



POLITECNICO
MILANO 1863

Assessment on WASTE
and RESOURCES



Life Cycle Assessment of CO₂ removal solutions based on ocean liming and pH-equilibrated ocean alkalization

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Roma, 9th September 2026

14TH ICSD 2026, ROME, ITALY

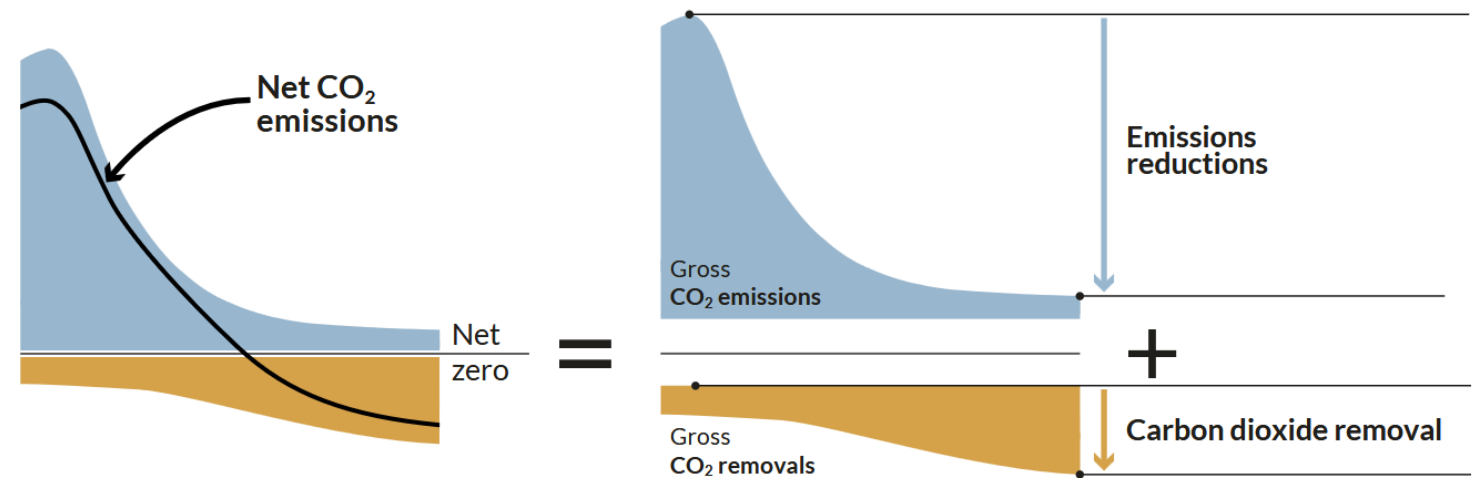
The **large-scale deployment of processes that remove and store durably CO₂** from the atmosphere is now a **crucial necessity** in all the scenarios that are consistent with the ambitious goal of the Paris Agreement, i.e. **to limit global warming to well below 2 °C**



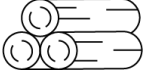
CO₂ removal solutions, including ocean liming, based on different energy sources and carbon storage methods

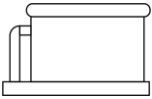


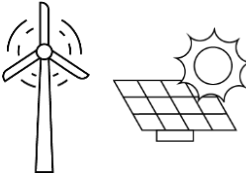
SUSTAINABILITY
ASSESSMENT



The state of carbon dioxide removal, 3rd Edition; A global, independent scientific assessment of Carbon Dioxide Removal.
<https://www.stateofcd.r.org/report/3rd-edition>

Woody biomass supply 

Gasification 

Renewable electricity production 

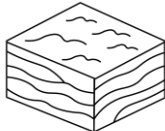


Limestone supply

Calcination



Ocean liming 

Geological CO₂ storage 

pH-equilibrated ocean alkalization 

Negative emission technology
2 CO₂ storage technologies

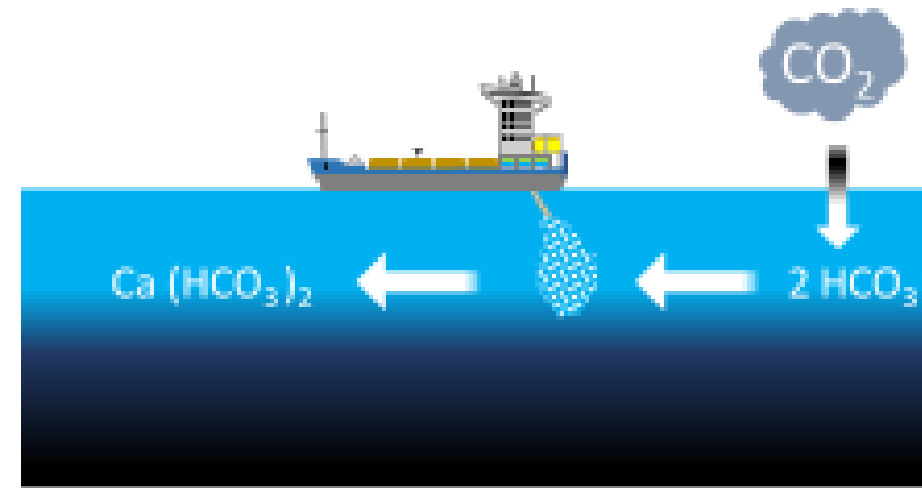
Ocean liming



Geological CO₂ storage

pH-equilibrated ocean alkalization

Negative emission technology



OCEAN LIMING (ocean alkalinity enhancement)

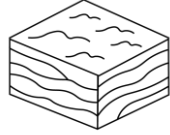
→ spreading alkaline materials, e.g. slaked lime, in surface ocean waters

(removal of CO₂ from the atmosphere + contrast of ocean acidification)

Slaked lime temporary increases seawater pH → **atmospheric CO₂ uptake** (in the form of bicarbonate ions)

