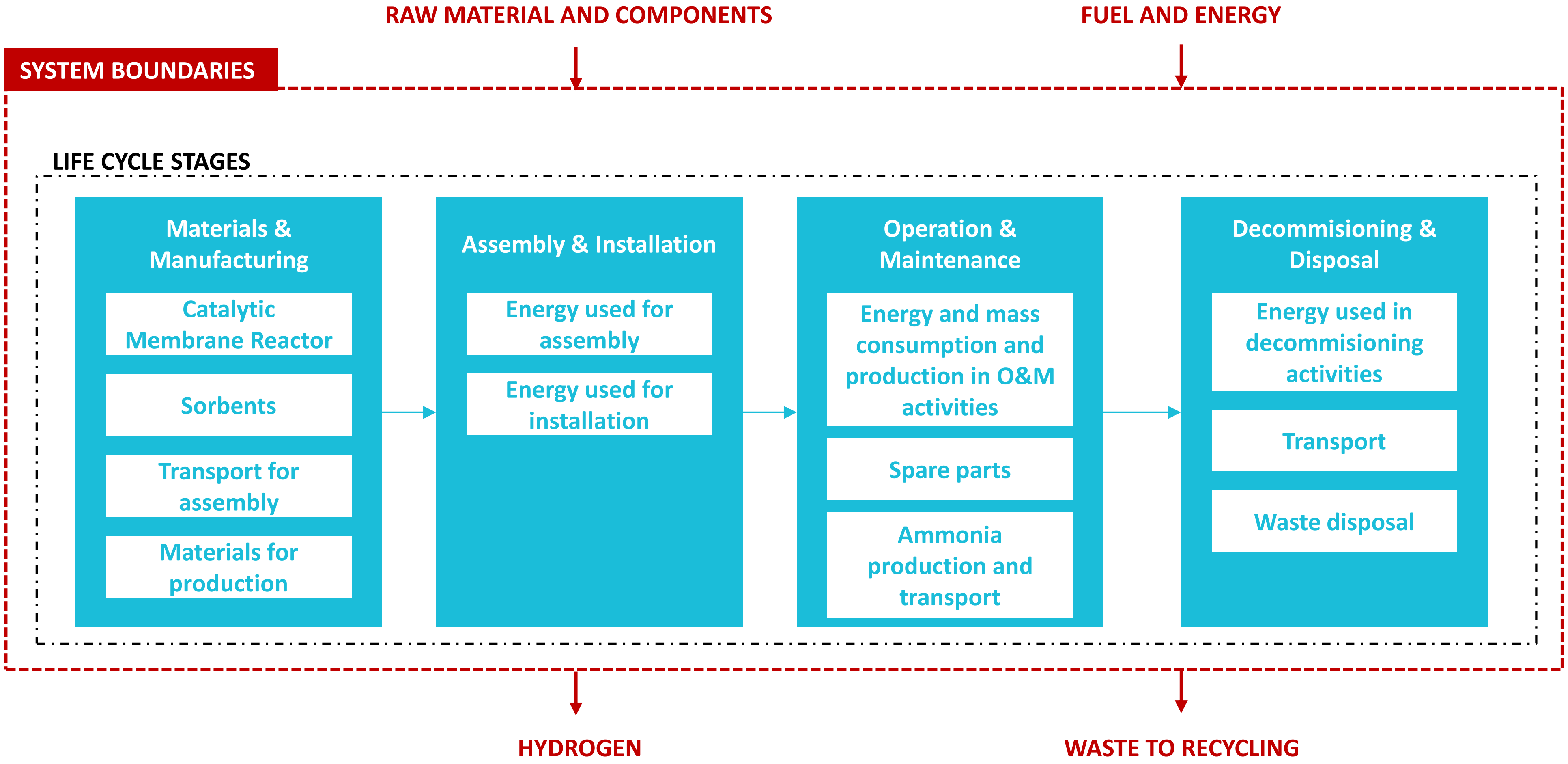
The project responds to urgent challenges, including rising energy prices and geopolitical tensions, such as Russia's invasion of Ukraine. In light of the European Commission's 'Fit for 55' initiative and the REPowerEU strategy, which aim to cut greenhouse gas emissions and diversify energy sources, renewable hydrogen, particularly green ammonia, is positioned as a key solution.

