Mobile CO_2 Capture

Feasibility Study - Scania

July 9th, 2025

Prepared & Submitted By

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ACRONYMS

EU: European Union

ICCT: International Council on Clean Transportation

MCC: Mobile Carbon Capture

CCUS: Carbon Capture, Utilization, and Storage

TSA: Temperature-Swing Adsorption

TVSA: Temperature-Vacuum-Swing Adsorption

MOF: Metal-Organic Framework

PFD: Process Flow Diagram

BFD: Block Flow Diagram

MOF-Dry: Simulation with MOF with prior exhaust drying

MOF-Wet: Simulation with MOF without prior exhaust drying

PTO: Power Take-Off

ELM: Engine Load Matrix

HPDI: High-Pressure Direction Injection

LCOC: Levelized Cost of Capture

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INTRODUCTION

Heavy-duty vehicles currently account for over 6% of the European Union (EU)'s total greenhouse gas emissions (Commission, 2024). In response, the EU has introduced increasingly stringent CO_2 emission reduction targets: 45% by 2030, 65% by 2035, and 90% by 2040, all relative to 2019 levels (Commission, 2024). These targets will apply progressively to new trucks and place growing pressure on manufacturers to drastically cut the carbon footprint of their fleets. Compliance with these targets for manufacturers is measured on a fleet-wide basis—meaning manufacturers can balance higher-emitting trucks with lower-emitting ones, as long as the overall average emissions per ton-kilometer improve over time. The financial consequences for non-compliance are substantial: €4,000 per gram of CO_2 per ton-kilometer over the limit. More information are provided by the International Council on Clean Transportation (ICCT, May 2024).

In this context, Scania has already begun to diversify its offering by developing gas-powered and electric trucks, and is actively exploring additional sustainable technologies to expand its portfolio of green solutions. Among these, mobile carbon capture (MCC) has emerged as a promising avenue to reduce CO_2 emissions on vehicles that continue to rely on combustion engines.

In 2024, Scania has engaged master's students to explore early-stage MCC concepts. The results were promising and Scania decided to pursue the investigation for both solvent and sorbent MCC.

Building on this momentum, Scania and Qaptis (sorbent-MCC expert, see below, Qaptis background) connected through the Combient Foundry program — a platform designed to foster collaboration between startups and corporates. Following initial exchanges, Scania and Qaptis agreed to conduct a feasibility study to evaluate sorbent-MCC technology could be integrated into Scania trucks.

The goal of the feasibility study has been defined as follows:

- Simulated feasibility study for sorbent-MCC for European diesel road tractors: Temperature Vacuum Swing Adsorption (TVSA)
- Elaboration: Under European certification conditions, which approximate CO_2 capture rates are possible with MCC systems in the limited installation space behind the tractors' sleeper cabs?

- Comparison of three simulated MCC systems for (i) CO_2 capture rate (ii) consumption penalty from additional power demand (iii) cost for mass production:
    1) Zeolite sorbent with prior exhaust drying.
    2) Metal Organic Framework (MOF) sorbent with prior exhaust drying.
    3) MOF sorbent with humid exhaust, without dryers

The feasibility study will conclude with a site visit to inspect the sorbent-based MCC prototype developed by Qaptis, either at its facilities in Lausanne (Switzerland):

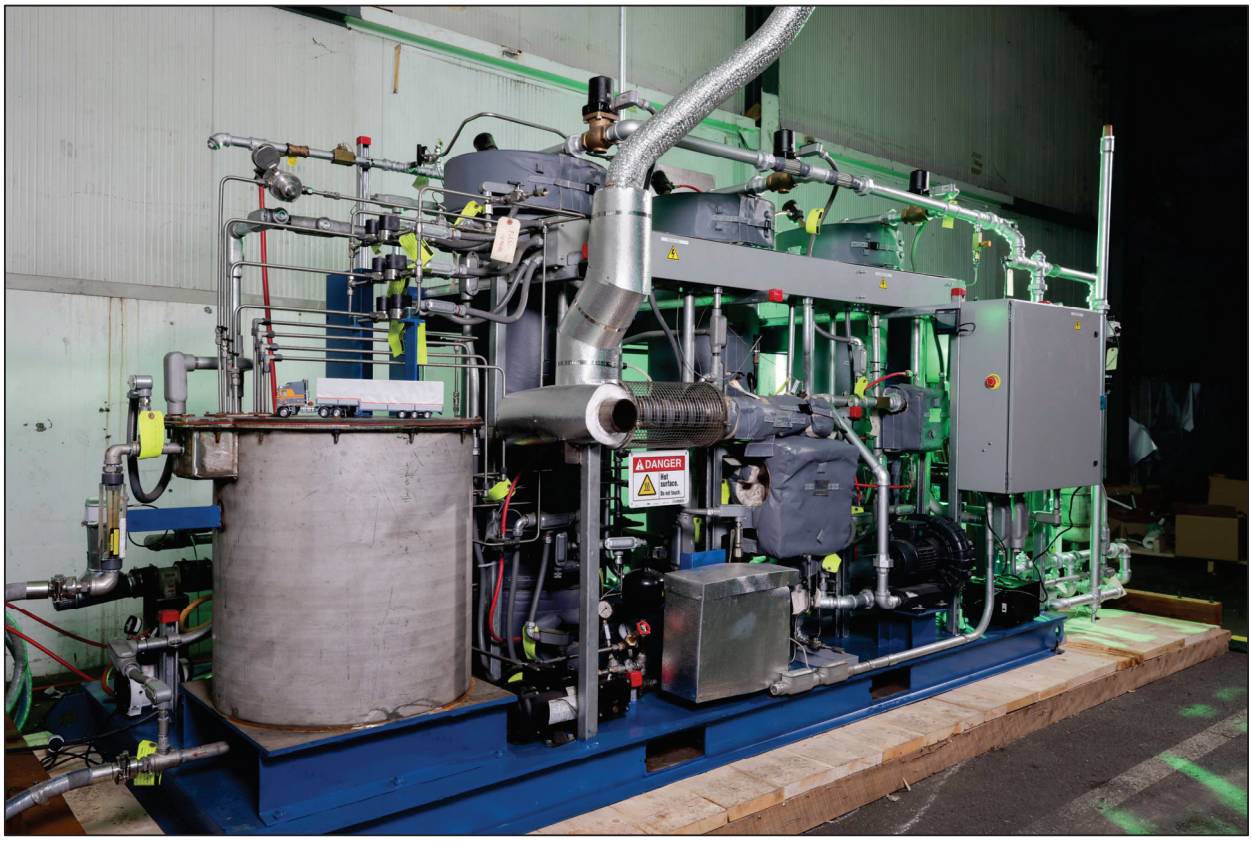

Figure 1 Qaptis Prototype I in Lausanne (CH)

or in Pittsburgh:

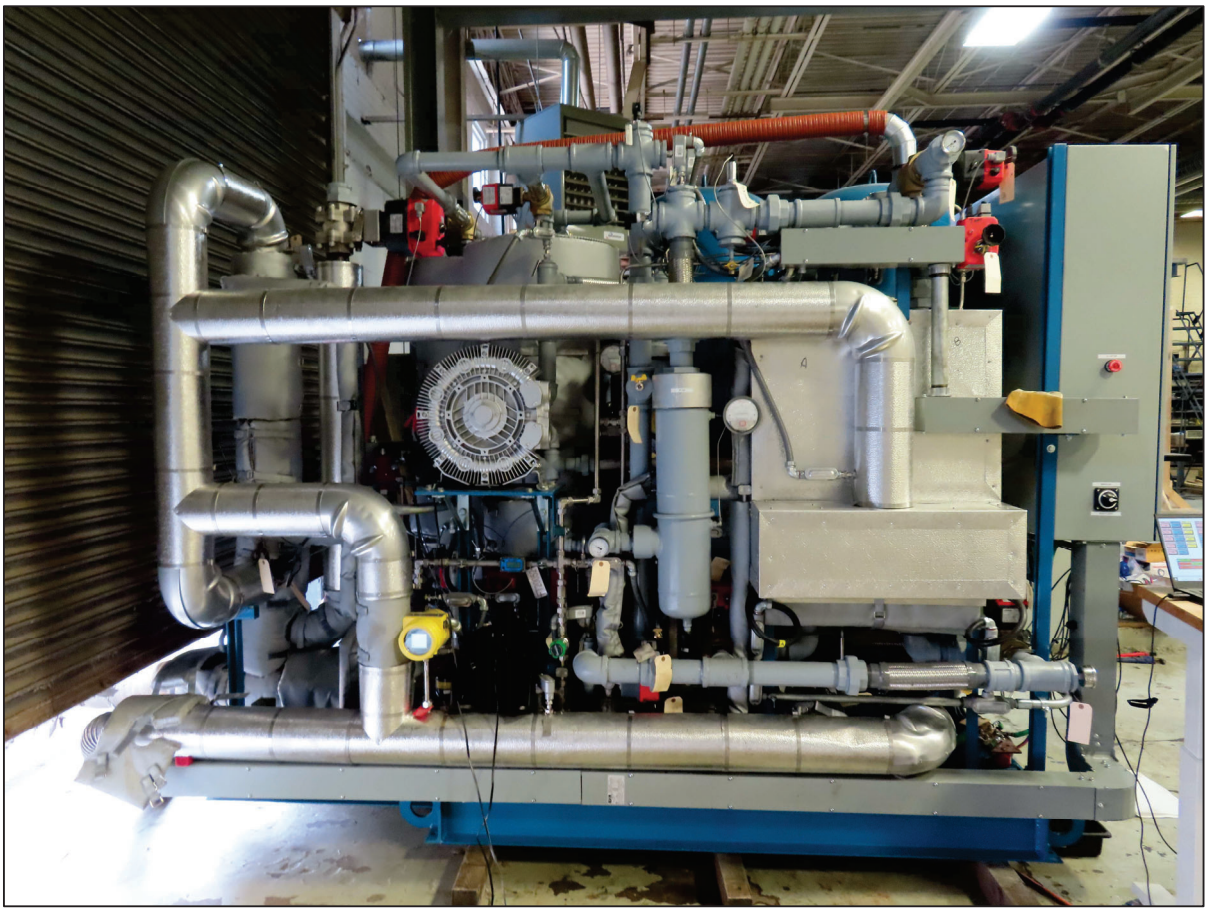

Figure 2 Qaptis Prototype II in Pittsburgh (US)

The visit date and scope are still under discussion and will be probably occur during Q2 or Q3 2025.

Qaptis background

Qaptis is a technology development startup focused on CO_2 capture from the sources of emissions, especially for retrofitting in small and medium scale applications. After successfully testing two prototypes we have reached proof of technology, proof of concept and technology readiness level (TRL) of 6. For manufacturers who want to explore the point-source CO_2 capture technology for decarbonizing their machines and vehicles, we provide the full prototyping

cycles up to industrialization. This includes techno-economic analysis, prototype design, manufacturing and commissioning.

The idea of Qaptis was initially originated in the group of Industrial Process and Energy Systems Engineering at EPFL, Sion. The motivation behind this research stemmed from the urgent need to tackle the growing environmental crisis caused by carbon emissions, particularly from the transportation sector. Despite significant progress in renewable energy and electric vehicles, heavy-duty transport continues to rely on fossil fuels, producing enormous amounts of CO_2. Current carbon capture technologies, such as amine absorption and membrane separation, have shown limited success in mobile and small to medium industrial scale applications due to their high energy demands, inefficiency in small-scale systems, and complexity in integration with existing infrastructure. As the world strives for a sustainable future, there was a clear gap: a need for a practical, cost-effective, and scalable solution that could be applied to the transportation sector without adding undue energy burdens. The years of research resulted in submission of a patent application in 2018 on a "System for CO_2 capture from internal combustion engine" followed up by a publication in 2019 (S. Sharma, 2019).

The group of cofounders came together in 2020, which resulted in incorporation of Qaptis Sàrl in July 2021. The headquarters of Qaptis was then moved to Lausanne in 2024, where the main team and offices has been located for its past 2 years. The team of cofounders was carefully selected through years of collaboration to establish the cultural and value alignments. This resulted in its current form which includes Professor Francois Marechal, Dr. Shivom Sharma, Dipl. Ing. Theodore Caby, and Dr. Masoud Talebi Amiri. All of whom were EPFL graduates and personnel.

During the past 3 years, Qaptis raised CHF 3m in grants and equity, considerably expanding our patent portfolio, and generating CHF 1.5m in revenue by acquiring clients from Japan, Switzerland, and the United states.

MOBILE CO_2 CAPTURE CONCEPT

Mobile CO_2 Capture (MCC) is a potential option for achieving decarbonization of the transport sector. MCC has some advantages for internal combustion engine applications such as availability of high-quality waste heat from the exhaust, clean exhaust due to the use of low sulfur fuels, availability of passive convective air cooling generated by the vehicle motion, the potential to

integrate with existing systems to power process equipment, and the potential to reduce cost through standardization and mass production. In addition, the opportunity exists to leverage substantial and growing CO_2 distribution infrastructure in the US and in Europe – an advantage not available yet to hydrogen and some alternative fuels, which may require significant, additional, and specialized infrastructure.

The development of MCC technologies has seen significant contributions from various players across the globe. Saudi Aramco, a leading name in the energy sector, began exploring MCC in 2011 as part of its sustainability initiatives, focusing on pick-up truck. Similarly, companies like Remora and Qaptis have made notable advancements in mobile applications of CO_2 capture technology.

Saudi Aramco is exploiting the solvent-MCC technology. Below is a Process Flow Diagram (PFD) from 2022:

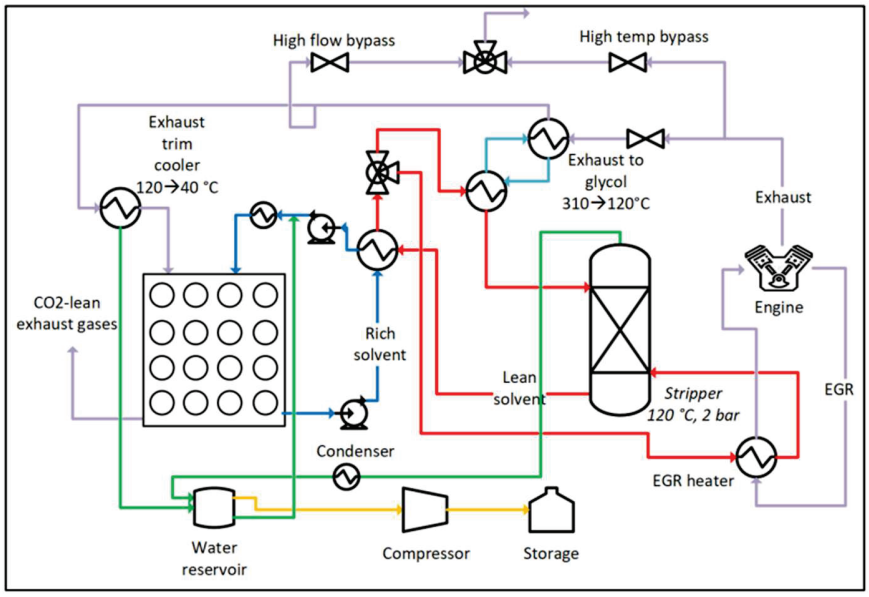

Figure 3 Process Flow Diagram of Aramco Technology

The CO_2 absorber is hollow fiber membrane contactors. As it can be seen in Figure 1, they absorb at around 35-40 °C. Solvent regeneration is carried out by heating the solvent to a maximum of 125 °C to release steam and CO_2 under pressure. Aramco noted that higher temperature and pressure regeneration is generally preferred to reduce water vaporization and compression work, however practical temperatures are limited by the amount of available heat from the exhaust as well as thermal degradation of the

solvent (Hamad, 2022). The gas (CO_2/water mixture) is cooled to 40 °C condensing out much of the water vapor through air-to-air heat exchanger + mist eliminator. Then, a 3-stage piston style compressor with air intercoolers compressor was installed on the truck to allow the product CO_2 to be compressed to 150 bar.

