Leilac

D2.5
Techno-economics report summary

A cost-effective path to carbon neutral industrial production

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Project partners:

- Calix
- HeidelbergCement
- CEMEX
- Tarmac, a CRH company
- Lhoist
- ECN (later incorporated into TNO)
- Imperial College of Science Technology and Medicine
- Process Systems Enterprise Limited (PSE)
- Quantis Sàrl
- The Carbon Trust
- Solvay

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The enhancements to the core technology are subject to pending patents. As much has been made public as is possible at this time.

Web: www.project-leilac.eu

1 Executive Summary

LEILAC (Low Emission in Lime and Cement) projects aim to apply a breakthrough in low-cost carbon capture technology that will enable Europe's cement and lime industries to reduce their emissions dramatically, while retaining their international competitiveness.

Focused on addressing these industries' unavoidable process emissions using Calix's novel carbon capture technology – and supported by leading industrial players – the LEILAC projects are on track to deliver commercially relevant solutions by the 2024.

A detailed technoeconomic model has been developed as part of the LEILAC project, aiming to provide a verified, integrated process and economic model that provides insight into the CAPEX and OPEX costs of the LEILAC technology at full scale, in a range of scenarios. The model allows for the identification of the optimal trade-off between energetic, economic and environmental performances and greatly de-risks the investment decisions needed to pursue the full-scale plant, as it provides accurate predictions of costs before plant construction, lessening investor risk.

The model is verified through the existing LEILAC pilot development and establishes a basis for objective, informed analysis and decisions.

Key Findings of the technoeconomic model confirm:

The LEILAC process represents a very low cost, efficient means of capturing process CO_2

- **Low operating costs:**
  - The technoeconomic model shows expected full chain CCS abatement costs (capture, transport, storage, including capex costs) for a future, full scale retrofit of a LEILAC installation, of around €38 per tonne of CO_2 avoided . Almost half of these costs relate to transporting and storing the CO_2.
  - LEILAC's Energy and Mass Balance (EMB) for an nth-of-a-kind full scale retrofit using alternative fuels indicates a possible efficiency penalty of 0.6 GJ/t CO_2 – with options for near zero penalty (the model does not assume energy is recovered from the CO_2, and the degree of heat integration with the host plant that could be increased). With an electrically powered LEILAC, there could be an improvement of 0.7 GJ/t CO_2.
  - The resulting thermal fuel costs are low when RDF is used; indeed, given similar energy consumption (+2–3%) and the same fuel as the baseline plant, this has little contribution to the cost of capture. If coal or other more expensive fuel is required, this raises the fuel OPEX, depending upon the level of heat integration able to be achieved in a retrofit
- **Low capital costs:**
  - The capital cost of the LEILAC plant is considerably lower than other technologies, with the gross costs for a full scale plant in the range of 58–64 M€ for greenfield projects, and retrofit projects costing around 66–74 M€.
  - When offset against the costs associated with conventional pre-calciners and preheaters but including the cost of CO_2 compressors, the project net additional CAPEX above an unabated reference plant is around 27–34 M€ for a greenfield plant, and 34–44 M€ for a retrofit.
  - This range is based upon the LEILAC1 completed installation, current basis-of-design costs of the LEILAC2 installation, and industry-standard escalation from first-of-a-kind to nth-of-a-kind costs. These capital costs are comparative, if not lower than, other technologies targeting CO_2 mitigation in lime and cement. The majority of the costs relate to the structural steel, foundations, and installation, as the technology is mechanically relatively simple.
- **Low, fair cost CO_2 transport and storage is required:**
  - While a baseline case of around €15 per tonne of CO_2 is used for transport and storage costs, this is a major variable. This represents a 'low cost transport and storage scenario', (excluding initial compression). However, it is expected that for first movers, or areas with transport/storage operators with limited capacity, the costs may be much higher. For this reason, within the 'high cost transport and storage scenario', a transport and storage estimate has been made of €50/tonne of CO_2 (excluding initial compression).
  - The significant variance in these transport and storage costs illustrate the need for low-cost solutions, and governmental assistance in developing solutions at large scale – ensuring free and fair access to smaller players.

Note the difference between the "cost of capture" and the "cost of avoidance". When using non-LEILAC technologies, there is a significant energy penalty, resulting in higher fuel consumption and therefore more CO_2 emissions. As the objective is to decarbonise, these additional emissions need to be captured in addition to those from the core process: increasing the volume of CO_2 to be capture and stored per unit of production.

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3 Scope

The LEILAC1 (Low Emissions Intensity Lime And Cement) project has piloted a breakthrough technology that aims to enable Europe's cement and lime industries to capture their unavoidable process carbon dioxide (CO_2) emissions, for a minimal environmental or economic burden.

In order to progress the development of the technology, and fully exploit the outcomes of LEILAC, it will be necessary to develop a large-scale project, operating at commercial scale. One of the most important aspects shaping the development of commercial application will be the conclusions resulting from the techno-economic simulation.

This intends to provide a holistic approach regarding the configuration and operation of the system, and allows the identification of the optimal trade-off between energetic, economic and environmental performances. This report is based on the independent academic and engineering R&D developed and validated by the LEILAC1 pilot itself, and engineering that has occurred for LEILAC2's Demonstration plant. It is hoped that the techno-economic study will greatly de-risk the investment decisions needed to pursue a full-scale plant, as it will provide accurate predictions of costs before plant construction, lessening investor risk.

The foundation of the technoeconomic model is the process model and associated stream table output for the LEILAC technology, which has been used to generate and derive parameters necessary for estimating capital and operating costs. The user interface, which allows different scenarios to be considered and technical options analysis, facilitates model operation and sensitivity analysis. The technoeconomic model connects the process and economic data to financial metrics and output reports, enabling easy understanding of the impact of decisions on CAPEX and OPEX.

The model is verified through the existing LEILAC pilot development and establishes a basis for objective, informed decisions. This allows both the development team and investors to undertake early economic analysis and provides a verified method of comparing and evaluating the LEILAC technology with other carbon capture technologies in the cement and lime industries.

The technoeconomic analysis report considers the following main cases– each with several models:

- Case A: Results for baseline, LEILAC, and advanced amines using alternative fuels
- Case B: Results for baseline, LEILAC scenarios by fuels and fully electrically powered
- Case C: Post-combustion scenarios
- Case D: Scenarios showing the synergies of LEILAC with other decarb options.

4 Headline LEILAC Results

It is expected that a future, full scale retrofit of a LEILAC installation may have a full chain CCS abatement cost (capture, transport, storage, including capex costs) of around €38 per tonne of CO_2 avoided. 40% of these costs relate to transporting and storing the CO_2.