Objectives

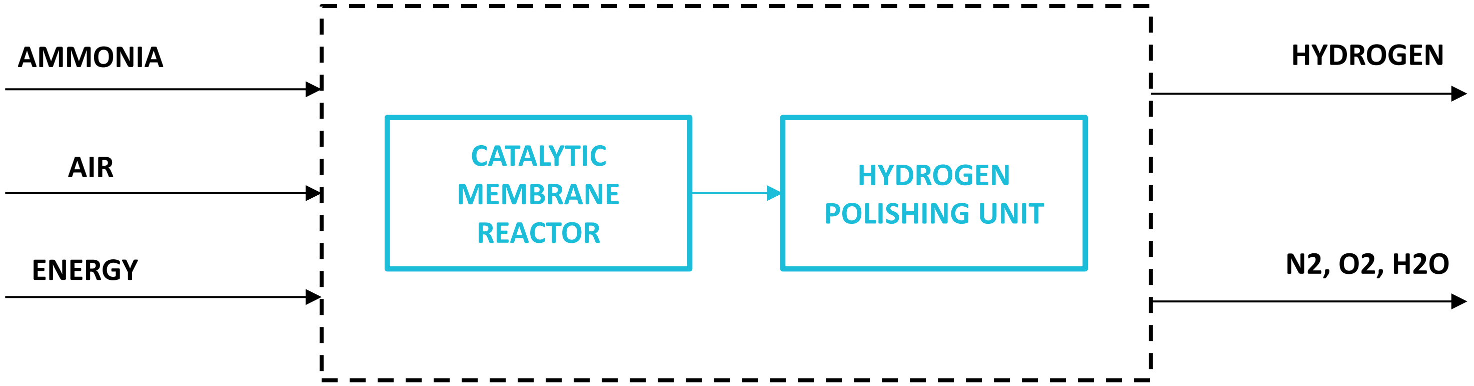
ANDREAH's main objective is to develop a Catalytic Membrane Reactor (CMR) system for efficient ammonia cracking, achieving hydrogen purity greater than 99.998%. Key targets include:

1. **Advanced Technology Development:** Establishing a network with universities and industry partners to create effective ammonia cracking systems.
2. **Environmental Impact Assessment:** Conducting a Life Cycle Assessment (LCA) to ensure sustainable materials and economic viability.
3. **Market Exploitation:** Engaging key players in the hydrogen economy to commercialize project results.
4. **Dissemination of Results:** Promoting findings to stimulate interest across various industrial sectors.

ANDREAH Project – Boundaries and Block Diagram



ANDREAH Project – Plug Flow Diagram (operation phase)



Geothermal plants
LCA – Cradle to gate

Geothermal plants – the overall projects

THE NEED
clear assessment of geothermal plants' emissions

THE CHALLENGE
- uniqueness of geothermal reservoir
- numerous of technological options to produce and utilize geothermal energy

THE PATHWAY
- **clusterise** geothermal plants: geographical & technological
- include a **validation**: sectoral stakeholders
- tailor a set of **common rules**: LCA in geothermal sector

THE RESULTS
- **quantitative data -** impact categories
- **recommendations**
- **guidance** document: LCA Sector (geothermal) Category Rules

Methodological guidance to be followed to perform a LCA study on geothermal sector

Background documents to drive the future developments (research and policy level) within renewable energy and decarbonisation targets

Geothermal plants – Data Collection

➢ Mapping main **geothermal areas** of Europe and classification of **reservoirs**