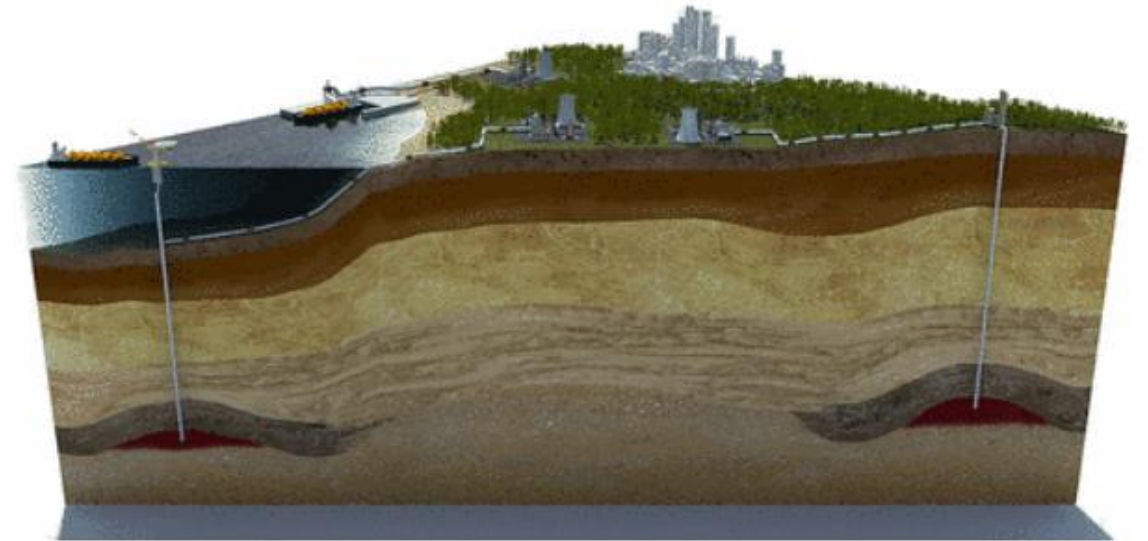
Ocean liming

Geological CO₂ storage



pH-equilibrated ocean alkalization

CO₂ storage technology



GEOLOGICAL STORAGE is the most advanced technology for storing CO₂

→ CO₂ injection in geological formations

Proposed many decades ago, it has not progressed as quickly as needed (50 plants)

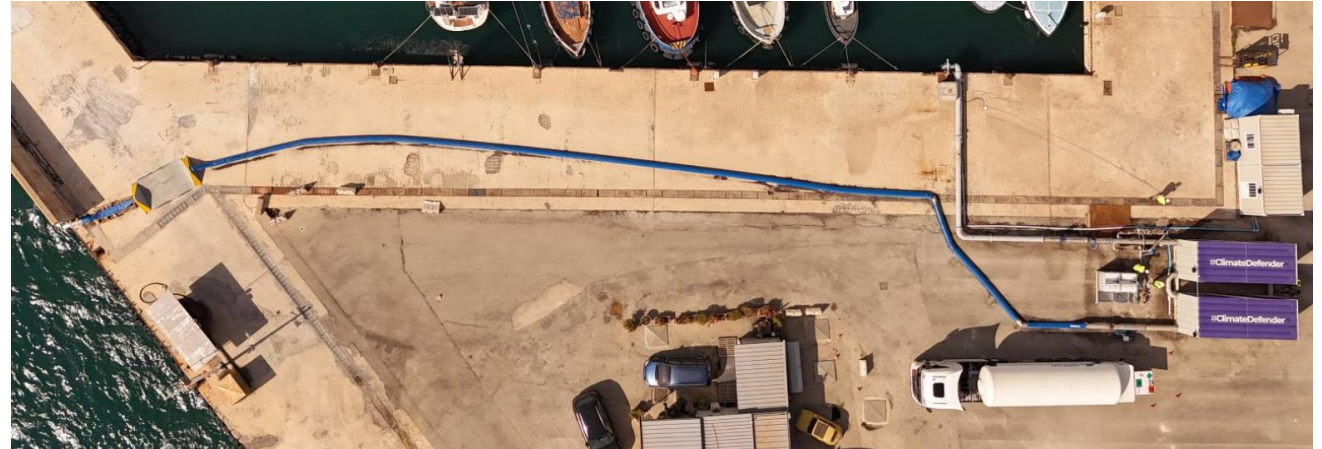
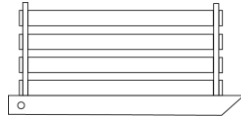
Development limited by a range of issues (e.g. long time required for the identification of a suitable geological formation, requirements of transport infrastructure, financial resources required)

Ocean liming

Geological CO₂ storage

pH-equilibrated ocean alkalization

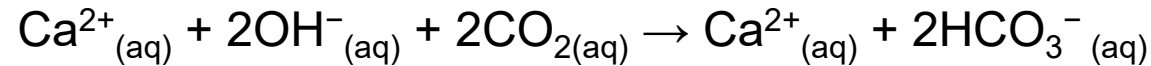
CO₂ storage technology



pH-EQUILIBRATED OCEAN ALKALINIZATION

is under development by Limenet®

→ direct dissolution in seawater of **slaked lime** and **CO₂ in a reactor**



→ **discharge of a CO₂-equilibrated solution** of bicarbonate (HCO₃⁻) in the ocean (pH similar to that of seawater)

It ensures a release in seawater already in equilibrium with dissolved CO₂, avoiding the risk of an abrupt pH spike in the marine environment

Limenet® (2024) [Apparatus and method for accelerated dissolution of carbonates with buffered solutions](#)