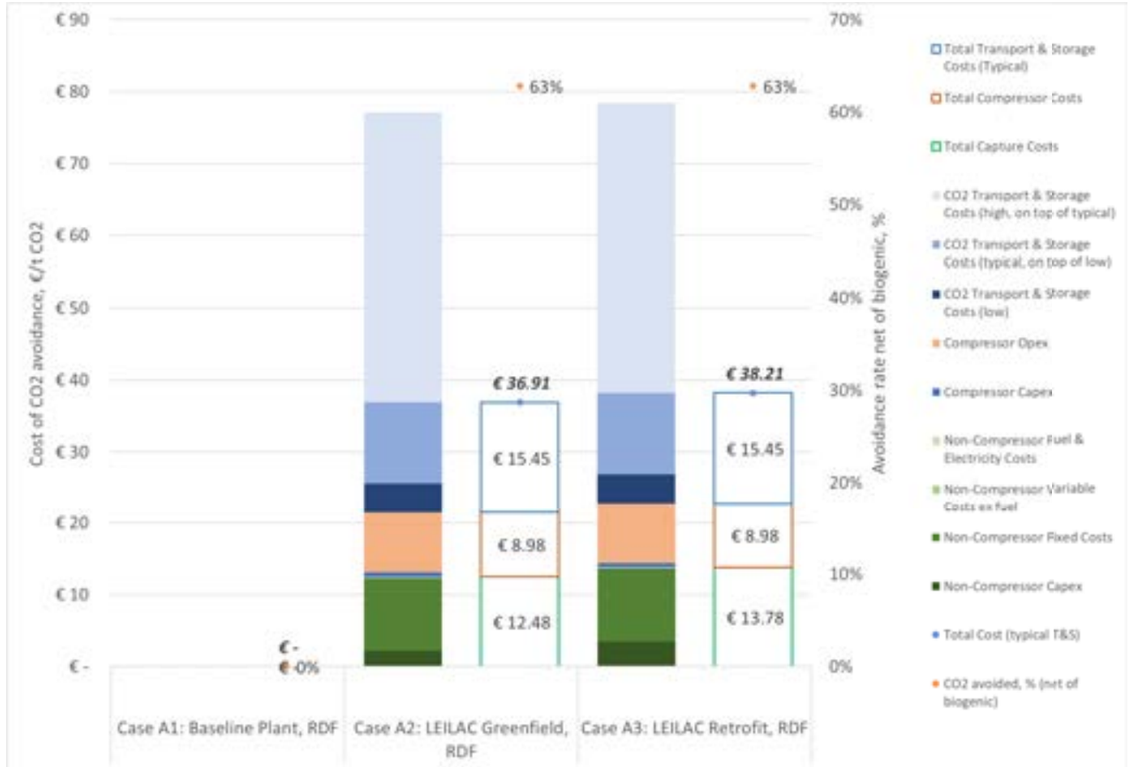

Figure 1 - Headline LEILAC Results for anticipated Greenfield and Retrofit nth-of-a-kind installation, including storage.

Note that most per-tonne costs in this document are tonnes of CO_2 emission avoided, rather than tonnes of CO_2 captured.

The figure below shows the results of the techno-economic study. It compares a baseline, unabated cement plant (Case A1) with four options: Case A2, which is a LEILAC greenfield plant, Case A3, a LEILAC retrofit plant, Case A4, an advanced amine scrubbing retrofit plant, and Case A5, a plant retrofitted with both LEILAC and advanced amines.

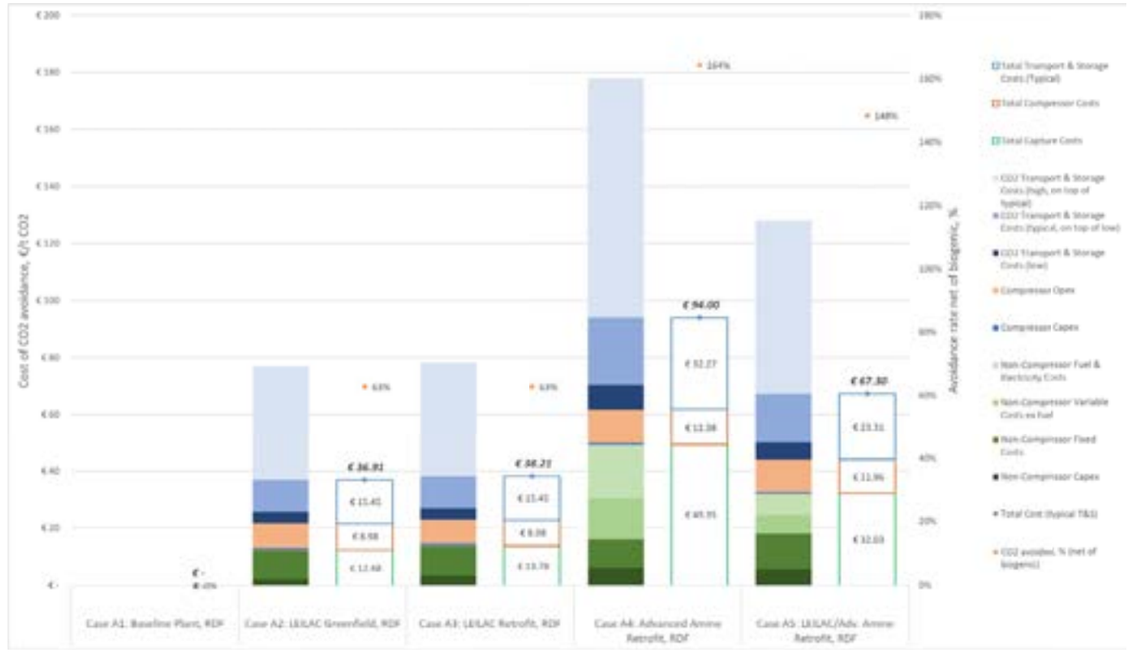

Figure 2 - Headline technoeconomic results for RDF-fired cement plants (Case set A): Case A1 = baseline plant; Case A2 = greenfield LEILAC cement plant; Case A3 = retrofit LEILAC cement plant; Case A4 = retrofit advanced amine cement plant, Case A5 = retrofit LEILAC and amines, combined. All costs are in €/t CO_2 avoided.

	Case A1: Baseline Plant	Case A2: LEILAC Greenfield	Case A3: LEILAC Retrofit	Case A4: Advanced Amine Retrofit	Case A5: LEILAC Retrofit with Advanced Amine
PCC Capture Rate, %	90%	-	-	90%	90%
Non-Compressor CAPEX	€ -	€ 2.19	€ 3.49	€ 6.26	€ 5.73
Non-Compressor Fixed Costs	€ -	€ 10.15	€ 10.15	€ 9.70	€ 12.12
Non-Compressor Variable Costs ex fuel	€ -	€ -	€ -	€ 14.28	€ 6.67
Non-Compressor Fuel & Electricity Costs	€ -	€ 0.14	€ 0.14	€ 19.11	€ 7.51
Compressor CAPEX	€ -	€ 0.60	€ 0.60	€ 0.63	€ 0.51
Compressor OPEX	€ -	€ 8.39	€ 8.39	€ 11.76	€ 11.46
CO_2 Transport & Storage Costs (low)	€ -	€ 4.12	€ 4.12	€ 8.60	€ 6.21
CO_2 Transport & Storage Costs (typical, on top of low)	€ -	€ 11.33	€ 11.33	€ 23.66	€ 17.09
CO_2 Transport & Storage Costs (high, on top of typical)	€ -	€ 40.16	€ 40.16	€ 83.90	€ 60.59
Total Cost (typical T&S)	**€ -**	**€ 36.91**	**€ 38.21**	**€ 94.00**	**€ 67.30**

Table 1 - Associated Data Table for Case set A. Costs are in €/t CO_2 avoided.