Remora Carbon is a startup based in the United states. It was incorporated in 2020 with the target to decarbonize heavy-duty trucks with on-board mobile carbon capture solution. They utilized a zeolite-based system with Temperature Swing Adsorption (TSA) for regeneration. The startup was set to start its field pilots on trucks in 2022, however, the lack of announcement on the results suggests that it was not successful. Based on our investigations, the main obstacles included the difficulty of drying the exhaust gas stream prior to adsorption process, and failure to reach the acceptable CO_2 capture rates in operational (dynamic) conditions. In May 2025, Remora Carbon announced $ 117m fundraising round to develop a CO_2 capture kit for locomotives. While it is not clear that Remora Carbon will completely shift its focus towards decarbonization of locomotives, as of today, they have not yet successfully commercialized their CO_2 capture system for trucks.

On its side, Qaptis has focused on a more-long term approach to develop a modular sorbent-MCC for heavy vehicles. The benefits of modular product is that it is possible to develop technologies in parallel and achieve best performance for each of them. In addition, it is easier to prioritize and change the priorities for development throughout years depending on the needs of the company. Currently, these 4 modules are categorized below:

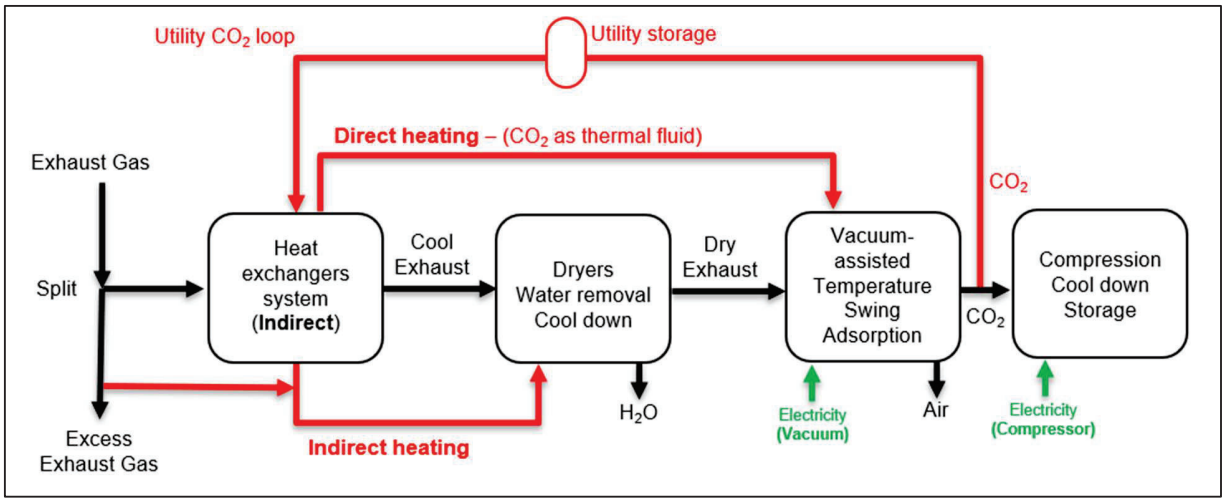

Figure 4 Block Flow Diagram of Qaptis Technology

(1) Heat Recovery

The partial exhaust gas from the internal combustion engine enters our kit. This is the first step. It is designed to be connected at the outlet of the Exhaust After Treatment System (EATS). This is to avoid the adverse effects of particle matters and corrosive material. The main difference is that heat and temperature available after the EATS is less than engine itself. The heat is extracted in this heat recovery step to be used in the next steps for Water Removal in the Dryers and for Vacuum-assisted Temperature Swing Adsorption. Our main innovation is in efficient recovery of this heat to provide the main energy to run the system.

(2) Water Removal (Condensation + Dryers)

To ensure optimal performance of the CO_2 adsorption system, it is critical to remove water vapor from the exhaust stream. Our process combines an initial condensation step (water knockout) with a proprietary drying system that operates based on Temperature-Swing Adsorption (TSA). This approach enables us to achieve dew points as low as -40°C without the need for high-pressure operation. Unlike conventional commercial dryers, which typically rely on Pressure-Swing Adsorption (PSA) and require pressures of at least 8 bar to reach similar dew points, our system operates efficiently at atmospheric or near-atmospheric pressure. This significantly reduces the energy demand, making it well-suited for mobile applications such as long-haul trucks.

(3) Temperature-vacuum Swing Adsorption

The dry exhaust gas then goes into this step where the CO_2 is separated from the rest of the exhaust gas (mainly air). The high purity CO_2 is then sent to compression prior to storage. We use a solid adsorbent such as zeolite based material. The variations of the material can be used for separating different pollutants, however, our goal is to have it maximized towards highest capture rates for CO_2. We are also capable of using other solid adsorbent material such as Metal Organic Frameworks (MOFs) if economically feasible. The CO_2 is adsorbed on the solid material at low temperature. When the material is close to saturation, we stop the adsorption by isolating the fixed-bed tank and heating up the tank to release the CO_2. After reaching a certain temperature and pressure in the tank, we open the tank to collect the CO_2. With the use of auxiliary equipment, we increase the amount of collected CO_2. To run a system continuously, we require at least 2 fixed-bed tanks working in parallel. Depending on some parameters, the optimal number of TSA tanks is 2 or 3. This heat is primarily provided from the heat recovery system.

(4) CO_2 compression

We compress CO_2 in order to minimize the required volume for storage, as it is more suitable for mobile applications. The storage conditions in our system is already defined by standards in CO_2 logistics. Therefore, the output conditions of this module are dictated by those standards. Storage is a separate module, as its boundaries are in connection with the external activities for CO_2 handling and logistics.

MODELS AND SIMULATION

A- DESIGN REQUIREMENTS

The models are created in DWSIM v9.0.2 (Apr 23, 2025). DWSIM is an open-source CAPE-OPEN compliant chemical process simulator compatible with multiple operating systems. The choice of this software makes the future use of the models for more advanced flow sheeting easier. We have successfully tested the compatibility of the models with older versions of the software.

The design of the MCC technology shall be applied for the European long-haul tractor best seller A6x2*4, part of the CO_2 subgroup 10-LH. Scania provided the design requirements which are listed below and in full details in Annex A.

Dimensional Constraint

The MCC shall fit within the designated installation space behind the cab (Figure 4):

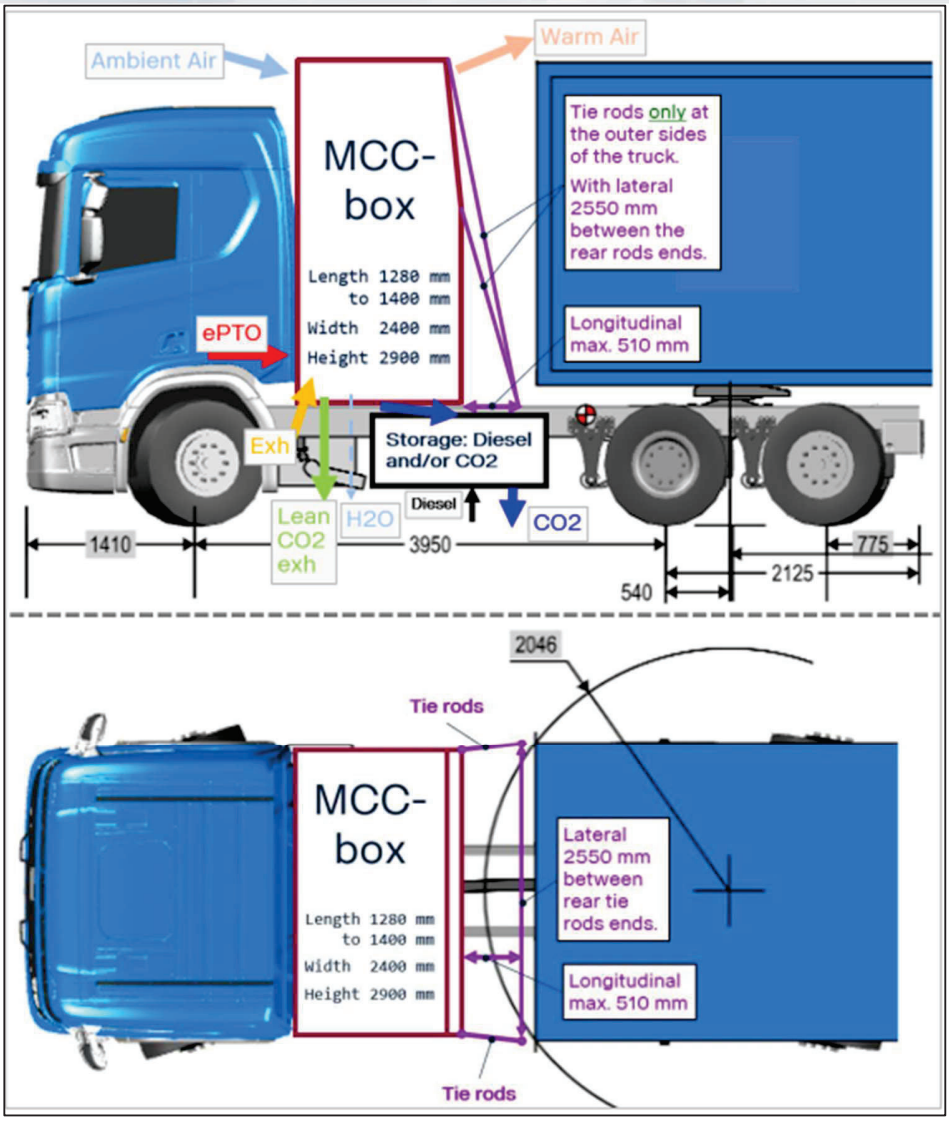

Figure 5 Long-haul tractor A6x2*4

Figure 5 shows that the MCC shall not be bigger than 2400 mm in width, 2900 mm in height and from 1280 to 1400 mm in length in driving direction. The length varies from 1280 mm at the top to 1400 mm at the bottom of the MCC to comply with the ISO 1726 specifications as explicated in Figure 3:

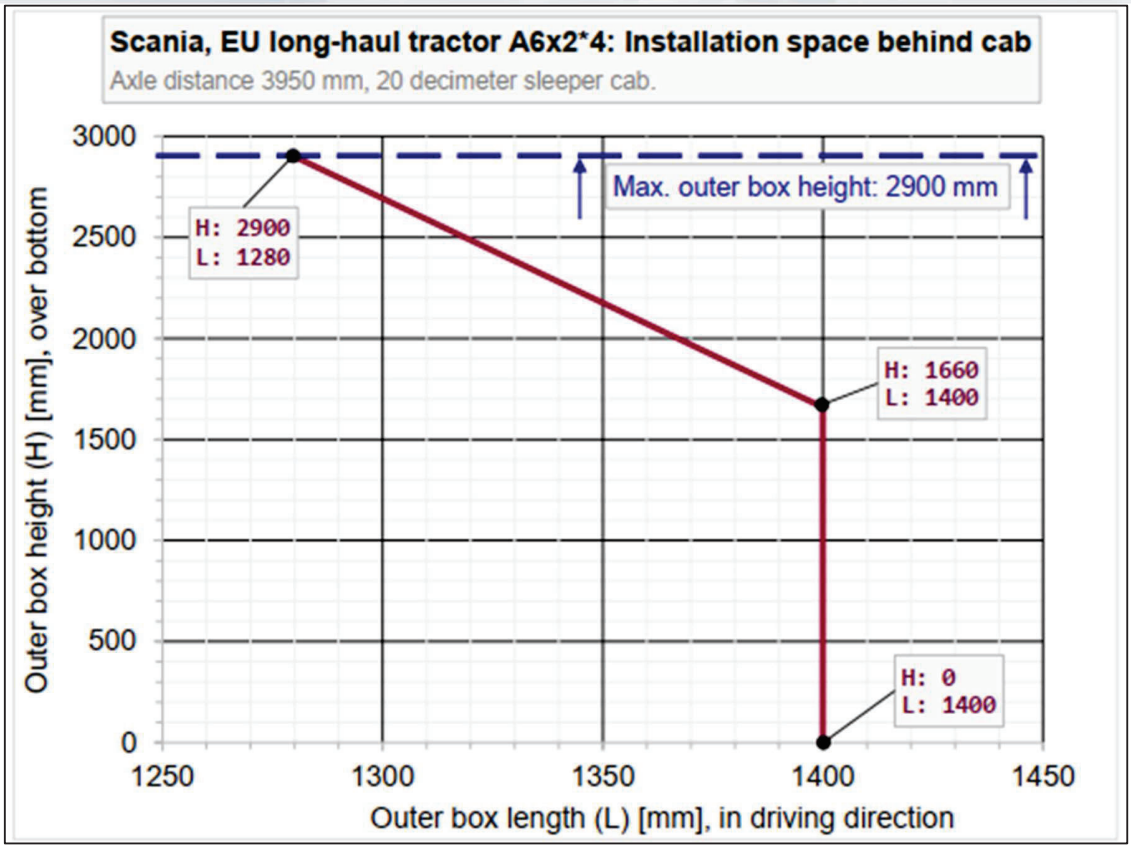

Figure 6 Installation space behind cab

Weight Limit

In addition to the dimensional constraint, the weight also plays an important role to limit the payload penalty. The maximum limit for the MCC system has been fixed at 2.90 tons (2900 kg including all system components, mountings and full CO_2 tanks.).

Noise Emission Compliance

Noise needs to be considered both for comfort and for noise legislation. Under the EU Regulation (EU) No 540/2014, heavy-duty vehicles (HDVs) are subject to specific pass-by noise limits at 81 dB(A) for N3 (heavy trucks above 12 tons).