[European Patent

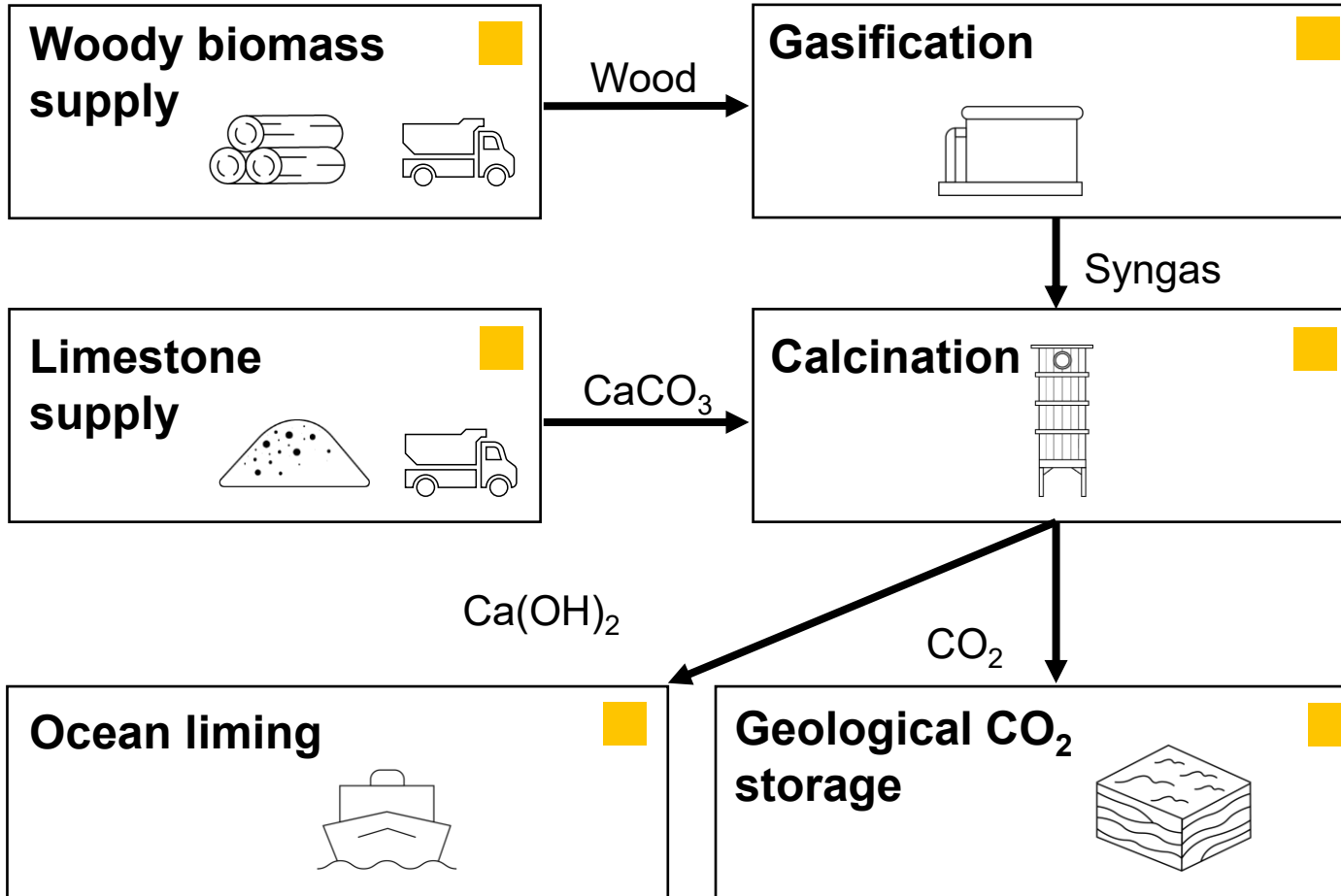
PHPCT/IB2022/051464,

WO2022175885]. United States

Patent and Trademark Office.