The LEILAC plants show avoidance costs of around 38 €/t CO_2. However, 40% of this (€15.45) is assigned to CO_2 transport and storage. Furthermore, electricity for compression is responsible for around 9 €/t CO_2; in total, these variable costs not associated with the core capture process are responsible for around 64% of the total costs of avoidance. Those core costs are 12–14 €/t CO_2 avoided.

In those core costs, the major contributors are €10.15 for non-compressor fixed costs, and €2.19/€3.49 for non-compressor capex.

The LEILAC costs can be compared to those of advanced amine scrubbing, shown in the final column. The cost of transport & storage per tonne avoided is significantly higher than for LEILAC because of the extra fuel that must be burned to raise steam for the amine stripper. This explains the significant \ difference in costs of CO_2 captured and CO_2 avoided. Interestingly, it is cheaper to run the boiler on natural gas than RDF, presumably due to the lower CO_2 intensity per unit of energy.

A question of enabling low, fair cost transport and storage.

While a baseline case of around €15 per tonne of CO_2 is used, this is a major variable. This represents a 'low cost transport and storage scenario', (excluding initial compression).

However, it is expected that first movers, or areas with transport/storage operators with limited capacity, the costs may be much higher. For this reason, within the 'high cost transport and storage scenario', a transport and storage estimate has been made of €50/tonne of CO_2 (excluding initial compression).

The dramatic variance in these transport and storage costs illustrate the need of low-cost solutions, and governmental assistance in developing solutions at large scale – ensuring their free a fair access to smaller players.

Note the difference between the "cost of capture" and the "cost of avoidance". When using non-LEILAC technologies, there is a significant energy penalty, resulting in higher fuel consumption and therefore more CO2 emissions. As the objective is to decarbonise, these additional emissions need to be captured in addition to those from the core process: increasing the volume of CO2 to be captured and stored per unit of production.

5 Results for baseline, LEILAC, and advanced amines using alternative fuels

Description		Case A1: Baseline Plant, RDF	Case A2: LEILAC Greenfield, RDF	Case A3: LEILAC Retrofit, RDF	Case A4: Advanced Amine Retrofit, RDF	Case A5: LEILAC/Adv. Amine Retrofit, RDF
Case		Case 1	Case 2	Case 2	Case 3	Case 4
Calciner Plant Fuel		RDF	RDF	RDF	RDF	RDF
Kiln Plant Fuel		RDF	RDF	RDF	RDF	RDF
Capture Plant Fuel		RDF	RDF	RDF	RDF	RDF
Location		Greenfield	Greenfield	Retrofit	Retrofit	Retrofit
Plant Capacity	**kt/y clinker**	1000	1000	1000	1000	1000
Emission reduction, fossil CO_2		0%	63%	63%	164%	148%
CO_2 captured	**kt/y**	0	498	498	1752	1410
CAPEX*	**M€**	0	27	34	98	99
CAPEX Annualised (over 30 years)	**M€/y**	0.00	1.3	2.0	5.6	5.7
Thermal Fuel OPEX	**M€/y**	1.8	1.8	1.8	5.3	3.7
Electricity OPEX	**M€/y**	10	14	14	31	25
Non-Fuel OPEX**	**M€/y**	27	40	40	73	65
Total Opex	**M€/y**	39	55	55	109	94
Total CCUS Cost	**€/t CO_2**	0	36	37	44	43
Cost of avoidance vs. unabated base case A1 including storage	**€/t CO_2 avoided**	0	37	38	94	67
of which capture processes	**€/t CO_2 avoided**	0	12	14	49	32

Table 2 - Headline technoeconomic results for RDF-fired cement plants (Case set A); baseline, LEILAC and amine scrubbing when firing RDF. Equivalent thermal energy includes electricity, assumed to be generated at 41% thermal efficiency.

6 Results for baseline, LEILAC scenarios by fuels and fully electrically powered

The results of the techno-economic study of LEILAC cement regarding different fuel options, primarily RDF, coal, natural gas, biomass, and electricity.

Case		Case A1: Baseline Plant (RDF)	Case B2: Baseline Plant (Coal)	Case A3: LEILAC Retrofit - RDF	Case B3: LEILAC Retrofit - Coal	Case B4: LEILAC Retrofit - Natural Gas	Case B5: LEILAC Retrofit - Biomass	Case B6: E-LEILAC, RDF Kiln	Case B7: E-LEILAC, E-Kiln
Calciner Plant Fuel		RDF	Coal	RDF	Coal	Natural Gas	Biomass	Electricity	Electricity
Kiln Plant Fuel		RDF	Coal	RDF	Coal	Natural Gas	Biomass	RDF	Electricity
Capture Plant Fuel		RDF	Coal	RDF	Coal	Natural Gas	Biomass	RDF	Electricity
Location		Greenfield	Greenfield	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit
Plant Capacity	kt/y clinker	1000	1000	1000	1000	1000	1000	1000	1000
Emission avoidance, fossil CO2		0%	-17%	63%	46%	70%	93%	84%	93%
CO2 captured	kt/y	0	0	498	498	498	498	498	498
CAPEX*	M€	0	0	34	34	39	34	44	137
CAPEX Annualised (over 30 years)	M€/y	0.0	0.0	2.0	2.0	2.2	2.0	2.5	7.8
Thermal Fuel Opex	M€/y	2	10	2	10	21	15	50	78
Electricity Opex	M€/y	10	8	14	12	11	12	11	10
Non-Fuel Opex**	M€/y	27	27	40	38	37	38	38	130
Total Opex	M€/y	39	45	55	60	70	65	98	198
Total CCUS Cost	**€/t CO2**	**0**	**0**	**37**	**47**	**67**	**57**	**125**	**200**
Cost of avoidance vs. unabated base case A1 including storage	**€/t CO2 avoided**	**0**	**0**	**38**	**40**	**43**	**56**	**76**	**104**
of which capture processes	€/t CO2 captured	0	0	14	18	24	32	58	88

Table 3: Results for various LEILAC retrofit options (case set B).