Engine Backpressure Limitation

Max. 50 mbar (= 5 kPa) additional pressure drop for an exhaust mass flow of 1824 kg/h and a tailpipe outlet temperature of 400 °C. A higher flow resistance from the MCC system can be managed, and in this case engine calibration and turbocharger need to be adapted.

Environmental Operation Conditions

The MCC shall operate for various ambient temperatures ranging from -30 to +50 °C. Cold start mode for winter. While the hotter temperature requires more cooling power to run the system, a choice has been made to run the simulation at 20°C ambient for simulation in order to comply with European certifications testing procedures namely WHSC, WHTC cold, WHTC hot, FCMC.

Selection of the Design Point

The Scania engine operates under varying loads throughout real-world duty cycles. These operating conditions are captured in the Engine Load Matrix (ELM), which provides a time-weighted distribution of engine speed and torque for the 6-cylinder, 450 hp diesel engine:

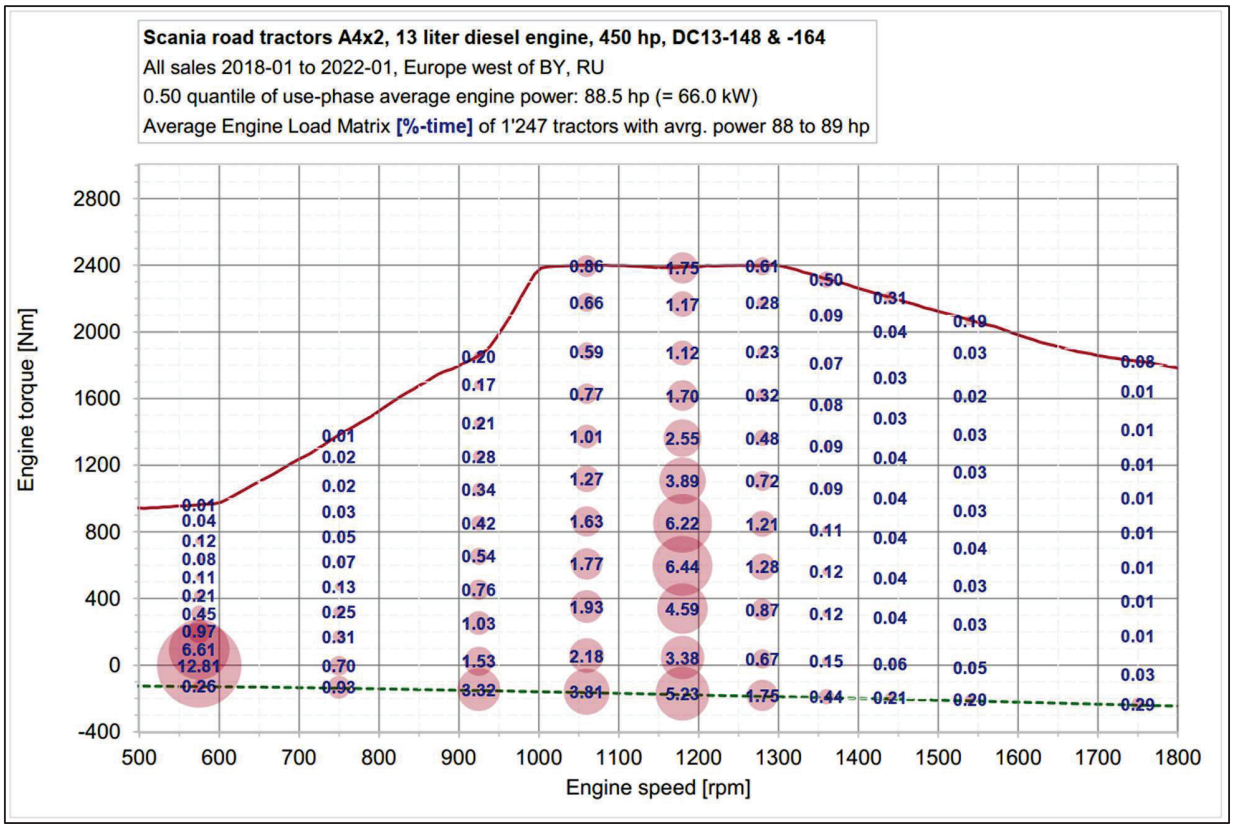

Figure 7 Average Engine Load Matrix

The exhaust characteristics for each of these varying loads are presented in the stationary diesel map in Figure 8:

				Humid exhaust					
Speed	Torque	Fuel flow		N2	O2	CO2	H2O	Humid exhaust	$T_{exh,\ tailpipe\text{-}out}$
rpm	Nm	kg / h	kW_{LHV}	kg / h	kg / h	kg / h	kg / h	kg / h	°C
600	0	1.1	13.1	98	26	3.5	1.4	130	79
600	400	5.2	61.4	209	46	16.4	6.4	278	187
600	800	9.6	114.0	230	37	30.4	11.8	309	284
600	1120	13.4	159.5	250	30	42.5	16.6	340	372
700	-120	0.0	0.0	89	27	0.0	0.0	116	42
700	0	1.3	15.2	124	33	4.1	1.6	164	81
700	400	6.0	70.7	252	56	18.8	7.3	335	189
700	800	11.0	130.2	284	49	34.7	13.5	381	284
700	1200	16.4	194.4	326	43	51.8	20.2	441	365
700	1640	22.6	268.6	360	32	71.5	27.9	491	435
800	-120	0.0	0.0	278	85	0.0	0.0	363	46
800	0	1.5	17.5	283	81	4.7	1.8	370	78
800	400	6.8	80.3	299	68	21.4	8.3	396	191
800	800	12.4	147.0	343	62	39.2	15.3	460	281
800	1200	18.3	216.9	392	57	57.8	22.5	530	352
800	1600	24.3	288.3	440	51	76.8	30.0	598	403
800	2000	30.5	362.2	506	50	96.5	37.6	690	445
800	2210	33.8	401.4	541	49	106.9	41.7	739	462

Figure 8 Excerpt of the stationary engine map

To ensure the relevance of the simulation, the design point must be selected based on realistic engine operating conditions. This selection should be guided by the ELM, which reflects the time-share distribution of engine speed and torque across typical duty cycles. The chosen design point must not only represent a high-frequency operating zone but also correspond to conditions where exhaust gas characteristics—notably temperature —are compatible with effective CO_2 capture.

This ensures that the simulation reflects both practical system performance and the thermal regime critical to MCC operation.

That said, the choice of the design point for the simulation was **1060 rpm** and **862 Nm**. At this load, the resulting exhaust is sufficiently close to the use-phase weighted average of the engine in the ELM:

Representative engine operation point													
n	Tq	Power	N2	O2	CO2	H2O	Humid exhaust	$\Delta h_{exh,\ 100\ °C}$	$\Delta H_{exh,\ 100\ °C}$	$T_{exh,\ tailpipe,\ stationary}$	Mass-share CO2	Mass-share H2O	Regene-ration heat
rpm	Nm	kW	kg / h	kg / h	kg / h	kg / h	kg_{exh} / h	$kJ_{th,exh}$ / kg_{exh}	$kW_{th,exh}$	°C	-	-	$MJ_{th,exh}$ / kg_{CO2}
1060	**862**	**95.7**	497.4	92.1	54.9	21.4	665.9	189	35.0	278	0.082	0.032	2.29
Deviation from weighted average													
+6.2%	+8.6%	+15.3%	+7.7%	+4.9%	+12.3%	+12.3%	+7.8%	-5.5%	+1.9%	-3.6%	+4.1%	+4.1%	-9.3%

Figure 9 Design point vs. weighted average engine load

As it can be seen in Figure 5, at this design point, the MCC benefits from a relatively high-quality heat in the exhaust: $T_{exh,\ tailpipe\text{-}out}$ = 278°C.

B- CAPTURE TARGET

After listing the design constraints, Scania and Qaptis agreed that the MCC-equipped diesel vehicle shall emit significantly less tailpipe-CO_2, tank to wheel, than an High-Pressure Direct Injection (HPDI) methane engine, a benchmark for low-emission internal combustion technologies. To meet this target, the net CO_2 capture rate must be at least 35%, accounting for both captured emissions and system-induced penalties (e.g. power consumption). This can position MCC as a competitive decarbonization solution for Scania.

C- ZEOLITE-MCC SIMULATION

The Flowsheet B1 in Annex B shows the detailed process for the zeolite-MCC simulation.

The total exhaust gas is evenly split into treated (330 kg/hr) and excess stream (330 kg/hr). The treated hot exhaust stream first passes through a piping section, where thermal losses are minimal, estimated at 1.40 kW. The

exhaust then undergoes a series of passive cooling steps designed to reduce its temperature before any active cooling is applied. This staged approach prioritizes energy efficiency by minimizing electrical power demand for downstream cooling systems. The first passive cooling step involves a heat exchanger with utility CO_2 in heat exchanger E01. Approximately 6.7 kW of heat is transferred from the exhaust gas to the utility CO_2 here which will be used to regenerate the TSA. The exhaust gas temperature into E01 is 264C at the outlet temperature is 196C. The next step in cooling the exhaust gas is direct thermal contact with dryer B (we have a dryer A, B and C) in regeneration mode. Despite the presence of water vapor in the exhaust, direct heating is feasible because, at this temperature level, the water is not adsorbed by the dryer sorbent, allowing regeneration to proceed effectively. The desorption heat requirement for the dryer sorbent is 3600 kJ/kg, and this heat is recovered from the exhaust stream, serving the dual purpose of completely regenerating the dryers and lowering the treated hot exhaust gas temperature. As a result, the exhaust temperature drops from 196°C to 145°C.

The stream then passes through the TSA B (we have TSA A, B and C) unit in regeneration mode for indirect heating, which extracts additional thermal energy from the stream and reduces the temperature by another 14%, bringing it down to approximately 125°C. The indirect heating provided by the hot treated exhaust stream is not sufficient to fully regenerate the TSA B and will be complemented by direct heating from utility CO_2. We will get back to that point later. Following this, an air-to-air radiator performs more efficient cooling, further reducing the exhaust temperature to 40°C, at which point still condensation is minimal.

Then, the gas enters the most efficient active cooling phase that allows condensation to happen. A chilled water heat exchanger (E-04) cools the stream to 20.5°C, enabling condensation of the majority of water vapor. Approximately 67% of the water content is removed at this stage—equivalent

to 8.7 kg/h—prior to entering the dryers. The remaining moisture is removed in the dryer A in adsorption mode, which brings the dew point down to -40°C. The resulting dried exhaust gas, referred to as the "dryer gas," contains only 0.02 kg/h of residual water and is then routed to the TSA beds for CO_2 capture.

The gas pressure is boosted by a regenerative blower which sets the mass flow of the treated gas. The dried gas then enters the TSAs units that operate cyclically to ensure continuous capture. In Flowsheet B1, the TSA A is in adsorption mode and will capture CO_2. The CO_2 physically binds to the zeolite in an exothermic process (7.5 kW of heat).

After 15 minutes is completed, the dried, CO_2-depleted and cooled exhaust gas —at approximately 33°C—is redirected to TSA Unit C, which is undergoing a cooling phase in preparation for the next adsorption cycle. In this step, the cold exhaust gas functions as a heat sink, absorbing residual thermal energy from TSA C. This heat exchange process raises the temperature of the exhaust gas to approximately 113°C at the outlet, while simultaneously lowering the temperature of the sorbent bed within TSA C to the target range required for efficient CO_2 adsorption.

Following this indirect cooling step, the warmed exhaust gas passes through a secondary heat exchanger (E-09), where it is further cooled to around 43°C. This final cooling stage ensures that the dryer associated with TSA C is brought to optimal temperature conditions for its upcoming adsorption phase. Once the heat recovery process is complete, the treated exhaust gas is safely vented to atmosphere, completing the post-capture exhaust handling cycle.

We mentioned earlier that TSA B benefits from the indirect heating of the hot exhaust stream and it is not enough to fully regenerate it within the cycle time. Indeed, this step is energy-intensive and requires direct controlled heating from the utility CO_2. The heat requirement is provided by the excess stream that was took apart at the beginning of the process. The utility CO_2 temperature will increase from 31°C to 257°C using the excess stream. It will be used to regenerate the TSA B. Both utility CO_2 streams and captured CO_2 will be combined in the TSA and will have a temperature of 125°C when exiting the TSA. They will be cooled down to 30°C through E-05 before being split: 235 kg/hr for the utility CO_2 loop and 26.5 kg/hr for captured CO_2.

Captured CO_2 is routed through a condensation and compression loop, where chillers and glycol/water cooling systems reduce its temperature for liquefaction. The final product—liquid CO_2—is stored after separation from non-condensable gases, while tail gas is vented or recycled.

D- MOF-DRY MCC SIMULATION

The MOF-Dry MCC simulation is using a MOF with prior drying before the capture process.

The selected MOF for this study is the Mg-MOF-74. Mg-MOF-74 consists of helical one-dimensional channels lined with open Mg^{2+} sites that strongly bind CO_2. This high density of exposed metal sites gives rise to a steep low-

pressure CO_2 isotherm and exceptional uptake at flue-gas CO_2 (Kenarsari, 2013).

Among MOFs, Mg-MOF-74 exhibits one of the highest CO_2 working capacities, especially when applying vacuum down to 0.1–0.2 bar for the desorption, like in the Prototype in Pittsburgh. In addition, Mg-MOF-74 releases CO_2 with moderate heating. CO_2 bound at the Mg sites can be fully desorbed by ~80–125 °C indicating that a 125 °C regeneration step would leave a residual loading of 23%, around 1.0 mol/kg (Z. Bao, 2010).

While some MOFs show even better CO_2 capacity, Mg-MOF-74 is a proven thermally stable MOF and maintains structure over many adsorption/desorption cycles in dry conditions. It is sensitive to moisture – water can degrade the framework. Thus, in real flue gas which also contains water vapor, Mg-MOF-74 needs protective measures. Despite this, its benchmark CO_2 capacity and fast kinetics under dry conditions have made it a reference MOF for CO_2.

The Flow Diagram for the Dry MOF is the same as the Zeolite. However, the MOF can hold twice as much CO_2 and the Uptake kinetics is faster than Zeolite. If the exhaust flow split is 50% treated and 50% excess as is used for the Zeolite option, the performance will be the same except the MOF option will cost significantly more than the Zeolite. As the MOF is capable of much higher performance, it was decided to increase the amount of treated exhaust to 90% of the exhaust flow to capture more CO_2 and use the same size volume of MCC.

The Flowsheet B2 in Annex B shows the detailed process for the Dry MOF-MCC simulation.