Scenario ■ A - BIOMASS + OCEAN LIMING + GEOLOGICAL STORAGE

BIOMASS

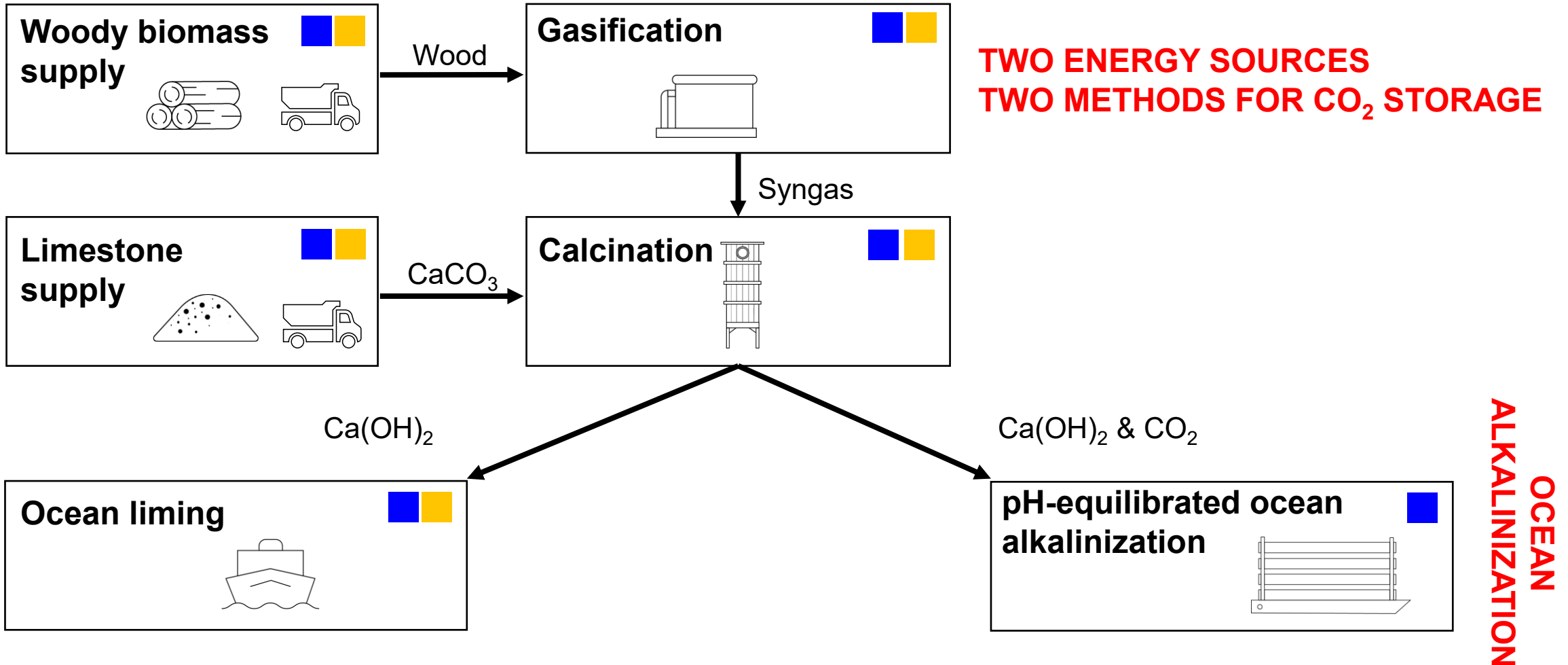


**TWO ENERGY SOURCES
TWO METHODS FOR CO₂ STORAGE**

GEOLOGICAL STORAGE

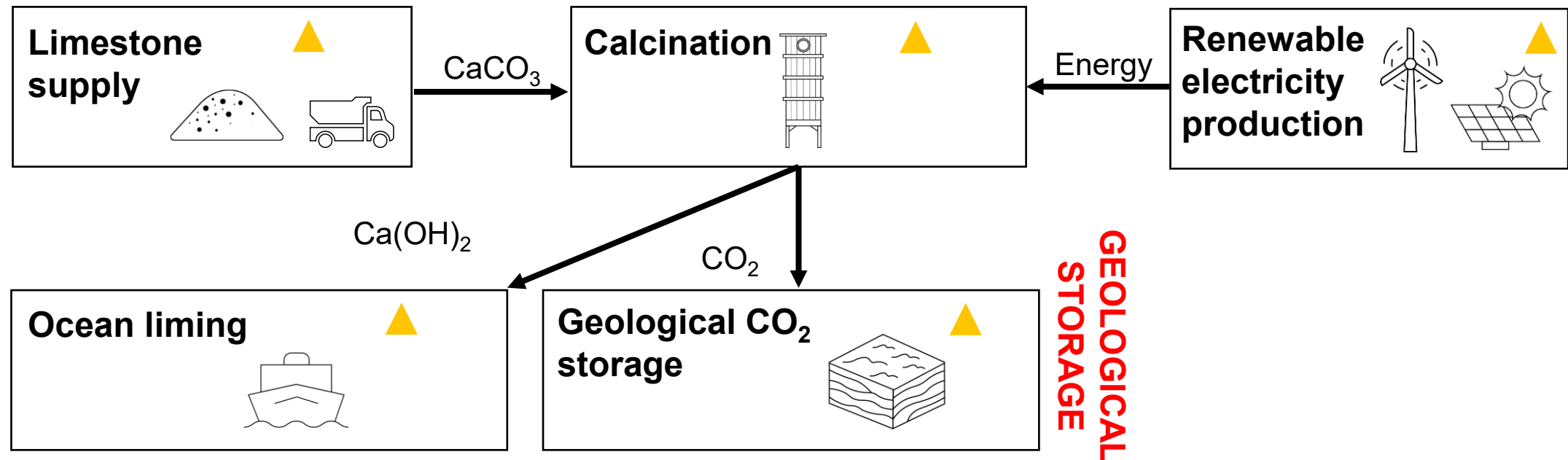
BIOMASS

Scenario	A - BIOMASS + OCEAN LIMING + GEOLOGICAL STORAGE
	B - BIOMASS + OCEAN LIMING + OCEAN ALKALINIZATION



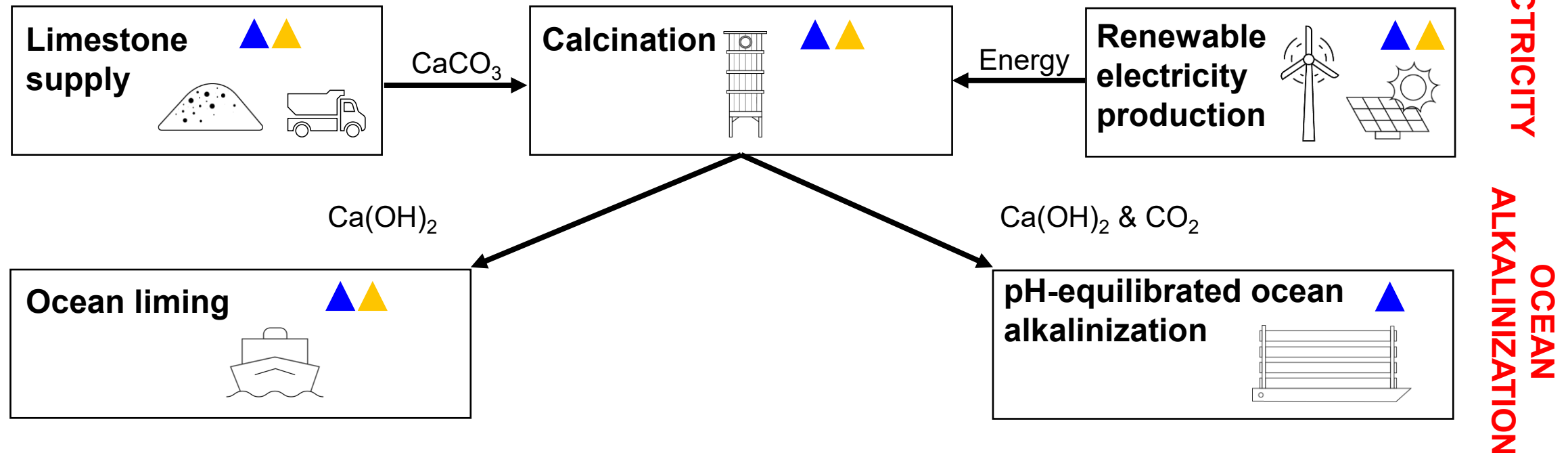
Scenario ▲ C - ELECTRICITY + OCEAN LIMING + GEOLOGICAL STORAGE