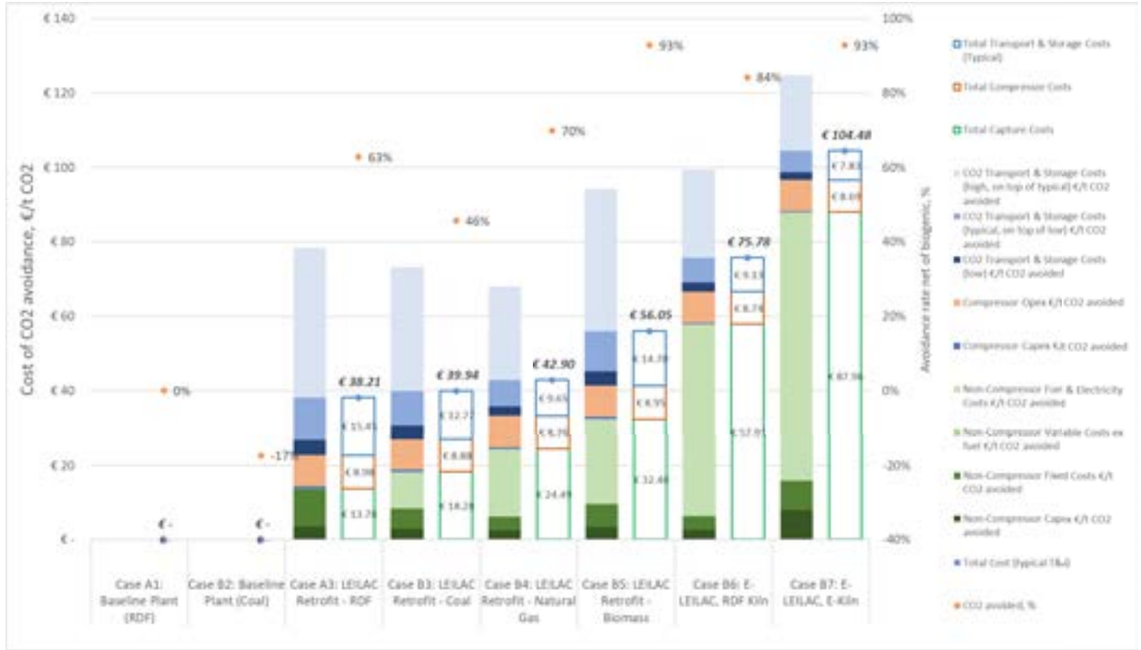

Figure 3 - Headline results for cost of CO_2 avoided in the LEILAC Cement Cases (Caseset B). All costs in €/t CO_2 avoided. Electricity is assumed to cost 80 €/MWh (22.2 €/GJ). Transport & Storage costs are 4 (low), 15 (typical) and 100 (high) €/t CO_2.

	Case B2: Baseline Plant (Coal)	Case A3: LEILAC Retrofit - RDF	Case B3: LEILAC Retrofit - Coal	Case B4: LEILAC Retrofit - Natural Gas	Case B5: LEILAC Retrofit - Biomass	Case B6: E-LEILAC, RDF Kiln	Case B7: E-LEILAC, E-Kiln
Inst. Type	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit
PCC Capture Rate, %	-	-	-	-	-	-	-
Non-Compressor CAPEX	€ -	€ 3.49	€ 2.89	€ 2.49	€ 3.32	€ 2.71	€ 7.92
Non-Compressor Fixed Costs	€ -	€ 10.15	€ 5.44	€ 3.65	€ 6.25	€ 3.66	€ 7.92
Non-Compressor Variable Costs ex fuel	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Non-Compressor Fuel & Electricity Costs	€ -	€ 0.14	€ 9.96	€ 18.36	€ 22.82	€ 51.53	€ 72.12
Compressor CAPEX	€ -	€ 0.60	€ 0.49	€ 0.37	€ 0.57	€ 0.35	€ 0.30
Compressor OPEX	€ -	€ 8.39	€ 8.39	€ 8.39	€ 8.39	€ 8.39	€ 8.39
CO_2 Transport & Storage Costs (low)	€ -	€ 4.12	€ 3.41	€ 2.57	€ 3.92	€ 2.43	€ 2.09
CO_2 Transport & Storage Costs (typical, on top of low)	€ -	€ 11.33	€ 9.37	€ 7.08	€ 10.78	€ 6.69	€ 5.74
CO_2 Transport & Storage Costs (high, on top of typical)	€ -	€ 40.16	€ 33.21	€ 25.10	€ 38.21	€ 23.73	€ 20.36
Total Cost (typical T&S)	€ -	€ 38.21	€ 39.94	€ 42.90	€ 56.05	€ 75.78	€ 104.48
CO_2 avoided, %	-17%	63%	46%	70%	93%	84%	93%

Table 4 Associated Data Table for Case set B. Costs are in €/t CO_2 avoided.

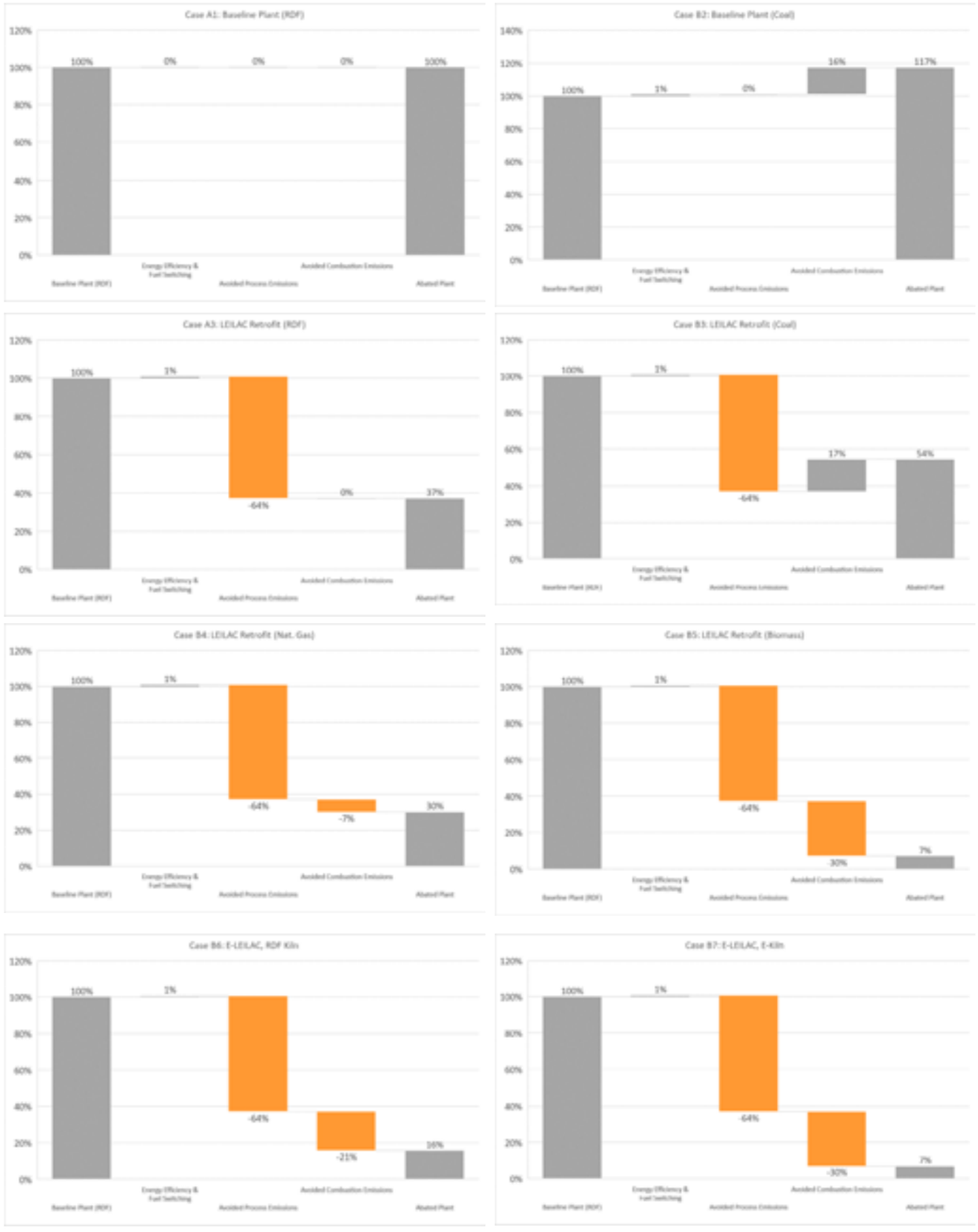

Figure 4: Waterfall diagrams of contributions of energy efficiency, carbon capture, and fuel switching to overall fossil CO_2 avoidance (on y-axis). Case Set B.