The total exhaust gas is split into treated (600 kg/hr) and excess stream (66 kg/hr). The treated hot exhaust stream first passes through a piping section, where thermal losses are minimal, estimated at 2.5 kW. The exhaust then undergoes a series of passive cooling steps designed to reduce its temperature before any active cooling is applied. This staged approach prioritizes energy efficiency by minimizing electrical power demand for downstream cooling systems. The first passive cooling step involves a heat exchanger with utility CO_2 in heat exchanger E01. Approximately 9.9 kW of heat is transferred from the exhaust gas to the utility CO_2 here which will be used to regenerate the TSA. The exhaust gas temperature into E01 is 264C at the outlet temperature is 208C. The next step in cooling the exhaust gas is direct thermal contact with dryer B (we have a dryer A, B and C) in regeneration mode. Despite the presence of water vapor in the exhaust, direct heating is feasible because, at

this temperature level, the water is not adsorbed by the dryer sorbent, allowing regeneration to proceed effectively. The desorption heat requirement for the dryer sorbent is 3600 kJ/kg, and this heat is recovered from the exhaust stream, serving the dual purpose of completely regenerating the dryers and lowering the treated hot exhaust gas temperature. As a result, the exhaust temperature drops from 196°C to 155°C.

The stream then passes through the TSA B (we have TSA A, B and C) unit in regeneration mode for indirect heating, which extracts additional thermal energy from the stream and reduces the temperature, bringing it down to approximately 125°C. The indirect heating provided by the hot treated exhaust stream is not sufficient to fully regenerate the TSA B and will be complemented by direct heating from utility CO_2. We will get back to that point later. Following this, an air-to-air radiator performs more efficient cooling, further reducing the exhaust temperature to 46°C, at which point still condensation is minimal.

Then, the gas enters the most efficient active cooling phase that allows condensation to happen. A chilled water heat exchanger (E-04) cools the stream to 19.5°C, enabling condensation of the majority of water vapor. Approximately 72% of the water content is removed at this stage—equivalent to 18.2 kg/h—prior to entering the dryers. The remaining moisture is removed in the dryer A in adsorption mode, which brings the dew point down to -40°C. The resulting dried exhaust gas, referred to as the "dryer gas," contains only 0.02 kg/h of residual water and is then routed to the TSA beds for CO_2 capture.

The gas pressure is boosted by a regenerative blower which sets the mass flow of the treated gas. The dried gas then enters the TSAs units that operate cyclically to ensure continuous capture. In Flowsheet B1, the TSA A is in adsorption mode and will capture CO_2. The CO_2 physically binds to the MOF in an exothermic process (12.50 kW of heat).

After 15 minutes is completed, the dried, CO_2-depleted and cooled exhaust gas —at approximately 37°C—is redirected to TSA Unit C, which is undergoing a cooling phase in preparation for the next adsorption cycle. In this step, the cold exhaust gas functions as a heat sink, absorbing residual thermal energy from TSA C. This heat exchange process raises the temperature of the exhaust gas to approximately 78°C at the outlet, while simultaneously lowering the temperature of the sorbent bed within TSA C to the target range required for efficient CO_2 adsorption.

Following this indirect cooling step, the warmed exhaust gas passes through a secondary heat exchanger (E-09), where it is further cooled to around 37°C.

This final cooling stage ensures that the dryer associated with TSA C is brought to optimal temperature conditions for its upcoming adsorption phase. Once the heat recovery process is complete, the treated exhaust gas is safely vented to atmosphere, completing the post-capture exhaust handling cycle.

We mentioned earlier that TSA B benefits from the indirect heating of the hot exhaust stream and it is not enough to fully regenerate it within the cycle time. Indeed, this step is energy-intensive and requires direct controlled heating from the utility CO_2. The heat requirement is provided by the excess stream that was took apart at the beginning of the process. The utility CO_2 temperature will increase from 31°C to 262°C using the excess stream. It will be used to regenerate the TSA B. Both utility CO_2 streams and captured CO_2 will be combined in the TSA and will have a temperature of 125°C when exiting the TSA. They will be cooled down to 32°C through E-05 before being split: 235 kg/hr for the utility CO_2 loop and 48.9 kg/hr for captured CO_2.

Captured CO_2 is routed through a condensation and compression loop, where chillers and glycol/water cooling systems reduce its temperature for liquefaction. The final product—liquid CO_2—is stored after separation from non-condensable gases, while tail gas is vented or recycled.

E- MOF-WET MCC SIMULATION

The MOF-Wet MCC simulation is using a MOF without prior drying before the capture process. There are newly developed Zirconium-based MOFs that don't degrade when exposed to water, so a wet exhaust is able to enter the TSAs Units. However, dryers are still required downstream of the TSAs. Current Compressor vendors require a dry (-40C) gas entering the compressors to prevent CO_2 and water from forming an acid that can cause corrosion. It is worth mentioning that based on our pre-screening for CO_2 compressors that can handle higher moisture contents, we were not able to find a suitable alternative at this moment. We've assumed that the compressor will be constructed of materials that will not corrode in a carbonic acid environment. It is still necessary to dry the gas prior to liquefaction to prevent water from condensing and plugging the cold heat exchangers and to remove the water impurity to allow the CO_2 to cool down. These Dryers will be smaller than Dryers in front of the TSAs. The Flowsheet B3 in Annex B shows the detailed process for the Dry MOF-MCC simulation.

The total exhaust gas is split 50% into treated (330 kg/hr) and 50% into excess stream (330 kg/hr). The treated hot exhaust stream first passes

through a piping section, where thermal losses are minimal, estimated at 1.4 kW. The exhaust then undergoes a series of passive cooling steps designed to reduce its temperature before any active cooling is applied. This staged approach prioritizes energy efficiency by minimizing electrical power demand for downstream cooling systems. The first passive cooling step involves a heat exchanger with utility CO_2 in heat exchanger E01. Approximately 6.6 kW of heat is transferred from the exhaust gas to the utility CO_2 here which will be used to regenerate the TSA. The exhaust gas temperature into E01 is 264C at the outlet temperature is 196C.

The stream then passes through the TSA B (we have TSA A, B and C) unit in regeneration mode for indirect heating, which extracts additional thermal energy from the stream and reduces the temperature, bringing it down to approximately 145°C. The indirect heating provided by the hot treated exhaust stream is not sufficient to fully regenerate the TSA B and will be complemented by direct heating from utility CO_2. We will get back to that point later. Following this, an air-to-air radiator performs more efficient cooling, further reducing the exhaust temperature to 40°C, at which point still condensation is minimal.

Then, the gas enters the most efficient active cooling phase that allows condensation to happen. A chilled water heat exchanger (E-04) cools the stream to 16.3°C, enabling condensation of the majority of water vapor. Approximately 76% of the water content is removed at this stage—equivalent to 8.2 kg/h—prior to entering the dryers.

The gas pressure is boosted by a regenerative blower which sets the mass flow of the treated gas. Some of the remaining moisture is removed in the TSA A in adsorption mode, and the remainder of the moisture continues to pass through the system. The gas enters the TSA units that operate cyclically to ensure continuous capture. In Flowsheet B3, the TSA A is in adsorption mode and will capture CO_2 and H2O simultaneously. The CO_2 & H2O physically binds to the MOF in an exothermic process (6.5 kW of heat).

After 15 minutes is completed, the CO_2-depleted and cooled exhaust gas —at approximately 25°C—is redirected to TSA Unit C, which is undergoing a cooling phase in preparation for the next adsorption cycle. In this step, the cold exhaust gas functions as a heat sink, absorbing residual thermal energy from TSA C. This heat exchange process raises the temperature of the exhaust gas to approximately 98°C at the outlet, while simultaneously lowering the temperature of the sorbent bed within TSA C to the target range required for efficient CO_2 adsorption. Once the heat recovery process is complete, the

treated exhaust gas is safely vented to atmosphere, completing the post-capture exhaust handling cycle.

We mentioned earlier that TSA B benefits from the indirect heating of the hot exhaust stream and it is not enough to fully regenerate it within the cycle time. Indeed, this step is energy-intensive and requires direct controlled heating from the utility CO_2. The heat requirement is provided by the excess stream that was took apart at the beginning of the process. The utility CO_2 temperature will increase from 31°C to 257°C using the excess stream. It will be used to regenerate the TSA B. Both utility CO_2 streams and captured CO_2 will be combined in the TSA and will have a temperature of 125°C when exiting the TSA. They will be cooled down to 30°C through E-05 before being split: 240 kg/hr for the utility CO_2 loop and 29.2 kg/hr for captured CO_2.

Captured CO_2 is routed through a condensation and compression loop, where chillers and glycol/water cooling systems reduce its temperature for liquefaction. The final product—liquid CO_2—is stored after separation from non-condensable gases, while tail gas is vented or recycled.

The Wet MOF system is limited by TSA velocity to the same cross-sectional area as the Dry MOF. The dryers are slightly smaller in this design than the Dry MOF design, but they are in the space below the TSAs and the system capacity cannot be increased. The Wet MOF CO_2 capacity is significantly reduced due to the H_2O uptake.

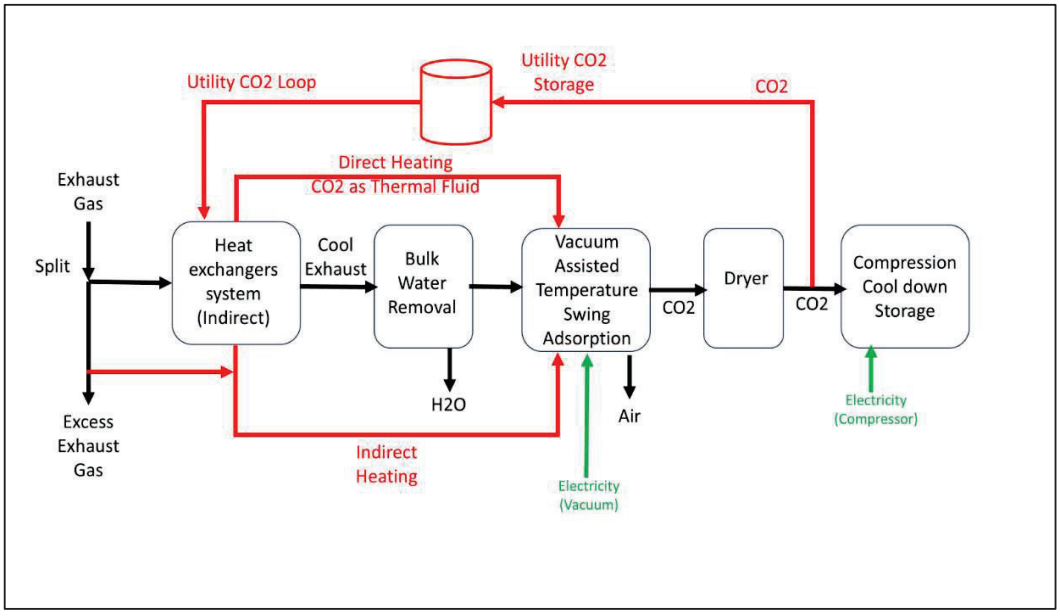

Figure 10 BFD Wet-MOF

F- RESULTS

I. Design Point

Ambient Temperature is 20 °C.

Gross capture rate

The gross capture rate is calculated as below:

gross capture rate	[kg/hr]	[kg/day]	%
Zeolite	19.7	158	35.8
MOF-Dry	35.3	282	64.3
MOF-Wet	17.0	136	30.9

The gross capture rate does not include the excess emissions linked to the additional electric consumption that are generated through PTO. The net capture rate which includes the deduction of CO_2 emissions from extra fuel consumption, will be compared with the capture target.

Estimated Electric Consumption

The Estimated Electric Consumption for Zeolite Simulation is breakdown into several single consumers in Table below:

Component	Power [kW]
C-01 Utility CO_2 Blower	5.15
C-02 CO_2 Compressor	4.36
C-03 Chiller Compressor	13.97
C-04 Vacuum Pump	0.62
C-05 Boost Blower	3.79
F-06 Fan TSA Aftercooler	0.21
F-07 Fan CO_2 Air Cooling	0.21
F-08 Fan Chiller Air	0.21
P-01 EGW Pump	0.04
Valves and Controls	0.75
Total kW	**29.31**

The Estimated Electric Consumption for MOF-Dry Simulation:

Component	Power [kW]
C-01 Utility CO_2 Blower	5.23
C-02 CO_2 Compressor	7.43
C-03 Chiller Compressor	19.92
C-04 Vacuum Pump	1.06
C-05 Boost Blower	7.26
F-06 Fan TSA Aftercooler	0.21
F-07 Fan CO_2 Air Cooling	0.21
F-08 Fan Chiller Air	0.62
P-01 EGW Pump	0.04
Valves and Controls	0.75
Total kW	**42.73**

The Estimated Electric Consumption for MOF-Wet Simulation:

Component	Power [kW]
C-01 Utility CO_2 Blower	5.41
C-02 CO_2 Compressor	3.82
C-03 Chiller Compressor	6.25
C-04 Vacuum Pump	0.54
C-05 Boost Blower	1.31
F-06 Fan TSA Aftercooler	0.41
F-07 Fan CO_2 Air Cooling	0.21
F-08 Fan Chiller Air	0.62
P-01 EGW Pump	0.04
Dryer Heater	0.75
Valves and Controls	0.75
Total kW	**20.11**

The MOF-Dry requires much more electrical power as it processes a higher exhaust flow of ~600 kg/hr.

Net carbon capture

The net carbon capture is calculated by the following equation:

$$\text{net capture}\left[\frac{\text{kg}}{\text{hr}}\right] = \text{gross capture}\left[\frac{\text{kg}}{\text{hr}}\right] - 0.17\left[\frac{kg_{diesel}}{kW_{mech}}\right] * \frac{1}{0.9}\left[\frac{kW_{mech}}{kW_{elec}}\right] * 3.14\left[\frac{kg_{CO2}}{kg_{diesel}}\right] * \text{P}_{\text{Elec}}[kW_{elec}]$$

The results are given below:

MCC	Gross capture [kg/hr]	Excess emissions [kg/hr]	Net capture [kg/hr]	Net capture [%]
Zeolite	19.7	17.1	2.6	4.7
MOF-Dry	35.3	25	10.3	18.7
MOF-Wet	17.0	11.7	5.3	9.6

Backpressure

The exhaust backpressure have been calculated :

- Zeolite: 120 mbar
- MOF-Dry: 120 mbar
- MOF-Wet 90 mbar

The difference between the backpressure for Zeolite/MOF-Dry and MOF-Wet is due to not having a dryer to create an additional pressure drop.

Summary Comparison for the Design Point

	Design Point Performance		
	Zeolite	MOF-Dry	MOF-Wet
Gross CO_2 Capture	35%	64%	31%
Elec. Consumption [kW]	29	43	20
Net CO_2 Capture	4.7%	18.7%	9.6%
Back Pressure @Tailpipe [mbar]	120	120	90

II. Evaluation Under European Certification Cycles

To assess the performance of the MCC (Modular Carbon Capture) system under realistic and dynamic truck operating conditions, simulations were conducted using standard European certification cycles. These include the World Harmonized Stationary Cycle (WHSC), the World Harmonized Transient

Cycle (WHTC) with both cold start and hot start conditions, and the Fuel Consumption Measurement Cycle (FCMC).