**TWO ENERGY SOURCES
TWO METHODS FOR CO₂ STORAGE**



Scenario ▲ C - ELECTRICITY + OCEAN LIMING + GEOLOGICAL STORAGE
▲ D - ELECTRICITY + OCEAN LIMING + OCEAN ALKALINIZATION

TWO ENERGY SOURCES
TWO METHODS FOR CO₂ STORAGE



The potential **environmental benefits/impacts associated with the CO₂ removal technology presented** should be carefully **assessed**
(also comparing the four different configurations of the process)



benefit



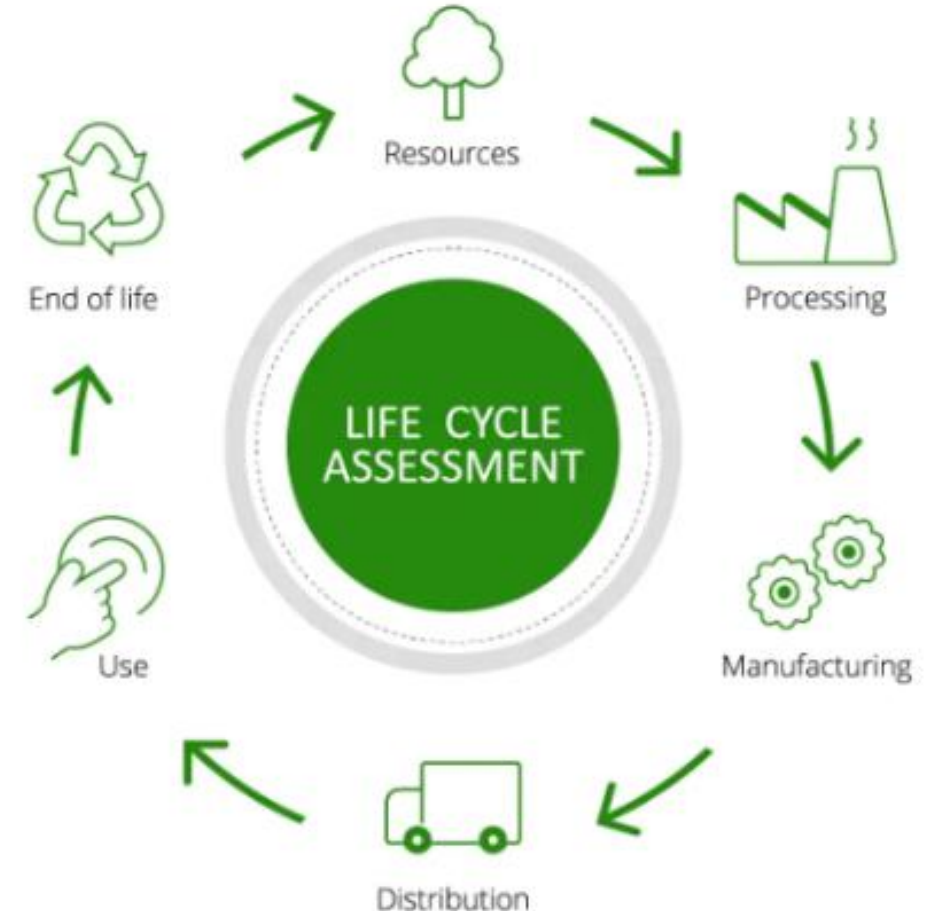
additional burden

The potential **environmental benefits/impacts associated with the CO₂ removal technology presented** should be carefully **assessed** (also comparing the four different configurations of the process)

SUSTAINABILITY
ASSESSMENT

LIFE CYCLE ASSESSMENT (LCA)

A tool to assess the **environmental impacts** throughout the **life cycle** of a **product, process, or service**

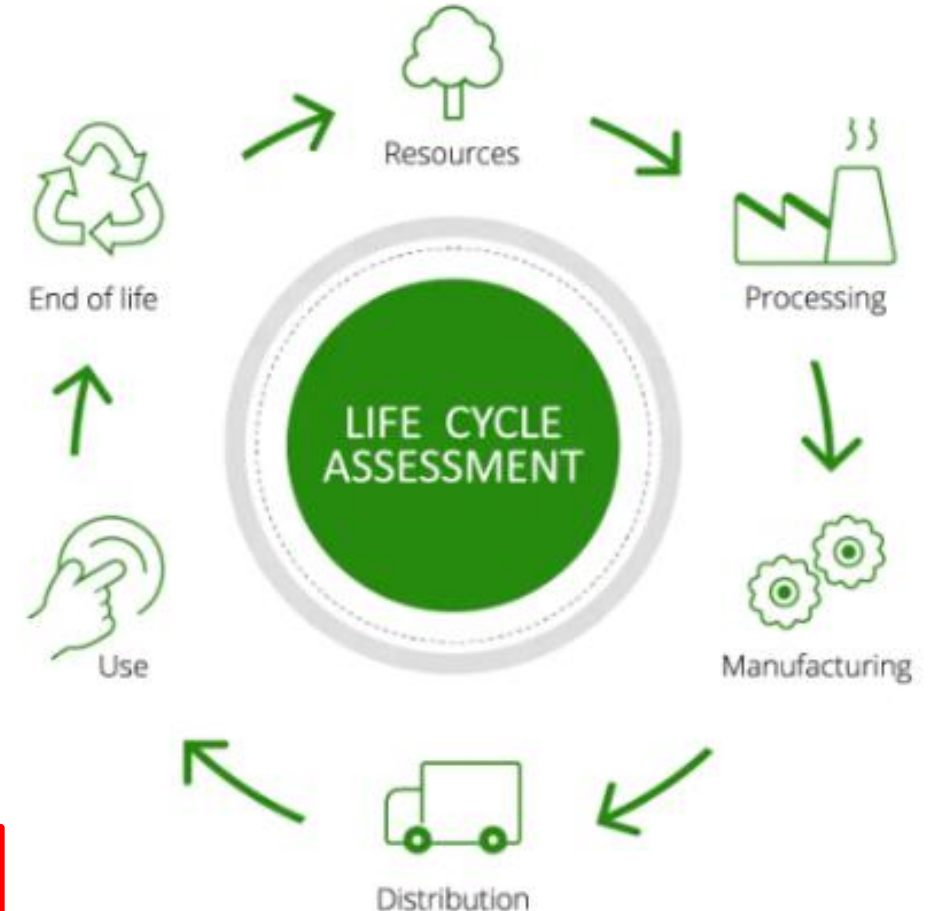


Environmental Footprint method

Acidification
Climate change ←
Ecotoxicity - freshwater
Eutrophication - freshwater
Eutrophication - marine
Eutrophication - terrestrial
Human toxicity - cancer
Human toxicity - non-cancer
Ionizing radiation (human health)
Land use
Ozone depletion
Particulate matter
Photochemical ozone formation (human health)
Resource use - fossils
Resource use - mineral and metals
Water use

Efficiency of CO₂ removal

→ ratio between the net CO₂ equivalent removal and
the gross amount of removed CO₂