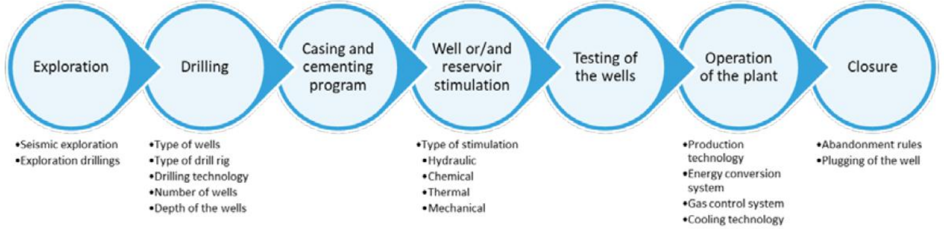
- Pannonian Basin
- Molasse basin
- South Permian Basin
- Paris and Aquitaine basins
- Upper Rhine graben
- Iberian Peninsula
- Italian peninsula
- Iceland
- Balkan region
- Greek Islands

- system temperature
- system depth
- dominant phase (liquid, vapor, gas)
- host rock type (igneous, carbonates, sandstones)
- reservoir type (matrix, void, fracture)
- stimulation requirements (hydrothermal or EGS)

➢ Classification of geothermal **plants**:

- *Power* production → electrical energy production
- *H&C* applications → thermal energy production
- Combined Heat and Power production (CHP)→ electrical and thermal energy

➢ Inventory of **technologies** used in each phase of plants' lifespan



➢ Clusterisation of European geothermal plants

"*group of geothermal plants having common characteristics in terms of geological and technological parameters.* "

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Geothermal plants – Life Cycle and GHG Emissions Inventory

Life Cycle Inventory (LCI): identify and quantify the input flows and output flows of a system.
<u>Cradle-to gate approach (decommissioning and downstream module omitted)</u>

GHG Emissions Inventory: split the emissions (energy source and gas released) along the life cycle phase of each geothermal energy technology investigated

- **Exploration**: Diesel consumption
- **Drilling**: Diesel consumption; Drilling mud; Steel; Cement and fillers; Disposal of residues
- **Testing**: Diesel consumption; Direct emissions to air
- **Stimulation**: Diesel consumption; Use of chemicals; Use of water
- **Construction**: Materials for plant building; Materials for heat and power equipment; Materials for collection pipeline
- **Operation**: Energy consumption for operation; Direct emissions to air
- **Maintenance & Replacement**: Replacement of construction materials; ORC fluid leakages; Cleaning operations; Chemicals for anti-scaling, anti-corrosion, fluid treatment

- Carbon Dioxide (CO_2)
- Methane (CH_4)
- Hydrogen Sulphide (H_2S)
- Nitrogen (N_2)
- Ammonia (NH_3)
- Mercury (Hg)
- Arsenic (As)
- Sulfur Dioxide (SO_2)

Direct emissions

Direct *emissions: deriving from the ground (e.g.: due to drilling phase) or emissions to atmosphere during operation phase*

Indirect *emissions: linked to other activities i.e. extraction of plants' construction materials*