The simulation framework calculates the dynamic CO_2 capture rate at a frequency of 1 Hz across all four certification cycles. In general, the performance of the MCC system closely correlates with the engine's operational behavior throughout these cycles.

Figures 11 through 14 illustrate the system's performance, showing how the capture rate responds to the varying load and speed profiles typical of each cycle.

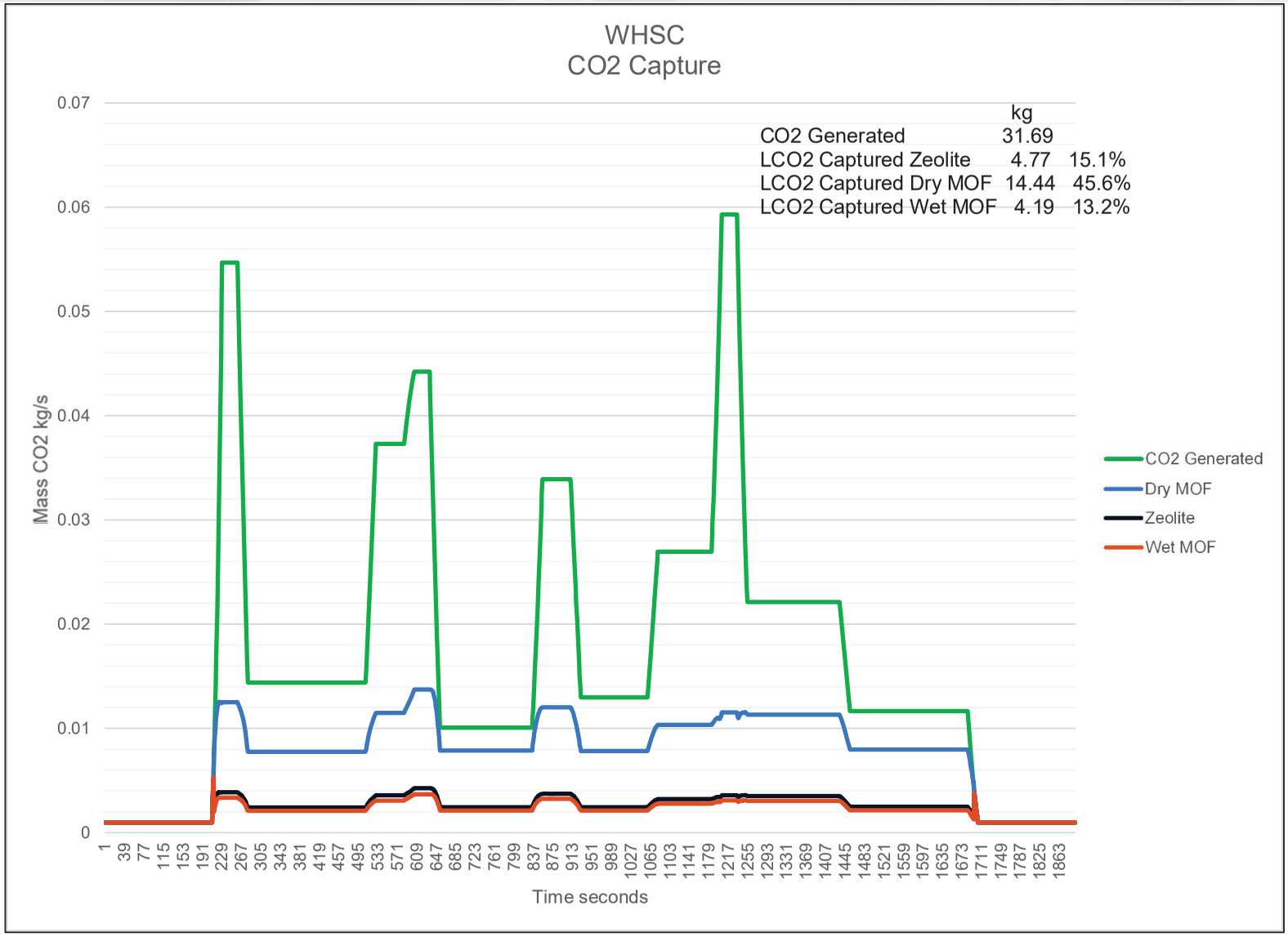

Figure 11 CO_2 Capture on WHSC cycle

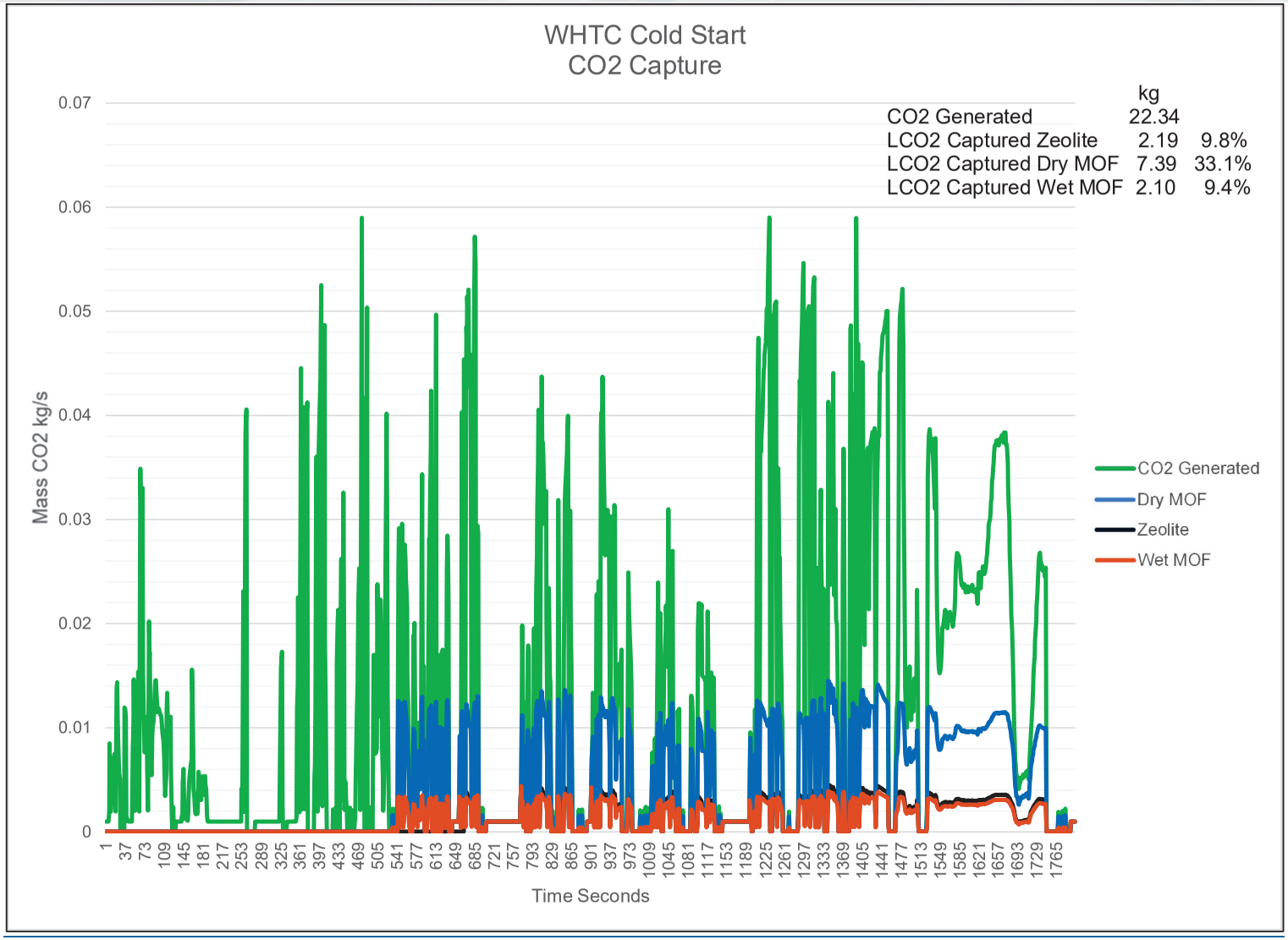

Figure 12 CO_2 Capture on WHTC Cold Start cycle

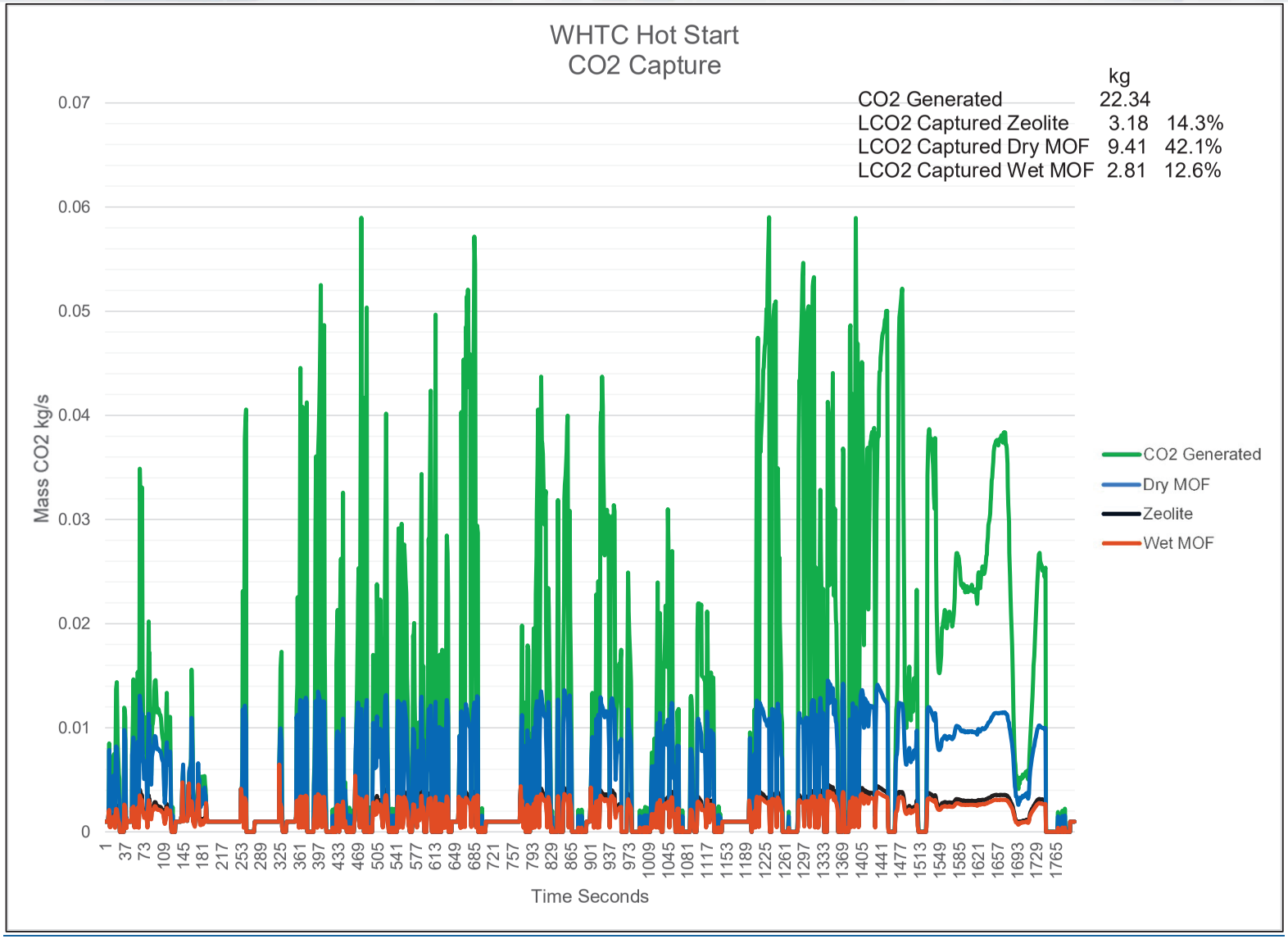

Figure 13 CO_2 Capture on WHTC Hot Start cycle

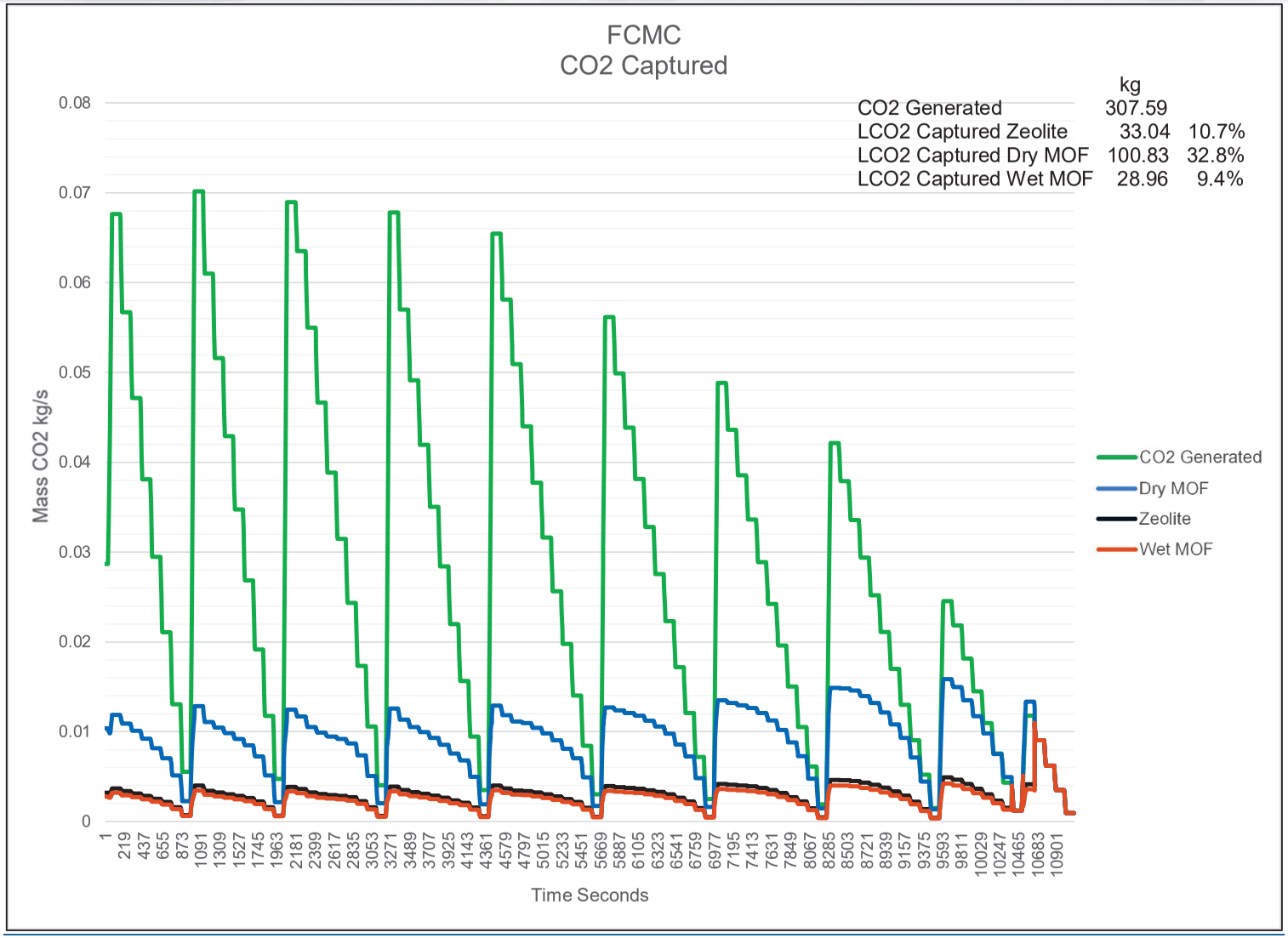

Figure 14 CO_2 Capture on FCMC cycle

Generic 3D model

The MCC is limited in size to the allotted volume on the truck. The first step in sizing the system is to determine the largest cross-sectional area of the TSA that will fit in the volume. The exhaust gas velocity into the TSA is limited to the uptake kinetics of the sorbent. Once the cross-sectional area of sorbent is set the length of adsorption cycle determines the height of the sorbent. Then space requirements need to be filled with Dryers, Heat Exchangers, Compressors, Storage Tanks, Piping, etc.