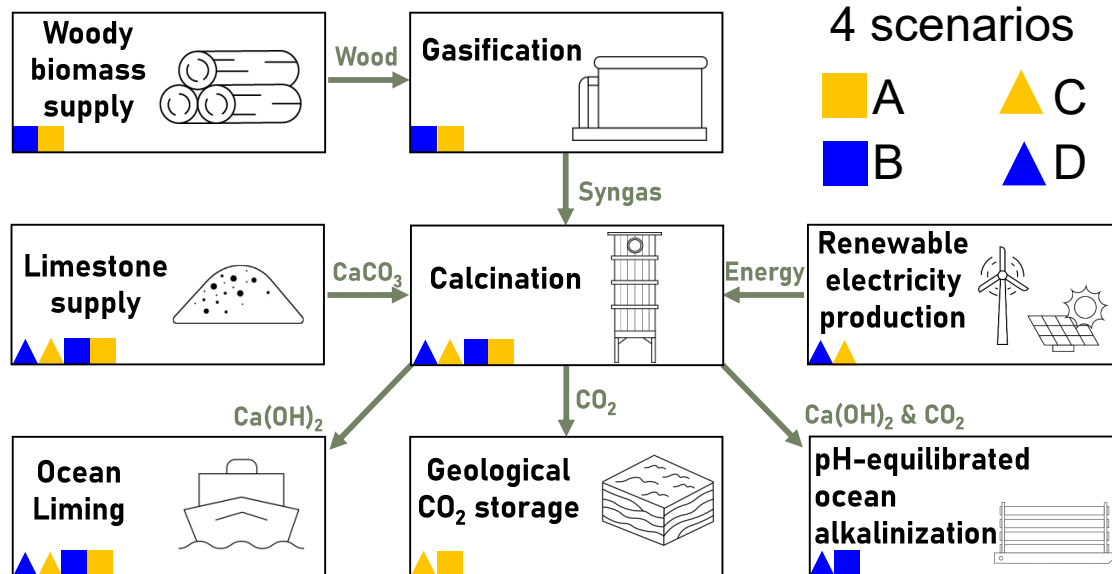
Fazio et al., 2018. <https://doi.org/10.2760/671368>

Functional unit

1 gross tonne of CO₂ removed from the atmosphere

System boundary

cradle-to-grave approach



- Supply of raw materials and energy
- Infrastructures of gasifier, calciner, and slaker and for CO₂ capture and storage and ocean liming
- Transport
- Residues management

Modeling

Plant

- location: Italy
- capacity: 100,000 t of gross CO₂ removed per year
- lifetime: 25 years

Foreground: data by the designers and from studies on pH-equilibrated ocean alkalization

Background: data from the literature and the ecoinvent database (version 3.10)

Focus on a more distant future to capture environmental implications of technologies at an early development stage



Prospective approach

100% renewable electricity mix (2050):

40% solar, 52% wind, 8% hydroelectric + geothermal

Parameter	Scenario				
	A BIOMASS OCEAN LIMING GEOLOGICAL STORAGE (GS)	B BIOMASS OCEAN LIMING OCEAN ALKALINIZATION (OA)	C ELECTRICITY OCEAN LIMING GEOLOGICAL STORAGE	D ELECTRICITY OCEAN LIMING OCEAN ALKALINIZATION	
Atmospheric CO ₂ removed through ocean liming	689 kg	172 kg	1,000 kg	1,000 kg	X Y -1000 kg Gross CO ₂ removed
Removal of biogenic CO ₂ from biomass gasification	311 kg (GS)	828 kg (OA)	-	-	
Process CO ₂ from calcination	430 kg (GS)	1,145 kg (OA)	625 kg (GS)	1,319 kg (OA)	
Life cycle greenhouse gas emissions	41 kg	67 kg	83 kg	148 kg	Z
Net CO ₂ removed	959 kg	933 kg	917 kg	852 kg	X+Y-Z

Parameter	Scenario			
	A BIOMASS OCEAN LIMING GEOLOGICAL STORAGE (GS)	B BIOMASS OCEAN LIMING OCEAN ALKALINIZATION (OA)	C ELECTRICITY OCEAN LIMING GEOLOGICAL STORAGE	D ELECTRICITY OCEAN LIMING OCEAN ALKALINIZATION

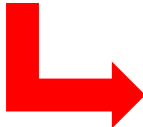
Net CO₂ removed

959 kg

933 kg

917 kg

852 kg

 **IMPACT ON
CLIMATE
CHANGE**

-959
kg_{CO2eq}
Functional
unit (FU)⁻¹

-933
kg_{CO2eq} FU⁻¹

-917
kg_{CO2eq} FU⁻¹

-852
kg_{CO2eq} FU⁻¹

Efficiency of CO₂ removal

$(X+Y-Z)/(X+Y)$

96%

93%

92%

85%

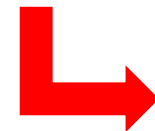
Climate change  benefit

Other 15 impact categories additional burden 

SCENARIOS A and B Most impactful stages:

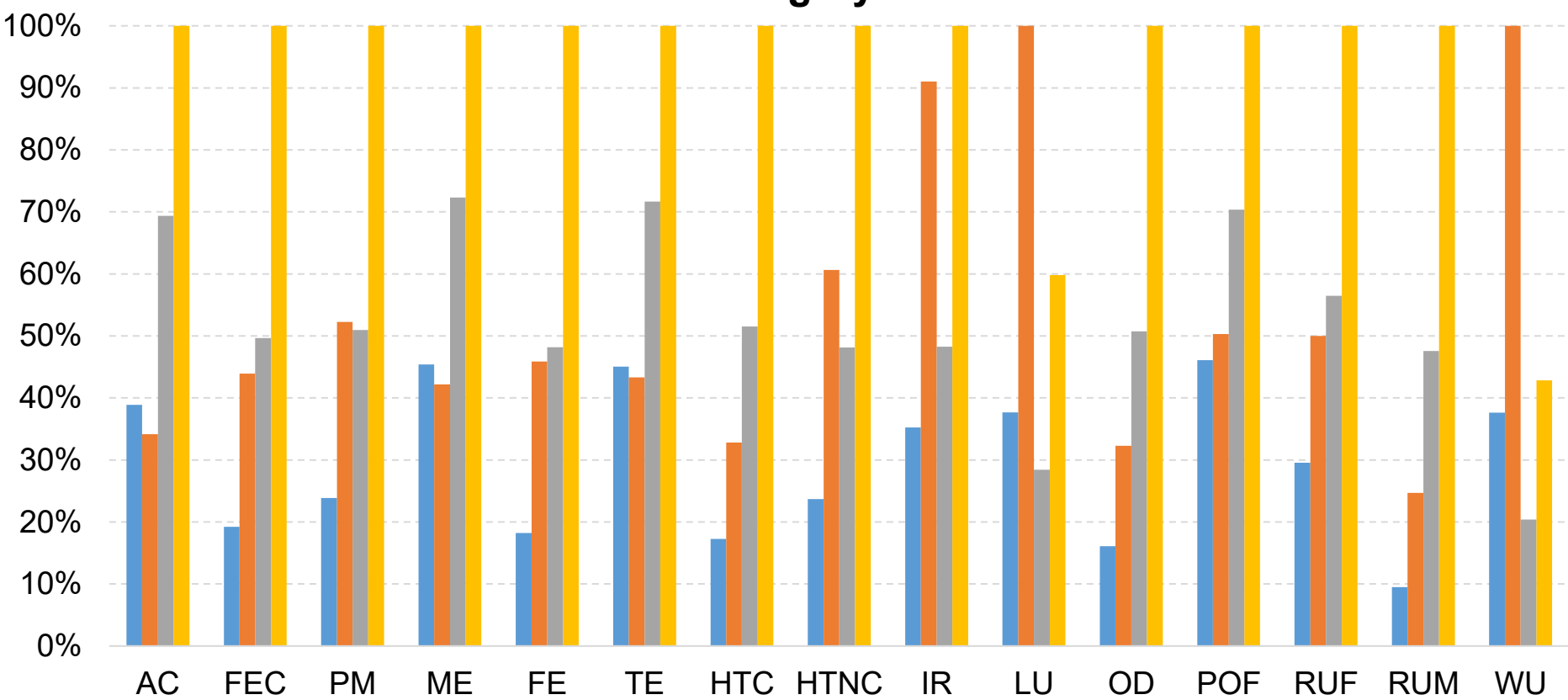
- electricity consumption in 5/6 categories
- biomass supply in 2/4 (higher than 80% in Land Use due to plant cultivation)
- limestone supply in 3/1
- slaked lime transport and discharge in 5

SCENARIOS C and D Electricity consumption in 11 categories



**COMPARISON
AMONG
SCENARIOS**

Impacts of scenarios normalised to the highest value for each category



Acidification	AC
Climate change	CC
Ecotoxicity - freshwater	FEC
Particulate matter	PM
Eutrophication- marine	ME
Eutrophication - freshwater	FE
Eutrophication - terrestrial	TE
Human toxicity - cancer	HTC
Human toxicity - non-cancer	HTNC
Ionizing radiation	IR
Land use	LU
Ozone depletion	OD
Photochemical ozone formation	POF
Resource use - fossils	RUF
Resource use - minerals and metals	RUM
Water use	WU

Normalization + weighting:

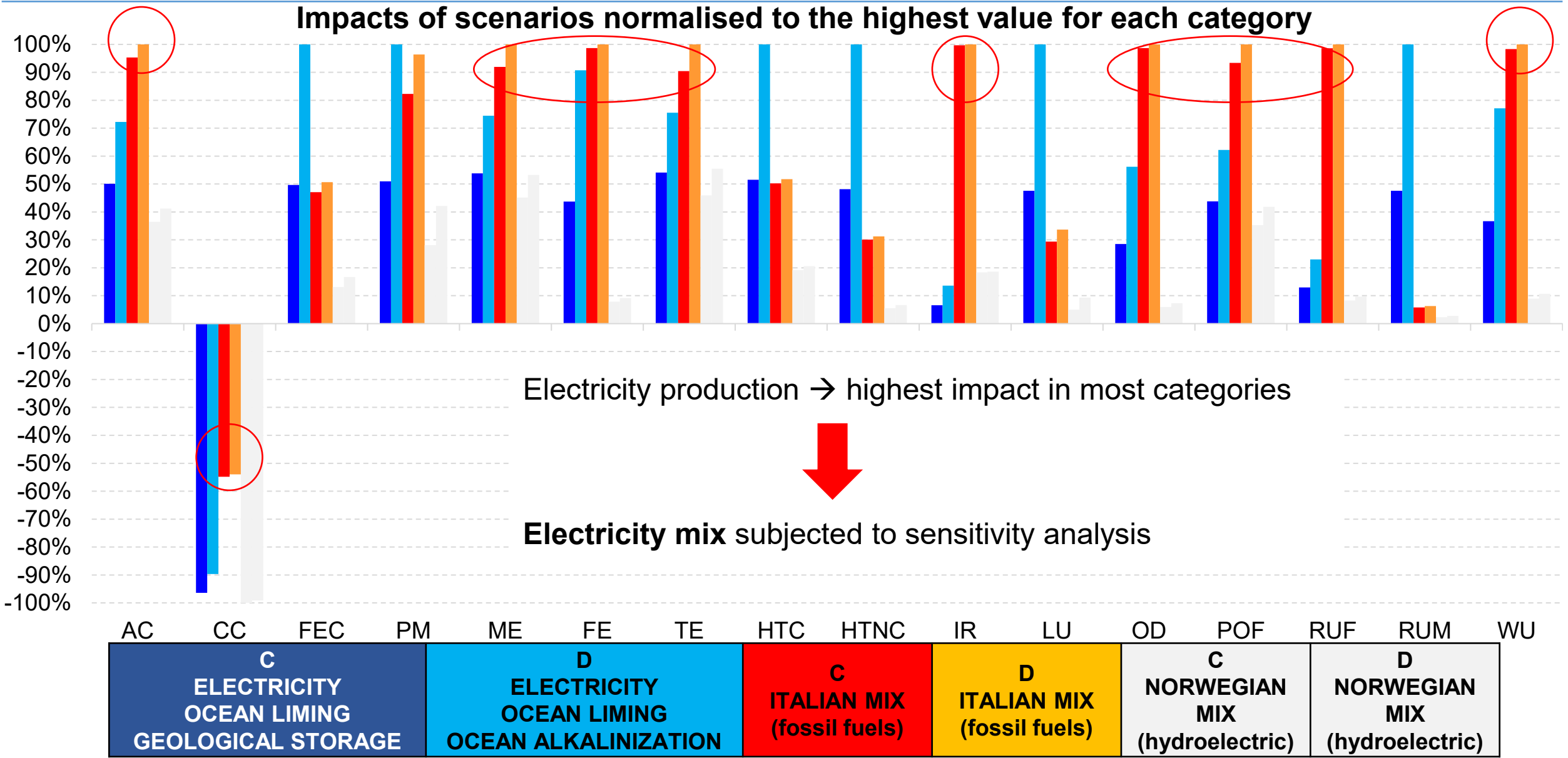
-19.7 mPt FU⁻¹ (A)