7 Post-combustion scenarios

Case		Case A3: LEILAC RDF Retrofit	Case C1: MEA on RDF, 63% capture rate	Case A4: Advanced Amines on RDF, 90% capture rate	Case C2: Advanced Amines on RDF, 67% capture rate	Case C3: Advanced Amines on Natural Gas, 90% capture rate	Case C4: Advanced Amines on Biomass, 90% capture rate	Case C5: Advanced Amines on Biomass, 43% capture rate
Calciner Plant Fuel		RDF	RDF	RDF	RDF	Natural Gas	Biomass	Biomass
Kiln Plant Fuel		RDF	RDF	RDF	RDF	Natural Gas	Biomass	Biomass
Capture Plant Fuel		RDF	RDF	RDF	RDF	Natural Gas	Biomass	Biomass
Location		Retrofit	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit
Plant Capacity	kt/y clinker	1000	1000	1000	1000	1000	1000	1000
Emission avoidance, fossil CO2		63%	100%	164%	100%	89%	261%	100%
CO2 captured	kt/y	498	1247	1752	1030	776	1812	551
CAPEX*	M€	34	81	98	73	63	100	52
CAPEX Annualised (over 30 years)	M€/y	2.0	4.7	5.6	4.2	3.6	5.7	3.0
Thermal Fuel Opex	M€/y	2	5	5	4	35	47	22
Electricity Opex	M€/y	14	26	31	22	16	31	15
Non-Fuel Opex**	M€/y	40	61	73	56	50	74	45
Total Opex	M€/y	55	92	109	82	101	152	82
Total CCUS Cost	€/t CO2	**37**	**47**	**44**	**46**	**85**	**66**	**85**
Total cost of avoidance vs. unabated base case A1 including storage	€/t CO2 avoided	**38**	**190**	**94**	**89**	**71**	**148**	**145**
of which capture processes	€/t CO2 captured	14	119	49	51	50	86	110

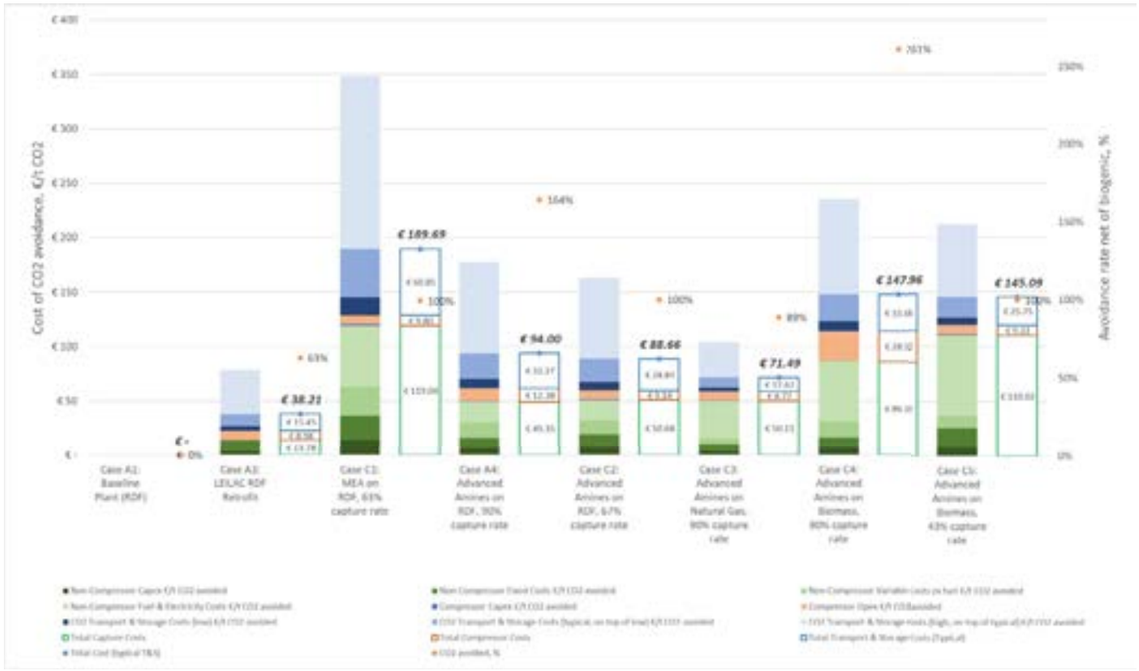

Figure 5 - Headline results for cost of CO_2 avoided in the Amine Cement Cases (Case set C). All costs in €/t CO_2 avoided. Electricity is assumed to cost 80 €/MWh (22.2 €/GJ). Transport & Storage costs are 4 (low), 15 (typical) and 100 (high) €/t CO_2.

	Case A3: LEILAC RDF Retrofit	Case C1: MEA on RDF, 63% capture rate	Case A4: Advanced Amines on RDF, 90% capture rate	Case C2: Advanced Amines on RDF, 67% capture rate	Case C3: Advanced Amines on Natural Gas, 90% capture rate	Case C4: Advanced Amines on Biomass, 90% capture rate	Case C5: Advanced Amines on Biomass, 43% capture rate
Inst. Type	Greenfield	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit
PCC Capture Rate, %	-	64%	90%	69%	90%	90%	45%
Non-Compressor CAPEX	€ 3.49	€ 13.71	€ 6.26	€ 7.08	€ 3.52	€ 6.44	€ 8.41
Non-Compressor Fixed Costs	€ 10.15	€ 22.76	€ 9.70	€ 12.27	€ 6.52	€ 9.90	€ 17.00
Non-Compressor Variable Costs ex fuel	€ -	€ 26.92	€ 14.28	€ 12.76	€ 5.58	€ 14.89	€ 11.39
Non-Compressor Fuel & Electricity Costs	€ 0.14	€ 55.64	€ 19.11	€ 18.57	€ 34.48	€ 54.94	€ 73.22
Compressor CAPEX	€ 0.60	€ 1.42	€ 0.63	€ 0.74	€ 0.38	€ 0.65	€ 0.94
Compressor OPEX	€ 8.39	€ 8.39	€ 11.76	€ 8.40	€ 8.39	€ 27.48	€ 8.39
CO_2 Transport & Storage Costs (low)	€ 4.12	€ 16.23	€ 8.60	€ 7.69	€ 3.37	€ 8.98	€ 6.87
CO_2 Transport & Storage Costs (typical, on top of low)	€ 11.33	€ 44.62	€ 23.66	€ 21.15	€ 9.25	€ 24.69	€ 18.88
CO_2 Transport & Storage Costs (high, on top of typical)	€ 40.16	€ 158.20	€ 83.90	€ 74.99	€ 32.81	€ 87.52	€ 66.94
Total Cost (typical T&S)	€ 38.21	€ 189.69	€ 94.00	€ 88.66	€ 71.49	€ 147.96	€ 145.09
CO_2 avoided, %	63%	100%	164%	100%	89%	261%	100%

Table 5 - Associated Data Table for Case set C. Costs are in €/t CO_2 avoided.