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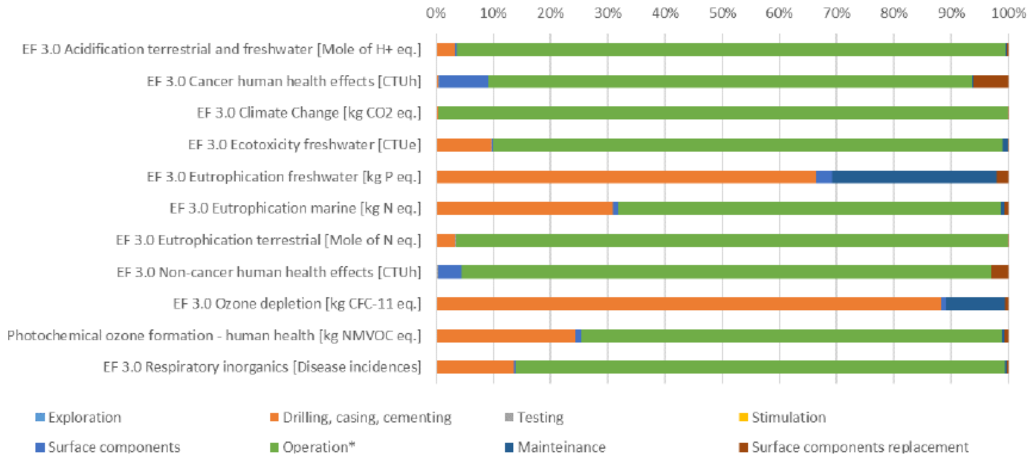
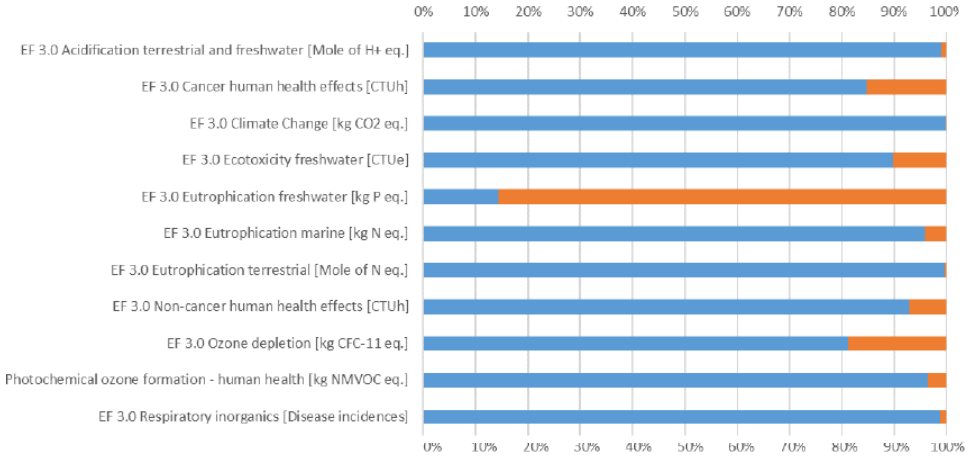
Geothermal plants – Results and Interpretation

Emissions during each phase of geothermal plants' lifespan - Italian Clusters

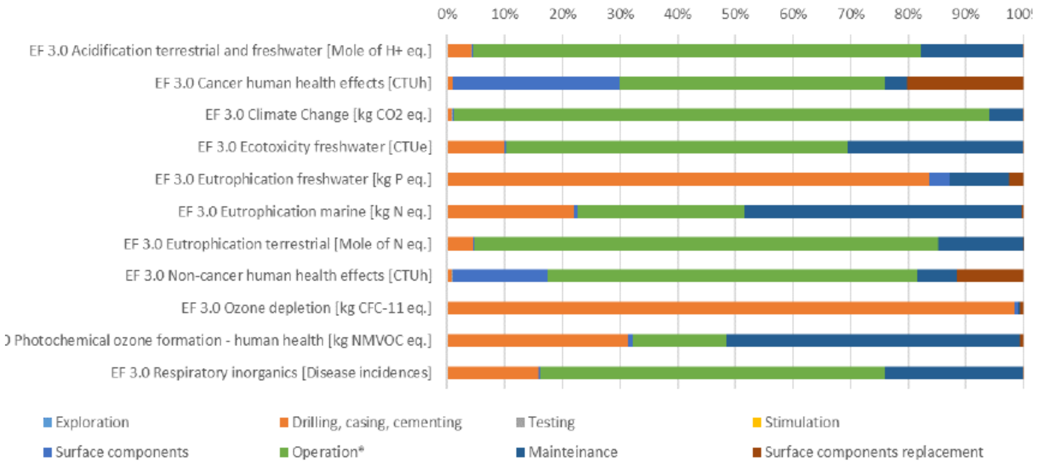
GaBi ts© by Thinkstep AG/Sphera professional database (8.7, service pack 39)
EcoInvent 3.5 database