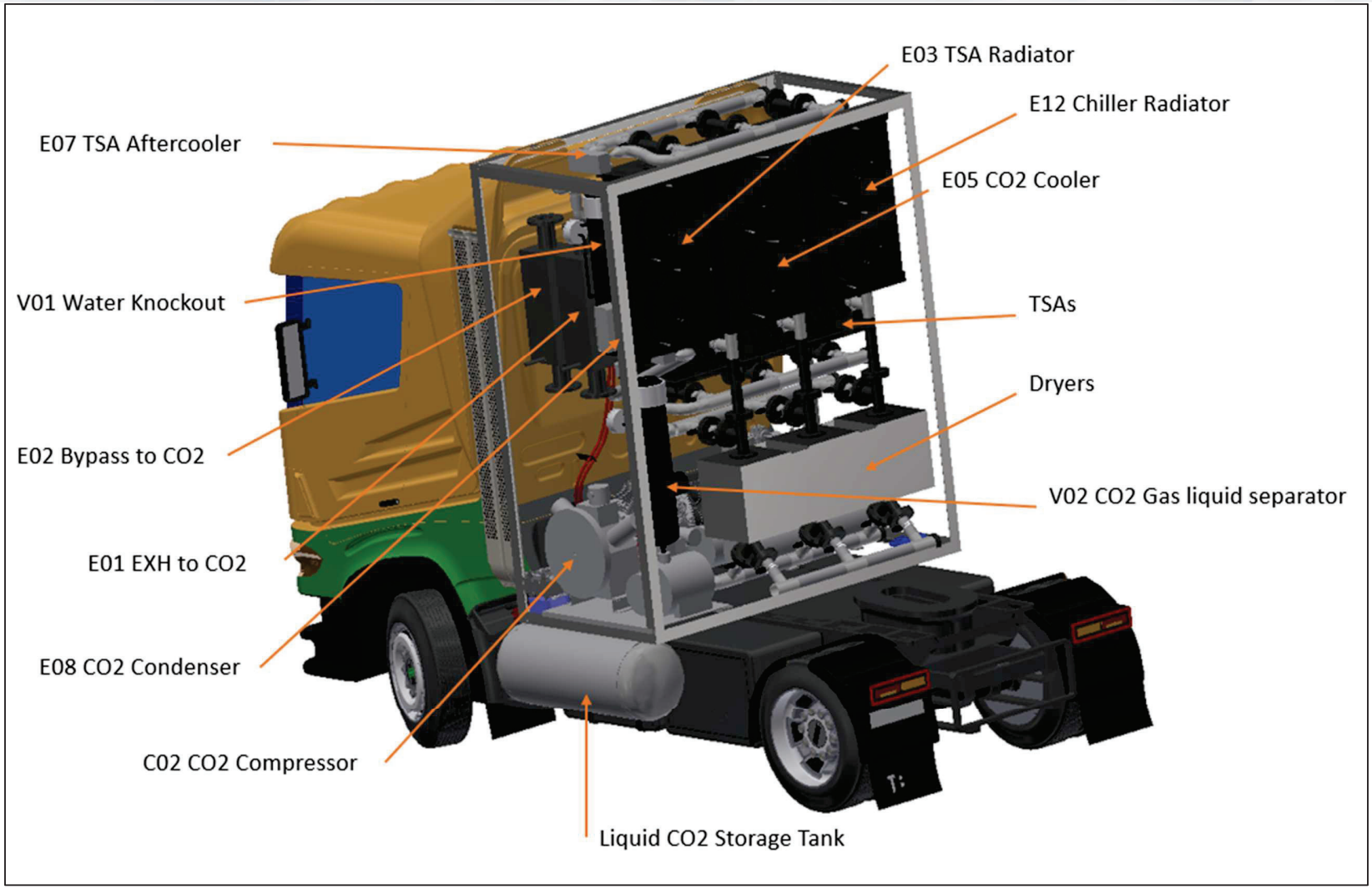

Figure 15 3D Model MCC – View 1

This preliminary layout shows the MCC from a rear view. The exhaust enters from the bottom passenger side. It flows upward through the indirect TSA heating passages and on to the heat exchangers where it is routed back down to a manifold at the top of the dryers. A set of valves opens or closes the path to allow it to flow downward through Dryer A, B or C for regeneration. From the Dryer bottom discharge manifold the exhaust gas flows to the heat exchangers, on to the water knockout then to the Boost Blower located near the bottom of the MCC. The blower outlet discharges to a manifold at the bottom of the Dryers where a series of valves direct the flow to Dryer A, B or C for upward Adsorption. The exhaust flows out the top of the Dryers during Adsorption into a manifold where a series of valves directs it to a cooling heat exchanger and into the bottom of the TSAs for upward Adsorption. The exhaust gas will exit the top of the Adsorption unit, travel through a manifold to a heat exchanger and travel downward through a TSA for Cooling. Leaving the bottom of the Cooling TSA the gas will be cooled one last time before traveling downward through a Dryer that is in the Cooling cycle, and it will exit the bottom of the Dryer and be vented.

Cooling air passages through the MCC will be designed during the Detailed Design Phase. It is envisioned the air will enter through scoops on the from top of the MCC, travel across the top of the TSAs and into the fan driven air cooled radiators across the top of the rear of the MCC where the air will exit the system.

The chiller system will consist of a compressor with R1234YF as a working fluid. The R1234YF will cool a water-glycol mixture which will circulate around the system. Most of the cooling power from the water-glycol mixture is necessary to liquefy the CO_2 and then it is used for cooling the exhaust gas to provide additional water removal before the Dryer. More detail on heat transfer can be found in Annex B.

The following two figures provide additional views of the components for the preliminary layout.

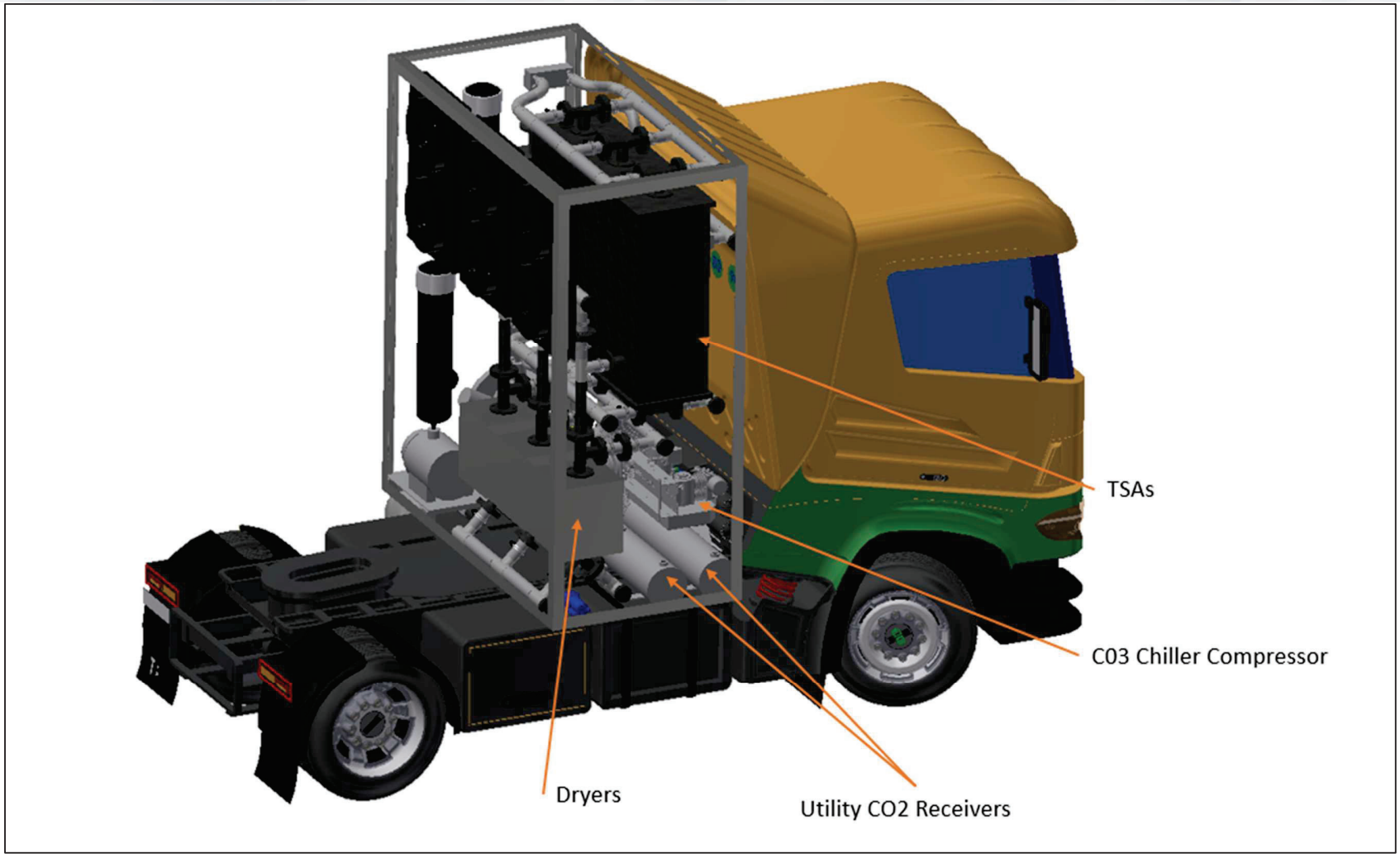

Figure 16 3D Model MCC – View 2

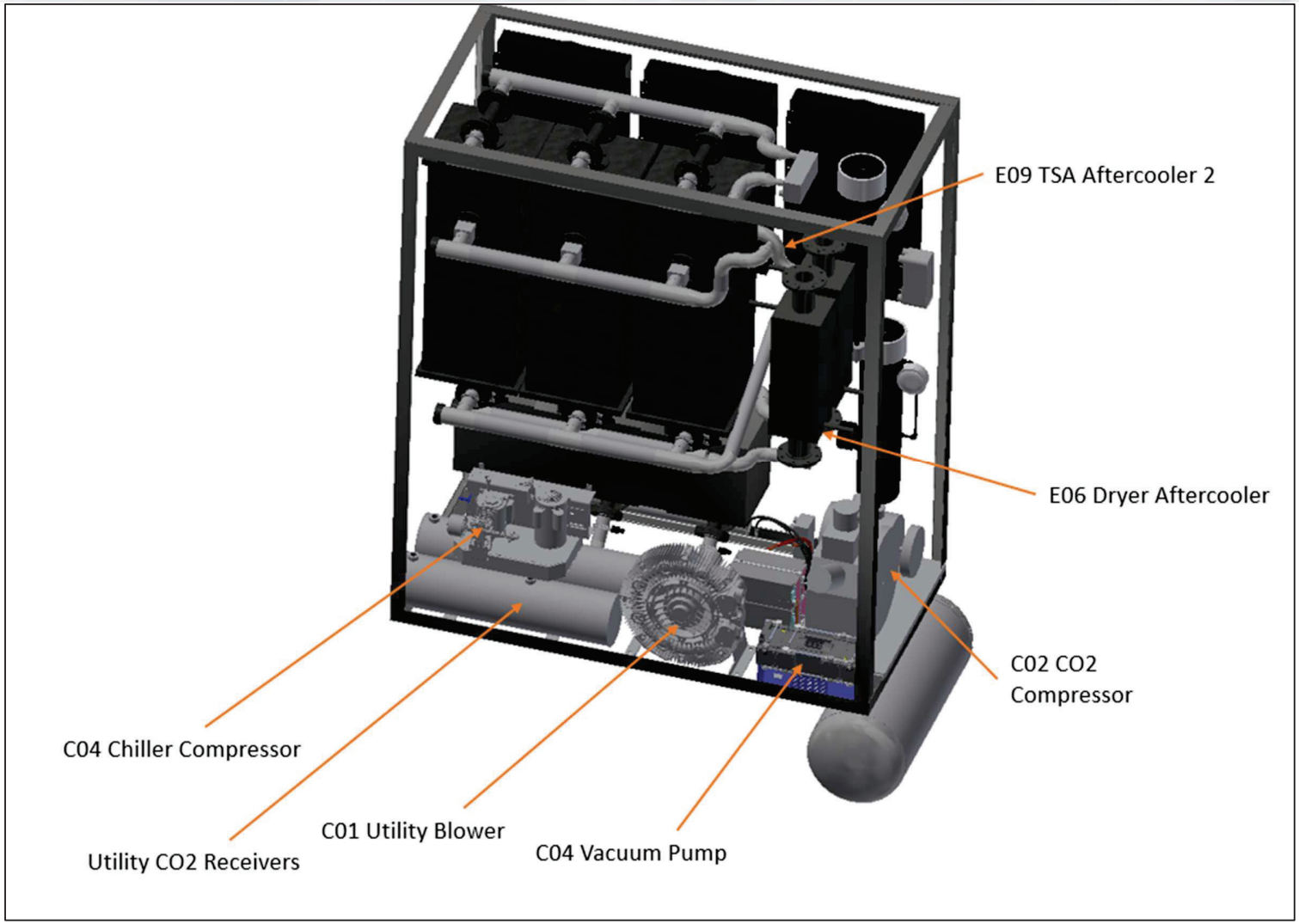

Figure 17 3D Model MCC – View 3

MCC ECONOMICS

This section estimates the mass-produced cost of the MCC and the levelized cost of capture based on the provided cost categories and assumptions. The levelized cost of capture is the average cost of capturing one ton of CO_2 over the lifetime of a carbon capture project: it includes mass-produced MCC kit cost, CO_2 discharge, CO_2 transportation, and operating costs. Every component includes sensitivity ranges to take into account the uncertainties.