-12.3 mPt FU⁻¹ (B)

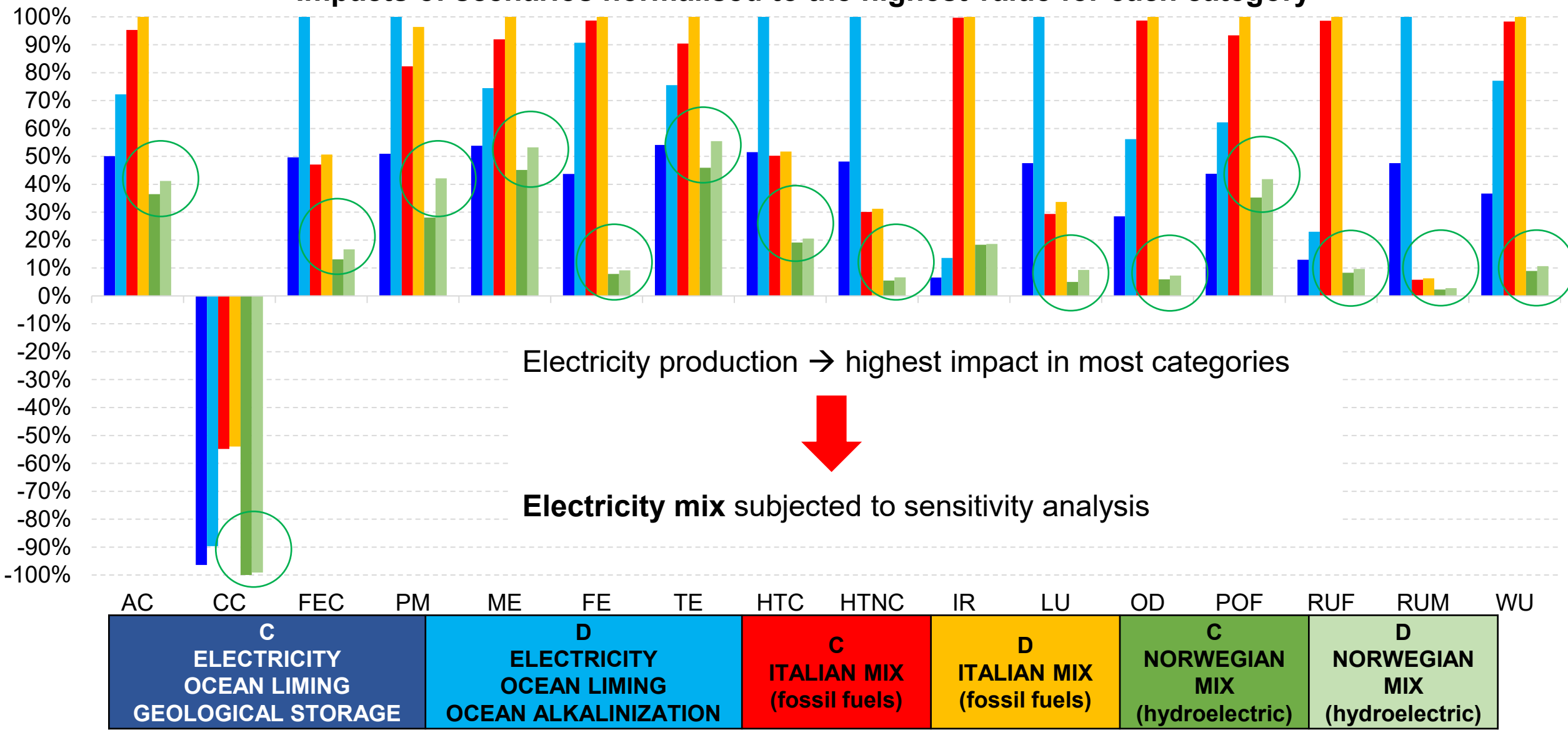
-12.1 mPt FU⁻¹ (C)

1.40 mPt FU⁻¹ (D)

A BIOMASS OCEAN LIMING GEOLOGICAL STORAGE	B BIOMASS OCEAN LIMING OCEAN ALKALINIZATION	C ELECTRICITY OCEAN LIMING GEOLOGICAL STORAGE	D ELECTRICITY OCEAN LIMING OCEAN ALKALINIZATION
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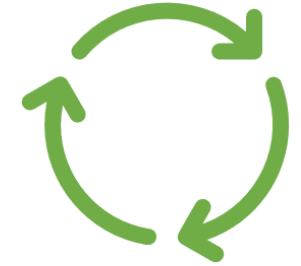


Impacts of scenarios normalised to the highest value for each category





LCA: efficiency of CO₂ removal in the range 85-96%
→ the carbon penalty (15-4%) due to all the material and energy used does not undermine the feasibility of the processes



Efficiency of CO₂ removal more influenced by the **energy source** than by the different storage techniques

Biomass-based configurations offer **higher benefits** in *Climate change*, but there is a trade-off with *Land use*



The **electricity mix** has a **significant influence** on the results

pH-equilibrated ocean alkalization is a **valid alternative** to geological storage, when the transport distance of CO₂ to the storage site is relevant

Further research → other configurations of this process, such as other biomass typologies, or other geographical locations



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and RESOURCES



Thank you for the attention

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International Journal of Greenhouse Gas Control 155 (2026) 104742



Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc



Comparative life cycle assessment of CO₂ removal solutions, including ocean liming, based on different energy sources and carbon storage methods

<https://doi.org/10.1016/j.ijggc.2026.104742>