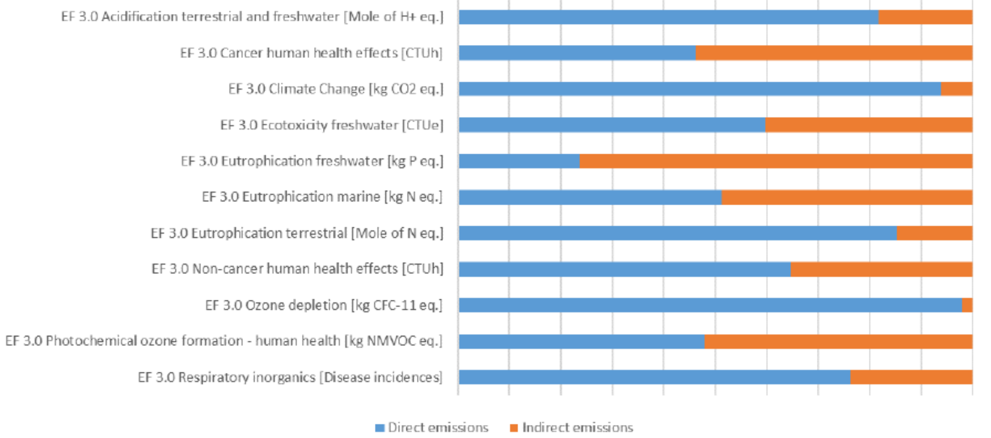
Power Clusters



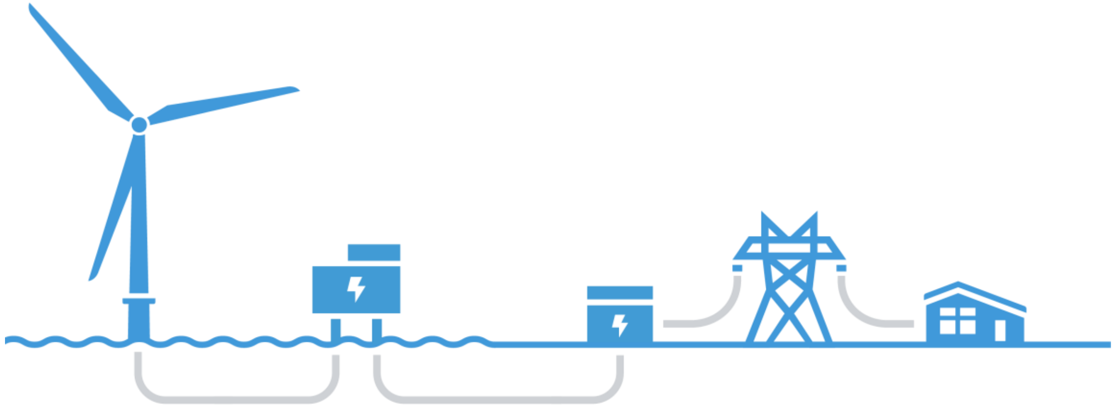


CHP Clusters

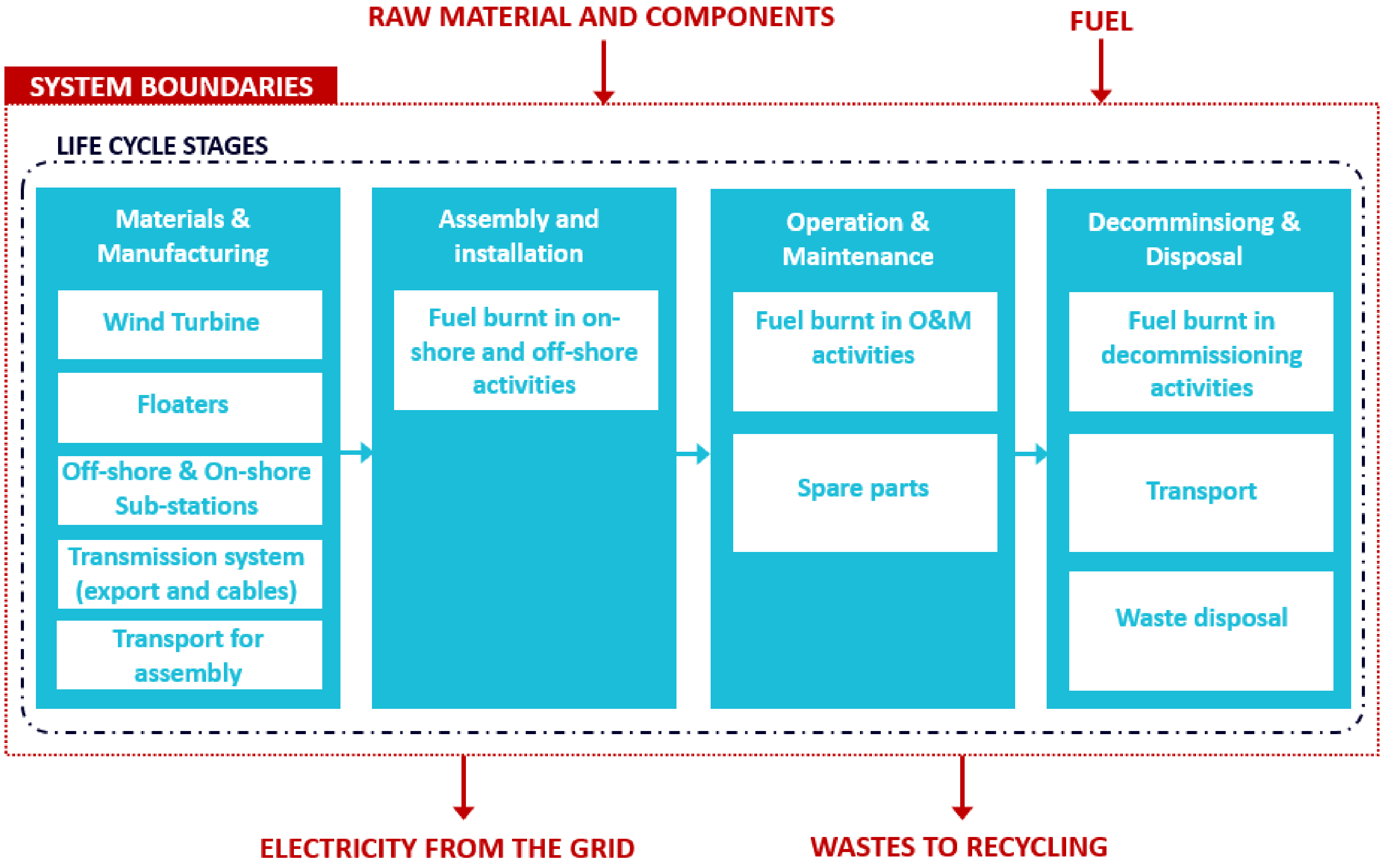




Offshore wind power
LCA – Cradle to grave



Offshore wind power – Boundaries and Block diagram



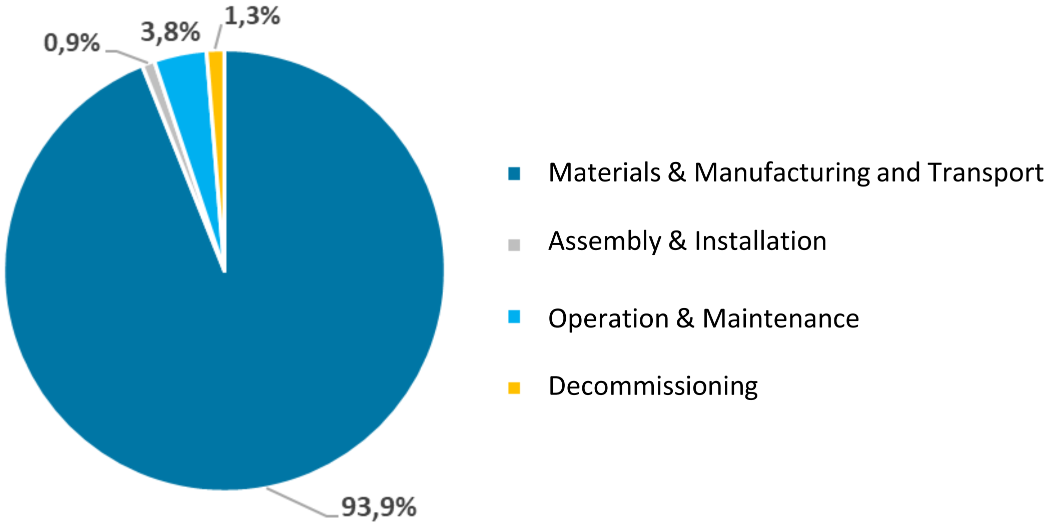
Offshore wind power – Inventory

Phase	Category	Flow	Foreground Data		Data Quality	
			Values	u.m.	Foreground Data	Background Data
Materials & Manufacturing	Floaters	Steel	0,004523810	[kg/kWh]	Primary (stimata)	Ecoinvent
	Wind Turbines	Steel	0,001205344	[kg/kWh]	Primary (stimata)	Ecoinvent
	Sea Cables	Aluminum	0,000254751	[kg/kWh]	Primary (stimata)	Ecoinvent
		Rubber	0,000071175	[kg/kWh]	Primary (stimata)	Ecoinvent
	Off-shore Sub-stations	Steel	0,000211640	[kg/kWh]	Primary (stimata)	Ecoinvent