The levelized cost of the MCC follows the below equation:

$$\mathrm{LCOC_{MCC}} = \frac{\text{MCC kit Cost} + \mathrm{CO_2}\ \text{Discharge} + \mathrm{CO_2}\ \text{Transport.} + \text{Operating Cost}}{\text{Total } \mathrm{CO_2}\ \text{capture}}$$

Total CO_2 capture per MCC

To start with, the amount of CO_2 captured by each MCC shall be calculated to quantify the total captured CO_2 of the MCC over its lifetime. The lifetime of each device is 15 years which is the standard lifetime of mechanical parts.

Below is the yearly CO_2 capture of each MCC:

- **Zeolite MCC**: 2.6 [kg/hr] * 2000 [hr/yr] = **5.2 tons/year**
- **MOF-Dry MCC**: 10.3 [kg/hr] * 2000 [hr/yr] = **20.6 tons/year**
- **MOF-Wet MCC**: 5.6 [kg/hr] * 2000 [hr/yr] = **11.2 tons/year**

Below is the CO_2 capture of each MCC over its lifetime:

- **Zeolite MCC**: 5.2 [tons/year] * 15 [years] = **78 tons CO_2**
- **MOF-Dry MCC**: 20.6 [tons/year] * 15 [years] = **309 tons CO_2**
- **MOF-Wet MCC**: 11.2 [tons/year] * 15 [years] = **168 tons CO_2**

Mass-produced MCC kit cost

The cost of a mass-produced MCC kit—based on an annual production exceeding 1,000 units—has been estimated using a triangulated approach that combines insights from literature, two years of industry experience, and direct input from equipment manufacturers, suppliers, and domain experts.
To structure the cost calculations, the MCC kit has been broken down into its core functional components. Each sub-category corresponds to major pieces of equipment required for the system to operate. These components, many of which have already been described in the technical section above, include:

- Adsorbent
- Heat Exchangers
- Compressors
- Chiller
- TSAs Units
- Dryers
- Storage Tank
- Controls & Instrumentation
- Piping & Valves

In addition to equipment costs, the calculation accounts for manufacturing-related costs that are essential for final integration and delivery of the kit:

- Labor/Final Assembly
- Packaging

Given the early stage of industrialization and variability in supply chains, we have modelled three cost scenarios to reflect uncertainty in input prices, economies of scale, and technological maturity:

- Minimum Scenario
- Average Scenario
- Maximum Scenario

The spread between these scenarios is not uniform but varies by component. It is determined by a certainty index (Low, Medium, High), detailed in the Excel sheet in the Complementary Information folder, which assigns a specific percentage range to each component based on the level of confidence in its cost estimation with the triangulated approach. This allows for a more nuanced and realistic assessment of potential cost fluctuations across the MCC kit.

Below are the calculated mass-produced MCC cost (without maintenance):

- **Zeolite MCC**:
  - Minimum: 29,900€
  - Average: 35,530€
  - Maximum: 41,150€

- **MOF-Dry MCC**:
  - Minimum: 43,660€
  - Average: 51,303€
  - Maximum: 58,950€

- **MOF-Wet MCC**:
  - Minimum: 28,010€
  - Average: 33,070€
  - Maximum: 38,130€

The detailed cost estimates are provided in the Excel sheet in the Complementary Information folder.

Discharge cost

The Discharge Cost includes the cost of the ground storage tank with its auxiliaries (valves, transfer pump, etc.). The total cost of the ground storage tank including the transfer pump is around 70'000€ for a 20-ton storage (based on quotations with Chart Industries, Inoxcva, All Cryo, Pentair), and 120'000€ for a 50-ton storage tank. Their lifetime is around 20 years.

$$\text{Cost}_{\text{Discharge}} = \frac{\text{Ground Storage Cost}}{(\text{CO}_2 \text{ storage capacity} * \text{number of discharges in Lifetime}) * \text{Lifetime}}$$

Based on our optimization sheet for CO_2 handling that calculated several scenarios across different projects, we found out that the optimal point between CAPEX investment vs. CO_2 logistics trips is to discharge the liquid CO_2 every **3 weeks to 1 month.** Therefore, we take 1 month as baseline scenario for discharging out the liquid CO_2 from the ground storage tank. It gives us an annualized cost :

- The Annualized cost is 10-15 €/ton CO_2

CO_2 Transportation to the consumer cost

In Europe, liquid CO_2 is mainly transported via road trucks (short distances: <500 km roundtrip on average) and rail/ship (longer distances: between 500 km to 1500 km), with pipelines gaining traction for CCS but still not in place in Europe.

Truck

The CO_2 Transportation includes the cost of contracting a third-party to take the CO_2 via trucks and to send it for end-use or storage. The following Tables shows the calculations that we performed and was validated with our 3PL strategic partner.

Component	Cost Range (€/year)	Notes
Truck/ Lease	25,000€ – 50,000€	Depends on size, countries.
Maintenance	4,000€ – 8,000€	Includes inspections, ADR compliance.
Insurance	2,000€ – 5,000€	Higher for ADR compliancy
Total Fixed Cost	**31,000€ – 63,000€/year**	Per truck.

Component	Cost Range	Notes
Fuel (Diesel)	0.35€ – 0.50€/km	Assumes 25–30 L/100km consumption.
Driver	0.20€ – 0.35€/km	
Tolls/Road Taxes	0.10€ – 0.30€/km	Varies by country
Total Variable Cost	**0.65€ – 1.15€/km**	

Total cost of transport per ton of CO_2

Formula:

$$CO_2\text{Transport.} = \frac{\text{Fixed Costs} + (\text{Variable Costs} * \text{Distance})}{\text{Payload (tons)}}$$

Example for 500 km roundtrip:

- Fixed Costs (annual): 31,000€ ÷ 200 trips/year = **155€/trip**.
- Variable Costs: 0.65€/km × 500 km = **325€**.
- Total Cost/Trip: 155€ + 325€ = **480€**.
- Cost per Ton: 480€ ÷ 20 tons = **24€/tCO₂**.

Cost Ranges by Distance

Distance	Cost per tCO_2 (€)
100 km	11€ – 21€
300 km	17€ - 33€
500 km	24€ - 44€

The cost varies between 11€ per ton CO_2 for 100 km roundtrip up to 44€ per ton CO_2 for 500 km. These estimates align with well-documented studies and reports that we can find online and that were also used during the master project (K. Stolaroff, 2021), (Roads2removal, 2023).

- The Transportation cost is between 0.05-0.21€/(tCO_2*km).

Other operating cost

The other operating cost includes the additional fuel consumption to run the system. The calculations for each MCC are presented below:

- **Zeolite-based MCC**: 1.5 [€/kg_{diesel}] * 0.17 [kg_{diesel}/kW_{mech}] * 0.9 [kW_{mech}/kW_{elec}] * 29.31 [kW_{elec}] * 2000 [hr/year] = **13,450 €**

- **MOF-Dry MCC**: 1.5 [€/kg_{diesel}] * 0.17 [kg_{diesel}/kW_{mech}] * 0.9 [kW_{mech}/kW_{elec}] * 42.73 [kW_{elec}] * 2000 [hr/year] = **19,610 €**

- **MOF-Wet MCC**: 1.5 [€/kg_{diesel}] * 0.17 [kg_{diesel}/kW_{mech}] * 0.9 [kW_{mech}/kW_{elec}] * 20.11 [kW_{elec}] * 2000 [hr/year] = **9,230 €**

N.B: Assumed bulk diesel price of 1.5 €/kg (average value across European countries, Q1 2025).

Therefore, we can calculate the Levelized Cost of Capture (LCOC) as follows:

Zeolite-MCC

Category	Certainty	Average Cost	Qty	Min Cost	Max Cost
Capture Hardware	Medium	614€/tCO_2	1 Unit	498€/tCO_2	710€/tCO_2
Discharge Station	High	12€/tCO_2	1 Unit	10€/tCO_2	15€/tCO_2
CO_2 Transportation	High	39€/tCO_2	300 km	15€/tCO_2	63€/tCO_2
Other Operating cost	High	2'586€/tCO_2	Diesel	2'586€/tCO_2	2'586€/tCO_2
LCOC		**3'251€/tCO_2**		3'109€/tCO_2	3'374€/tCO_2

MOF-Dry MCC

Category	Certainty	Average Cost	Qty	Min Cost	Max Cost
Capture Hardware	Medium	270€/tCO_2	1 Unit	208€/tCO_2	319€/tCO_2
Discharge Station	High	12€/tCO_2	1 Unit	10€/tCO_2	15€/tCO_2
CO_2 Transportation	High	39€/tCO_2	300 km	15€/tCO_2	63€/tCO_2
Other Operating cost	High	952€/tCO_2	Diesel	952€/tCO_2	952€/tCO_2
LCOC		**1'273€/tCO_2**		1'185€/tCO_2	1'349€/tCO_2

MOF-Wet MCC

Category	Certainty	Average Cost	Qty	Min Cost	Max Cost
Capture Hardware	Medium	355 €/tCO_2	1 Unit	261 €/tCO_2	417€/tCO_2
Discharge Station	High	12€/tCO_2	1 Unit	10€/tCO_2	15€/tCO_2
CO_2 Transportation	High	39€/tCO_2	300 km	15€/tCO_2	63€/tCO_2
Other Operating cost	High	824 €/tCO_2	Diesel	824 €/tCO_2	824 €/tCO_2
LCOC		**1'230€/tCO_2**		1'110€/tCO_2	1'319€/tCO_2

Analysis

The initial scope of the feasibility study was to assess whether MCC using 3 different types of sorbent: Zeolite, MOF-Dry, and MOF-Wet with liquefaction on-board are technically and economically feasible for integration into Scania's strategy to increase the green portfolio solutions for their trucks best seller.

While this is technically feasible, the amount of captured CO_2 is too low to provide a cost-competitive solution: the break-even point is to sell the liquid CO_2 at a price of 3'251€/tCO_2 for Zeolite-MCC, 1'273€/tCO_2 for Dry-MOF and 1'230€/tCO_2 for Wet-MOF.

While it appears that even if the MOF-cost are prohibitively high today, current cost projections from 5-50€/kg for 1k ton production scale tend to give some perspectives for the use of MOFs for MCC.

Breaking down the cost of capture per ton of CO_2, there are two main reasons for the high costs.

(1) Massive extra fuel consumption in "other operating costs" which is the biggest cost block. This is due to the electrical consumption of the MCC unit which is supplied by the engine through PTO, and finally translated into extra fuel consumption.

(2) Low amount of "net" CO_2 capture rates. This is a major factor as it directly affects the cost per ton of captured CO_2. There are two reasons for the low capture rates. Space constraints for installation of MCC unit limits the gross CO_2 capture rates. And considerable amount of extra CO_2 released due to the extra fuel consumption.

This means that extra fuel consumption to supply the electrical power, plays a massive role in increasing the cost per ton of captured CO_2. Further attention to the details shows that about 80% of the electrical power consumption of the MCC is for on-board liquefaction of CO_2 and regeneration of TSA. This immediately made Qaptis team to think of an alternative MCC technology that we are developing for smaller vehicles (passengers and vans). For easier communication, we call this concept Design B in this report.

In this concept, the on-board MCC is targeting the purification and capture of CO_2, while the ground discharge system provides the regeneration of the adsorbent, CO_2 liquefaction and its storage. Figure below illustrates the differences between the two design concepts.

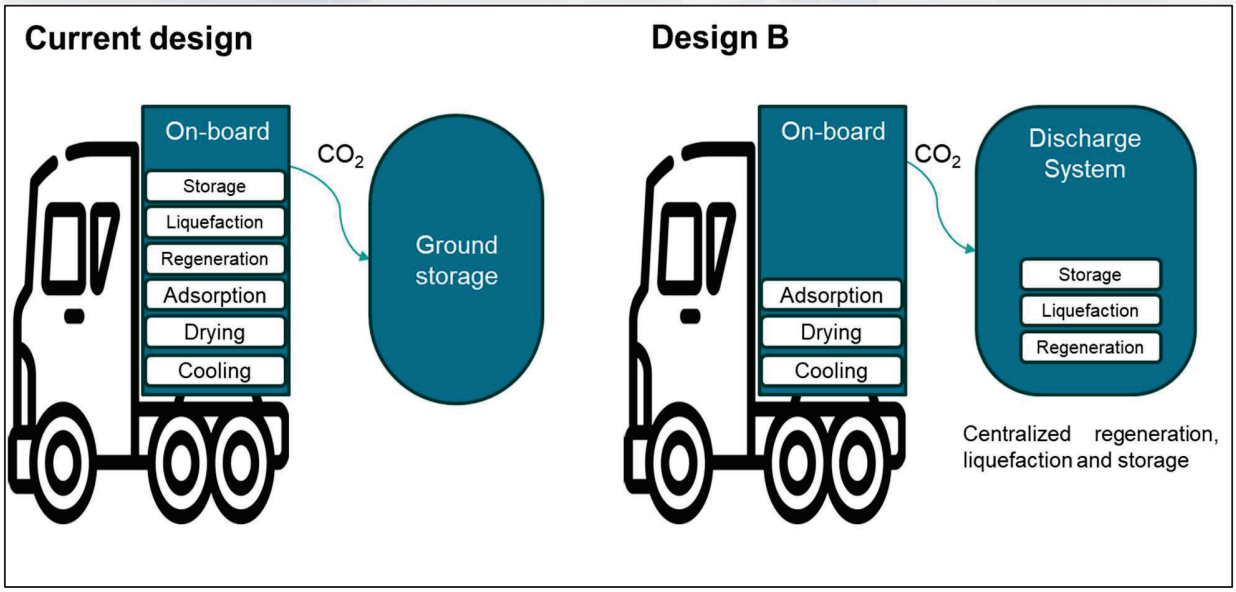

Figure 18 Comparison of Design B concept

We eliminate the regeneration and liquefaction systems from the MCC which eliminates about 80% of on-board power consumption. This will help to drastically reduce the cost of capture per ton of CO_2 in two ways.

(1) Reducing the extra fuel consumption by 80% and therefore "other operating costs".

(2) Reaching much higher "net" CO_2 capture rates since the added CO_2 emissions from extra fuel consumption is much lower.