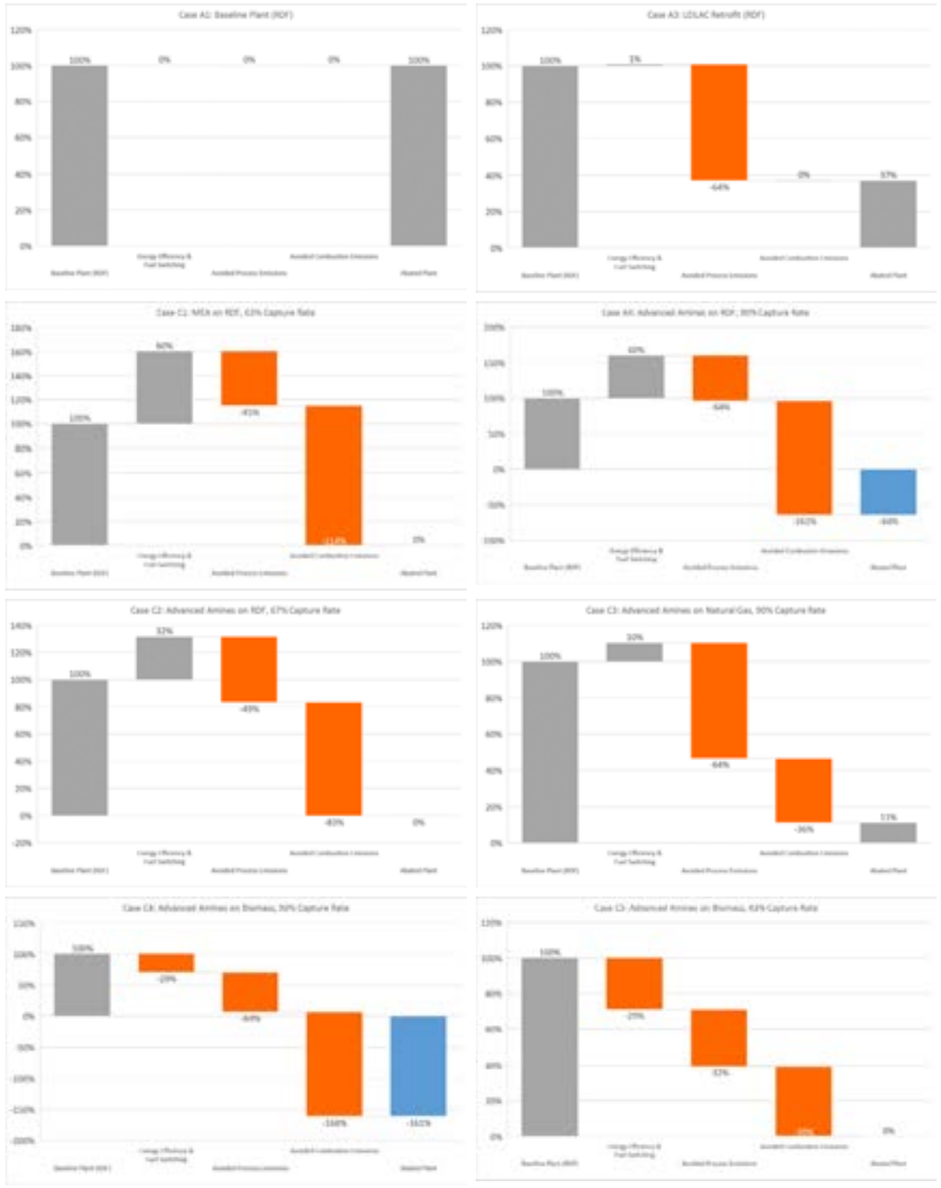

Figure 6 - Waterfall diagrams of contributions of energy efficiency, carbon capture, and fuel switching to overall fossil CO_2 avoidance (on y-axis). Case Set C.

The low thermal energy penalty of LEILAC technology means that very little extra CO_2 is generated by this capture process. For other capture technologies, more energy is required to run their processes - and additional CO_2 is generated that needs to be captured (creating a bigger difference between capture rates and avoidance rates). That is why the storage costs are higher for the advance amine scenarios using the same fuel.

8 Scenarios showing the synergies of LEILAC with other decarb options

Case		Case A3: LEILAC RDF Retrofit	Case A4: Advanced Amines on RDF, 90% capture rate	Case A5: LEILAC/Adv. Amine Retrofit, RDF	Case D1: E-LEILAC/Adv. Amine (RDF) Retrofit	Case D2: E-LEILAC/Adv. Amine (Biomass) Retrofit	Case D3: E-LEILAC with E-Kiln	Case D4: LEILAC with MEA Retrofit (RDF)	Case D5: LEILAC/Adv. Amine (Biomass)
Calciner Plant Fuel		RDF	RDF	RDF	Electricity	Electricity	Electricity	Electricity	Biomass
Kiln Plant Fuel		RDF	RDF	RDF	RDF	Biomass	Electricity	RDF	Biomass
Capture Plant Fuel		RDF	RDF	RDF	RDF	Biomass	Electricity	RDF	Biomass
Location		Retrofit	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit
Plant Capacity	kt/y clinker	1000	1000	1000	1000	1000	1000	1000	1000
Emission avoidance, fossil CO2		63%	164%	148%	103%	138%	93%	95%	210%
CO2 captured	kt/y	498	1752	1410	526	548	498	515	1413
CAPEX*	M€	34	98	99	56	59	137	66	99
CAPEX Annualised (over 30 years)	M€/y	2.0	5.6	5.7	4.1	4.7	7.8	3.8	5.7
Thermal Fuel Opex	M€/y	2	5	4	50	60	78	50	31
Electricity Opex	M€/y	14	31	25	13	15	10	12	73
Non-Fuel Opex**	M€/y	40	73	65	46	50	42	44	109
Total Opex	M€/y	55	109	94	109	125	130	106	119
Total CCUS Cost	€/t CO2	37	44	43	108	107	200	116	61
Cost of avoidance vs. unabated base case A1 including storage	€/t CO2 avoided	38	94	67	81	94	104	83	95
of which capture processes	€/t CO2 captured	14	49	32	61	68	88	64	49