	Underground cables	Aluminum	0,000006116	[kg/kWh]	Primary (stimata)	Ecoinvent
		Rubber	0,000001079	[kg/kWh]	Primary (stimata)	Ecoinvent
	On-shore Sub-stations	Steel	0,000105820	[kg/kWh]	Primary (stimata)	Ecoinvent
Transport	By ship	Distance	0,006379735	[tkm /kWh]	Primary (stimata)	Ecoinvent
	By truck	Distance	0,000000026	[tkm /kWh]	Primary (stimata)	Ecoinvent
Assembly and Installation	Fuel burnt in construction activities	Diesel	0,001734187	[MJ/kWh]	Primary (stimata)	Ecoinvent
Operation & Mantenaince	Spare parts	Steel	0,001458743	[kg/kWh]	Primary (stimata)	Ecoinvent
		Aluminum	0,000065217	[kg/kWh]	Primary (stimata)	Ecoinvent
		Rubber	0,000018063	[kg/kWh]	Primary (stimata)	Ecoinvent
	Maintenance	Diesel	0,002299000	[MJ/kWh]	Primary (stimata)	Ecoinvent
Decommissioning and Waste Disposal	Fuel burnt in decommissioning activities	Diesel	0,000433547	[MJ/kWh]	Primary (stimata)	Ecoinvent
	Transport by ship	Distance	0,006379735	[tkm /kWh]	Primary (stimata)	Ecoinvent
	Transport by truck	Distance	0,000797467	[tkm /kWh]	Primary (stimata)	Ecoinvent
	Waste disposal	Non recycled waste	0,001202476	[kg/kWh]	Primary (stimata)	Ecoinvent

Offshore wind power – Results and Interpretation

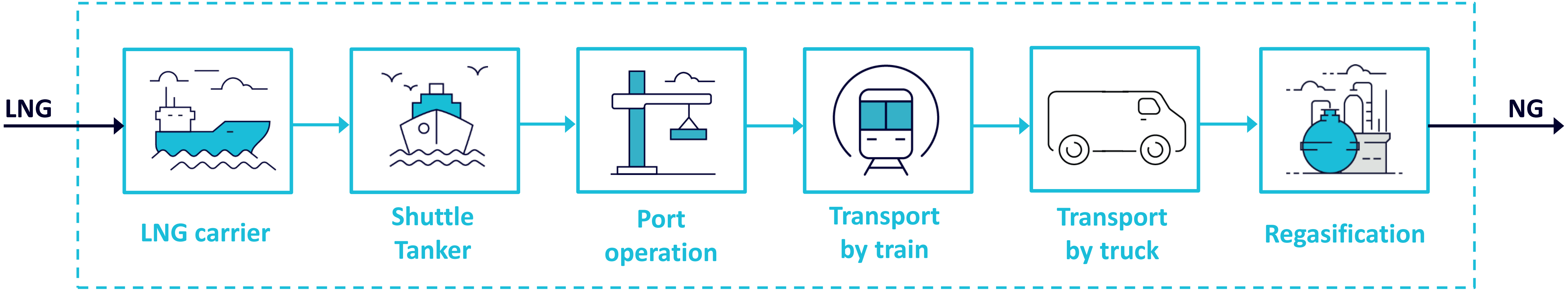
Indicators	Value	u.m.
Acidification Potential (AP)	0,000062900	kg SO_2 eq. / kWh
Eutrophication Potential (EP)	0,000037000	kg Phosphate eq. / kWh
Global Warming Potential (GWP 100 years)	0,0163	kg CO_2 eq. / kWh
Ozone Layer Depletion Potential (ODP, steady state)	0,000000001	kg R11 eq. / kWh