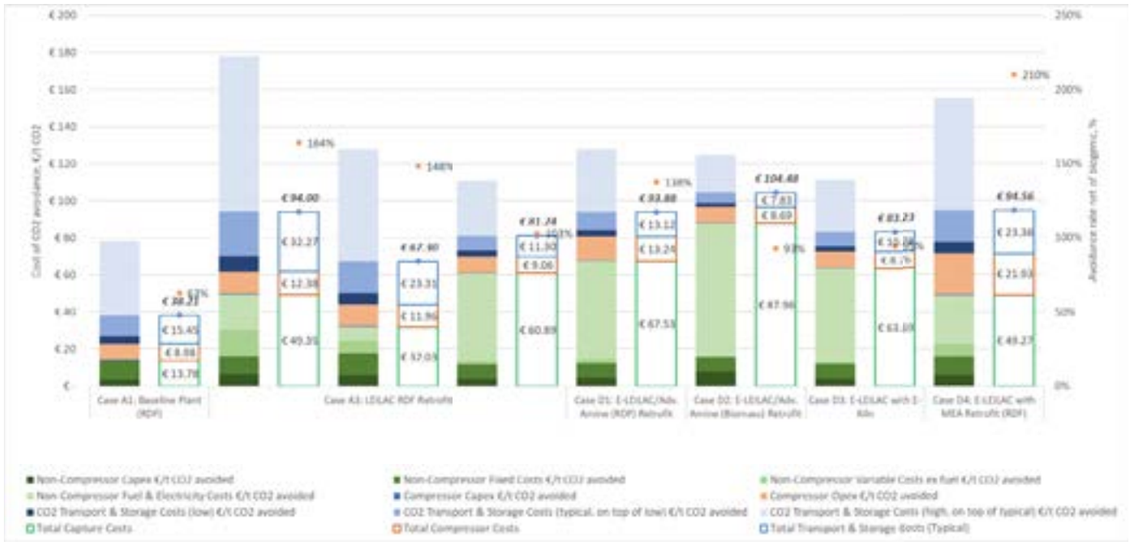

Figure 7 - Headline results for cost of CO_2 avoided in the Amine Cement Cases (Case set D). All costs in €/t CO_2 avoided. Electricity is assumed to cost 80 €/MWh (22.2 €/GJ). Transport & Storage costs are 4 (low), 15 (typical) and 100 (high) €/t CO_2.

	Case A1: Baseline Plant (RDF)	Case A3: LEILAC RDF Retrofit	Case A4: Advanced Amines on RDF, 90% capture rate	Case A5: LEILAC/Adv. Amine Retrofit, RDF	Case D1: E-LEILAC/Adv. Amine (RDF) Retrofit	Case D2: E-LEILAC/Adv. Amine (Biomass) Retrofit	Case D3: E-LEILAC with E-Kiln	Case D4: LEILAC with MEA Retrofit (RDF)	Case D5: LEILAC/Adv. Amine (Biomass)
Inst. Type	Greenfield	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit	Retrofit
PCC Capture Rate, %	-	-	90%	90%	69%	90%	-	45%	90%
Non-Compressor CAPEX	€ -	€ 3.49	€ 6.26	€ 5.73	€ 4.11	€ 4.45	€ 7.92	€ 4.02	€ 5.74
Non-Compressor Fixed Costs	€ -	€ 10.15	€ 9.70	€ 12.12	€ 7.78	€ 7.92	€ 7.92	€ 7.95	€ 10.23
Non-Compressor Variable Costs ex fuel	€ -	€ -	€ 14.28	€ 6.67	€ 1.40	€ 2.40	€ -	€ 0.93	€ 6.69
Non-Compressor Fuel & Electricity Costs	€ -	€ 0.14	€ 19.11	€ 7.51	€ 47.60	€ 52.76	€ 72.12	€ 50.79	€ 26.61
Compressor CAPEX	€ -	€ 0.60	€ 0.63	€ 0.51	€ 0.36	€ 0.38	€ 0.30	€ 0.37	€ 0.51
Compressor OPEX	€ -	€ 8.39	€ 11.76	€ 11.46	€ 8.70	€ 12.86	€ 8.39	€ 8.39	€ 21.42
CO_2 Transport & Storage Costs (low)	€ -	€ 4.12	€ 8.60	€ 6.21	€ 3.01	€ 3.50	€ 2.09	€ 2.88	€ 6.23
CO_2 Transport & Storage Costs (typical, on top of low)	€ -	€ 11.33	€ 23.66	€ 17.09	€ 8.28	€ 9.62	€ 5.74	€ 7.91	€ 17.13
CO_2 Transport & Storage Costs (high, on top of typical)	€ -	€ 40.16	€ 83.90	€ 60.59	€ 29.37	€ 34.10	€ 20.36	€ 28.03	€ 138.61
Total Cost (typical T&S)	€ -	€ 38.21	€ 94.00	€ 67.30	€ 81.24	€ 93.88	€ 104.48	€ 83.23	€94.56
CO_2 avoided, %	0%	63%	164%	148%	103%	138%	93%	95%	210%

Table 6 - Associated Data Table for Figure 25 (Case set D).

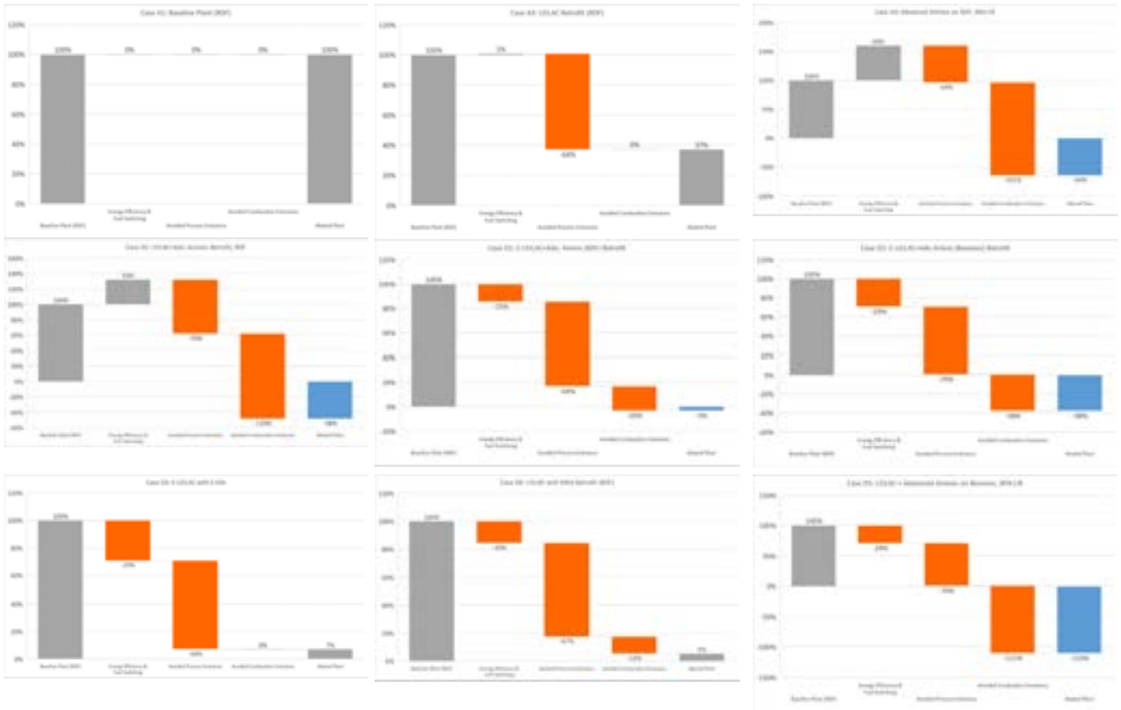

Figure 8 - Waterfall diagrams of contributions of energy efficiency, carbon capture, and fuel switching to overall fossil CO_2 avoidance (on y-axis). Case Set D.

A LEILAC system and rotary kiln using a renewable energy source (such as electricity, biomass or hydrogen), which enables a low-cost route to near carbon-neutral cement production.

For a carbon-negative solution, a LEILAC system works effectively when combined with any other capture technology. These strong synergies exist when a LEILAC system capturing unavoidable process-emissions is used with a small additional capture unit to capture CO_2 generated during heating. Compared to a stand-alone system trying to capture everything, overall far the less overall energy is required – and less additional CO_2 is generated.

As a result, a combined system may represent one of the most resource and cost-efficient means of carbon-negative cement production.

9 LEILAC: cost breakdown

The capital cost of applying LEILAC technology varies across retrofit and greenfield sites, for several fuels. The cost is broken down into capital and operational expenses (CAPEX and OPEX). For the latter, there is further breakdown, into thermal fuel, electricity, and other OPEX.

The capital cost of the LEILAC plant (above that of a reference cement plant) is dependent on size (a constant 1 Mt/y clinker capacity in this report, separating 498 ktpa of CO_2), fuel choice and greenfield vs retrofit. Net costs (i.e. above a conventional plant or retrofit) range from 27 M€ for a greenfield project using solid fuels to around 44 M€ for a retrofit using electrical heating. These two values are annualised to 1.3 M€/y and 2.5 M€/y, respectively. If not part of a scheduled upgrade, the CAPEX costs may be in the region of 66–74 M€. As has been found with the LEILAC1 installation and estimated so far in the LEILAC2 basis of design, the capital costs (CAPEX) are relatively low, and the majority of the costs relate to the structural steel, foundations, and installation. These costs are regionally specific, and may require locally adjustment from western European pricings.

Thermal fuel costs are low when RDF is used; indeed, given similar energy consumption (+2–3%) and the same fuel as the baseline plant, this adds around €0.11 / tonne CO_2 to the cost of capture. If coal or other more expensive fuel is required, this raises the fuel OPEX, in this case by €8M, to approximately 16.5 €/t CO_2 captured, although this figure will depend upon the level of heat integration able to be achieved in a retrofit, and could be optimised further.

Electricity is required to run the compressors and other equipment; this adds around 4.18 M€/y of cost. Other OPEX comes in at 4.9 M€ above baseline. Excluding CO_2 transport and storage costs, total OPEX increase for the RDF and coal cases is 9.0 M€/y and 13.9 M€/y. With the plant size being 1 M t clinker per year, the specific increase is 9 €/t clinker and 14 €/t clinker.

This can also be normalised to tonne of CO_2 captured, and tonne of CO_2 avoided. For the RDF cases, where very little extra fuel is burned and no captured CO_2 is expected to escape, these numbers are almost identical. With transport & storage costs of 15 €/t taken into account, the cost is 35.8 & 36.9 €/t CO_2 captured and avoided for a greenfield plant, and 37.1 & 38.2 €/t CO_2 captured and avoided for a retrofit.

9.1 Sensitivity to Capital Cost & Financing

The modelling undertaken has been designed to align with other techno-economic modelling that has been undertaken for the cement industry. The models used have been created from the findings of LEILAC1, and engineering of LEILAC2, and scaled to a full-size plant – representing nth-of-a-kind possible cost projections. Regional cost differences will change such projections. In the case of retrofit applications, such costs may be highly variable as infrastructure and ancillary systems need to be adapted. Examples of these extra costs are removing disused buildings, constructing new access roads, and adding soil improvements prior to construction. For any actual installation, an engineered feasibility study considering all of a plant-specific requirements are required to get an appropriate cost estimate. However, for the purposes of illustrating some of the cost sensitivities that arise from a real-project application, the following graph shows some of the variables the projects need to contend with.

In Figure 9, using the scenarios outlined above, variations are made to reflect a 50% increase of the expected CAPEX to cover those extra non-capture unit expenses (Scenario 1). It also models changes to the cost of financing, for example by doubling the weighted average cost of capital (WACC) from 3% to 6% whilst reducing the payback period to 20 years from the baseline of 25 years (Scenario 2). (25 was used for consistency with the CEMCAP modelling). This is not particularly expected, given the increase in financing available to environmental technologies that are attempting to reach our climate change targets, but is used to illustrate the impact of such changes.

The impact of an unscheduled retrofit, with full additional costs applied, are also modelled (scenario 3).

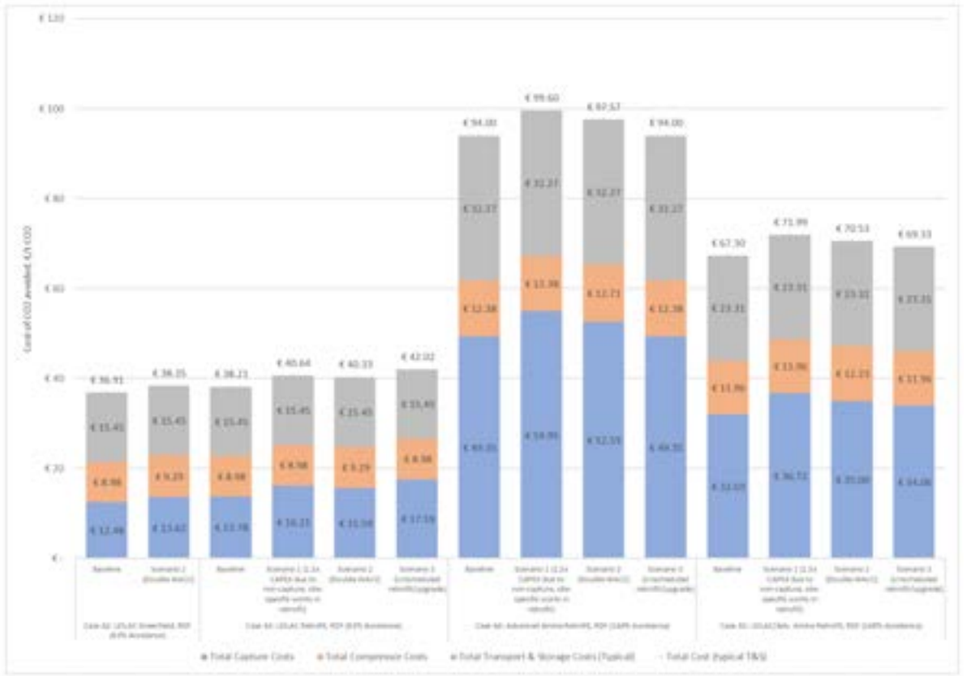

Figure 9 - Sensitivity Analysis: Increasing the CAPEX of the project by 50% (Scenario 1), doubling WACC & reducing payback period to 20 years (Scenario 2)

10 Conclusion

The techno-economic modelling undertaken within LEILAC1's Roadmap to 2050 is for nth-of-a-kind implementation.

The primary inputs and configurations used within this modelling, are based on the findings of the plants that have been constructed (primarily LEILAC1), and the engineering activity that has taken place within the framework of LEILAC2.

To reach such nth-of-a-kind implementation, further research, development, testing and scaling up is required. Much of this will be undertaken within LEILAC2. It is anticipated that the projections being made here, based on the current state of knowledge, are realistic.

The cement and lime sectors must rapidly decarbonise. They currently contribute around 8 percent of global CO2 emissions, and – due to their unavoidable process emissions – are a hard-to-abate industrial sector. To reach neutrality by 2050 every decarbonisation option available, not just LEILAC, must be pursued vigorously and to the greatest extent possible – requiring significant investments in all technologies.

Decarbonising industry is difficult, and must fulfil three criteria in every region of the world:

- maintain economic prosperity,
- meet cement and lime market demand,
- dramatically lower CO_2 emissions.

The LEILAC consortium believe, with this techno-economic modelling and roadmap, that LEILAC can be a critical component in our collective endeavours to reach net-zero by 2050.

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