Phase	Absolut contribution (kg CO_2eq/kWh)	Relative contribution (%)
Materials & Manufacturing and Transport	0,015300	93,9%
Assembly & Installation	0,000151	0,9%
Operation & Maintenance	0,000627	3,8%
Decomissioning	0,000212	1,3%
TOTAL	0,016290	100,0%



LNG transport and decompression in situ

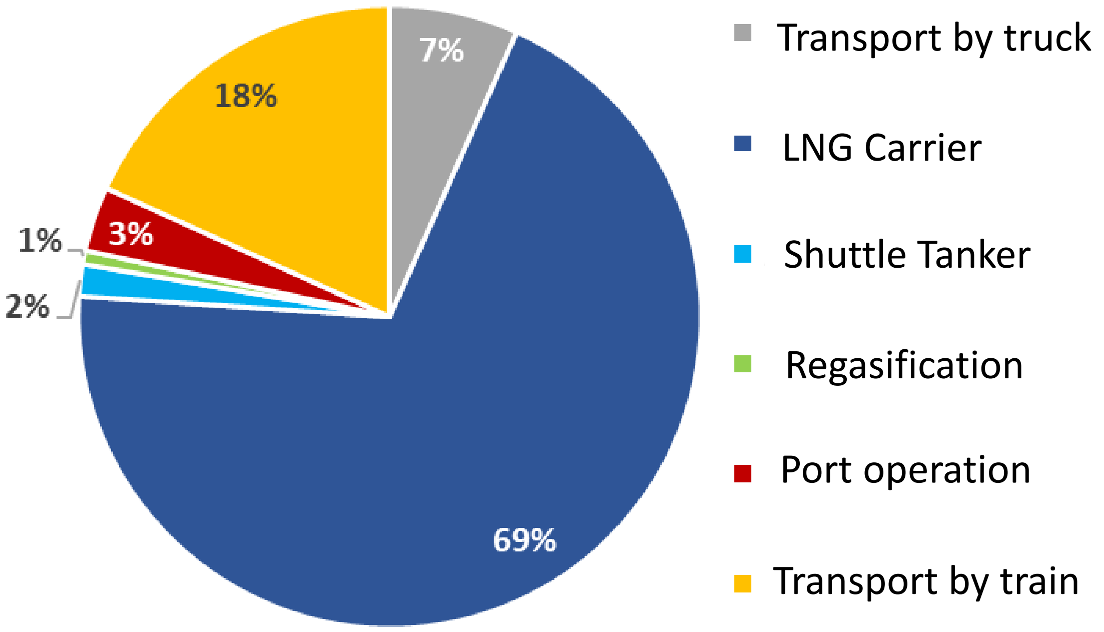
LNG transport and decompression in situ – Block diagram



LNG transport and decompression in situ – Inventory

Phase	Flow	“Foreground” Data		Data Quality	
		Value	u.m.	“Foreground” Data	“Background” Data
LNG carrier	LNG	0,45169575	MJ/m^3	Primary	Ecoinvent
Shuttle Tanker	Diesel	0,08332271	$MJ/\ m^3$	Primary	Ecoinvent
Port Operation	Electricity	0,00055676	$kWh/\ m^3$	Primary	Ecoinvent
	Nitrogen	0,00136466	$Kg/\ m^3$	Primary	Ecoinvent
Transport by train	Diesel	0,0072	$km\ t_{NG}/m^3$	Primary	Ecoinvent
	Electricity	0,1977	$km\ t_{NG}/m^3$	Primary	Ecoinvent
Transport by truck	Electricity	0,00260612	$kWh/\ m^3$	Primary	Ecoinvent
	Diesel	0,0215	$km\ t_{NG}/m^3$	Primary	Ecoinvent
Regasification	Electricity	0,00000082	$kWh/\ m^3$	Primary	Ecoinvent

LNG transport and decompression in situ – Results and Interpretation



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