There are few considerations with Design B which are presented below:

This concept comes with its own limitations too. The lack of regeneration unit means that the CO_2 capture rates are solely defined by the amount of adsorbent on board and their CO_2 uptake rates. This means that the capture rate might be very limited depending on the application. This is the main reason that Qaptis was considering this concept mainly for small emitters. On the other hand, there will be more room available on-board which can be used to increase the size of adsorption tanks and amount of adsorbents which consequently increases the CO_2 capture rate.

This concept requires a more advanced discharging station on the ground. While it does not require high-tech components, this increases the cost of capture per ton of CO_2 borne by the discharging system. Regeneration unit,

liquefaction unit, and the high pressure storage tanks are well established technologies that can be supplied by off-the-shelf products.

In addition, the MCC power consumption is shifted from on-board to the discharging system. However, we cannot compare the power level of the two cases directly. On-board, the adsorbents go through multiple cycles of adsorption and regeneration, over an 8 to 10 hours of operating time. In Design B, the adsorbents go through regeneration once, while the discharging time is in the range of 30 to 60 minutes. Overall, the energy consumption for regeneration of adsorbents is expected to be lower in Design B.

Since the regeneration and liquefaction takes place in discharging station, we can utilize green energy production on the ground such as wind or solar, instead of burning fuel. This way, overall CO_2 emissions of the system will be considerably reduced. We are currently building the Life Cycle Analysis for this concept for a more accurate comparison.

Finally, by using centralized regeneration and liquefaction units we can expect a lower overall cost for these units since we are benefiting from the economy of scale. Instead of having many of such units on board of many vehicles, we end up with a single larger unit per several vehicles.

Since Design B was out of scope for this project, it has been decided not to pursue the full design of this concept for trucks. However, at Qaptis we came to the conclusion that considering the adaption of this concept for trucks is a major output for this project, we decided to provide a preliminary insight.

To investigate the consideration that were discussed above, we adapted the on-board MCC and discharging system for the truck application for both Zeolite and Mg-MOF-74 according to Design B. In both cases, we can further increase the CO_2 uptake and release of the adsorbent, since we are not restricted by on-board conditions. In the case of MOF, this has major impact in reaching about 24 wt% of CO_2 working capacity. This is a massive improvement compared to initial working capacities of less than 14 wt% we observed previously for MOF. This shows that Design B maximizes the advantage of using MOF versus Zeolite. The isotherms for Mg-MOF-74 is in the figure below.

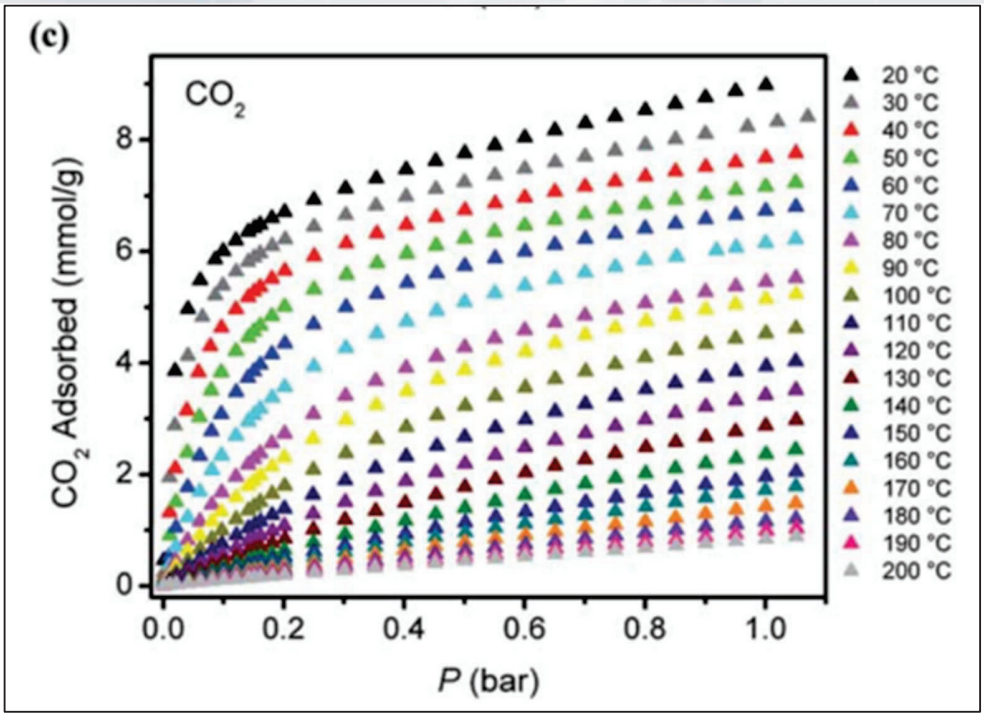

Figure 19 Mg-MOF-74 isotherm

To use this graph, we locate the temperature and pressure of adsorption and regeneration on the plot. The pressure in the case of adsorption is partial pressure of CO_2 in the stream (volumetric or molar percentage of CO_2), and in the case of regeneration it is the pressure of the tank under vacuum. We set the adsorption temperature at 20 °C and regeneration at 130 °C. The difference between the Adsorbed CO_2 (Y axis) for adsorption and regeneration represents the CO_2 working capacity. Considering the 44 gr/mmol of CO_2, one can calculate the CO_2 working capacity as percentage of the weight of adsorbent.

$$\mathrm{CO_2\ working\ capacity\ [wt\%]} = (\mathrm{CO_2}_{Ads.} - \mathrm{CO_2}_{Reg.})\left[\frac{mmol}{g}\right] * 44\left[\frac{g}{mol}\right] * \frac{100\ [wt\%]}{1000\ [\frac{mmol}{mol}]}$$

Considering the high level of CO_2 working capacity for Mg-MOF-74, we present the corresponding results in this report. The process flow diagram is shown in the figure below.

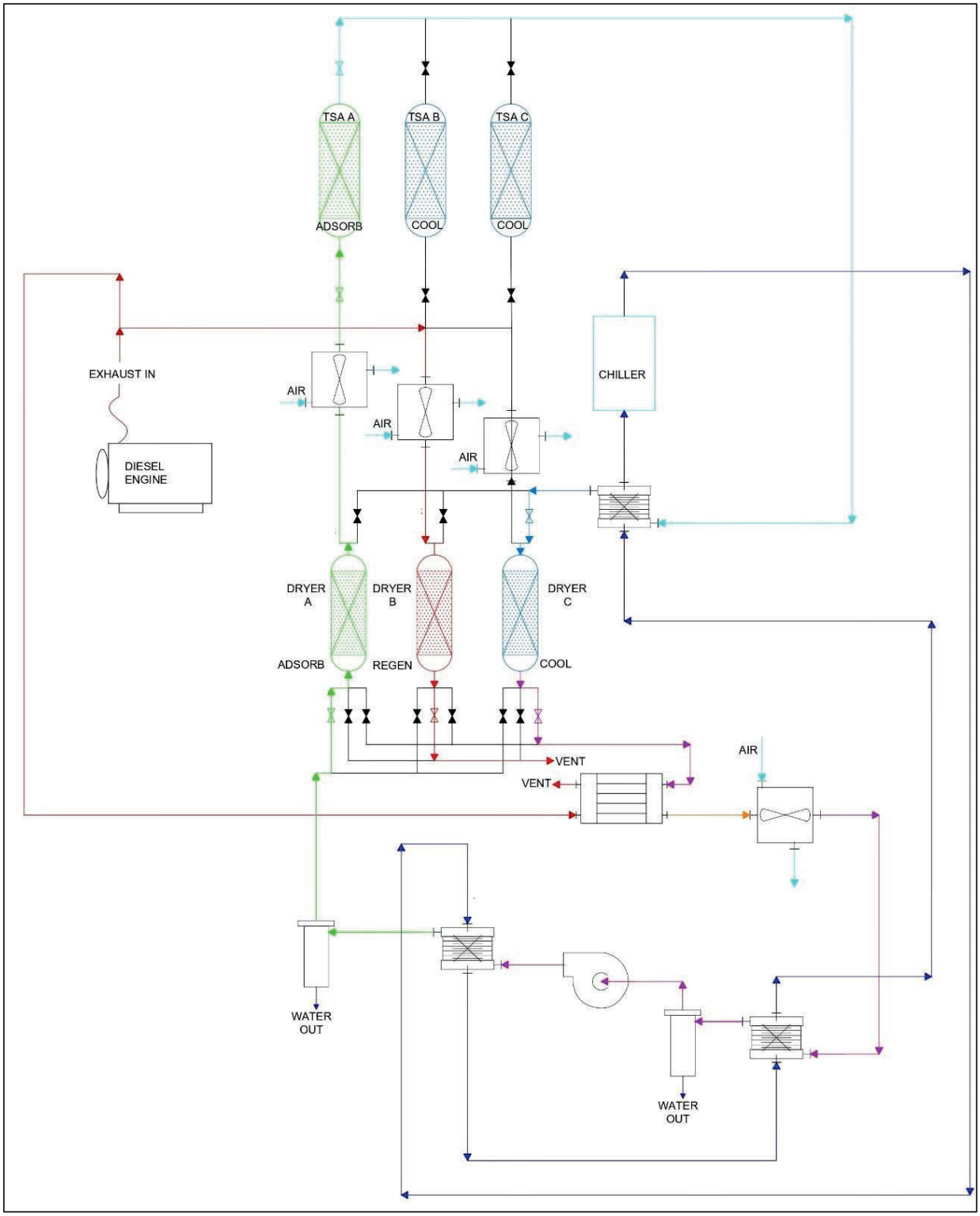

Figure 20 MCC Design B

The exhaust gas goes through air coolers and a chiller to maximize the moisture removal before entering the dryer and reaching the adsorption temperature. The remaining moisture is trapped in the dryer and the remaining gasses go to the adsorption tank. The CO_2 is adsorbed on the MOF and the purified air is vented to the environment. The captured CO_2 will be removed by using the regeneration system from the discharging system that is on the ground. Since we are currently writing the patent application for discharging system, we did not include its design in this report.

Another interesting point in this case is the regeneration of the dryers. In the initial design, we use the energy in the exhaust gas to regenerate the dryers and TSA tanks. This could be challenging as under some operational conditions where the temperature of the exhaust gas was too low. This concern is much less in the picture with Design B. Since the energy required for regeneration of the dryers is much less than the TSAs. Based on our preliminary calculation, an energy storage of between 5 to 10 kWh can cover the energy for operational conditions where the temperature of the exhaust is too low. This becomes very important knowing that, based on our recent investigations, one of the main reasons for the failed pilots of Remora Carbon, was due to the inability to run the system when the exhaust temperatures were low, under dynamic behavior of the engine in operational conditions.

Based on the results, Design B with Mg-MOF-74 can capture about 30 kg/hr of CO_2 with the maximum limit of 300 kg captured CO_2 before it needs to be discharged. Considering the 55 kg/hr of CO_2 in the exhaust gas stream for the design point, this represents 55% gross capture rate. This is slightly lower than the case of MOF-Dry, and considerably higher than the cases of Zeolite and MOF-Wet that was presented earlier.

Point 1: We realized that Design B is restricted by the weight constraint (2.9 tons) in contrast with the original design which was constrained by the volume available on board. This means that the size of the MCC unit with Design B will be slightly smaller than the original design.

Point 2: Another important point here is again about the dynamic behavior of the engine in operation. In the original design, if the temperature of the exhaust gas is lower than a threshold, the MCC unit is not able to capture the CO_2. While it was out of the scope for this project, this is a source of concern since a considerable amount of time, the truck seems to be working in such ranges. However, in Design B this concern is eliminated since we do not need the energy from the exhaust gas to regenerate the TSA and as earlier

explained, there is a solution to keep the dryers running even if the temperature of exhaust gas drops. This makes Design B considerably more robust.

The power consumption of Design B is also much lower. Design B requires about 6 kW of power. For similar comparison, with slightly higher gross capture rate the MOF-Dry requires 42.7 kW of power.

Component	Power [kW]
C-03 Chiller Compressor	2.00
C-05 Boost Blower	1.85
F-06 Fan TSA Aftercooler	0.21
F-07 Fan CO_2 Air Cooling	0.60
F-08 Fan Chiller Air	0.21
P-01 EGW Pump	0.04
Valves & Controls	0.75
Total kW	**5.66**

By taking into account the extra CO_2 emissions from the power consumption, the net CO_2 capture rate for Design B is about 26.7 kg/hr which is about 48% net capture rate at the design point. This is has a dramatic impact on the cost of capture per ton of CO_2.

Category	Certainty	Average Cost	Qty	Min Cost	Max Cost
Capture Hardware	Medium	146 €/tCO_2	1 Unit	100€/tCO_2	169€/tCO_2
Discharge Station	Medium	28€/tCO_2	1 Unit	23€/tCO_2	35€/tCO_2
CO_2 Transportation	High	39€/tCO_2	300 km	15€/tCO_2	63€/tCO_2
Other Operating cost	High	48 €/tCO_2		48 €/tCO_2	48 €/tCO_2
LCOC		261 €/tCO_2		186 €/tCO_2	315 €/tCO_2

Table of results

Table below presents a summary of the results.

		Zeolite	MOF Dry	MOF Wet	Design B MOF
Capture rate	Gross Capture rate	35%	64%	31%	55%
	On-board power	29 kW	43 kW	20 kW	5.7 kW
	Net Capture rate	4.7%	18.7%	9.6%	48%
Weight	kg	<2900	<2900	<2900	~2900
Volume	cum	~8	~8	~8	<8
Back press.	mbar	120	120	90	75
Unit Cost	€	35 k	51 k	33 k	51 k
Cost of capture	€/tCO_2	3'251	1'273	1'230	261

As it was expected, the total cost of capture per ton of CO_2 is highly dependent on the net capture rate of the system. In this regard, on-board power consumption plays a significant role in cancelling out the effect of captured CO_2 from the exhaust stream. For example, MOF Dry with 64% gross capture rate has the considerably high cost of capture of 1'273 €/tCO_2, due to its massive on-board power requirement. This suggests that independent of the capture technology (solid, amine, PSA, etc.), if the on-board power consumption through the PTO is above 10 kW, reaching economic viability with any technology of choice will be extremely challenging.

In the case of Design B where most or all of the on-board power consumption can be supplied with energy storage such as batteries, the extra emitted CO_2 from the extra burnt fuel can reach close to 0. This can potentially bring the minimum cost of capture per ton of CO_2 as low as 125 €/tCO_2, which enables economic viability based on recent case studies that we have done with our partners such as Friderici Special. It is important to mention that the results for Design B are preliminary and more accurate estimations requires further investigations and improvement of models.

Validation data from Prototype visit

A visit of the prototype in Pittsburgh took place in early July 2025, during which the system was tested. The objective was to showcase some of the operational and technical aspects of the system to Scania team. It is important to mention that the prototype configuration and capacity is different from the designs in this report, due to incorporation of methods to meet the requirements of this project and remain within the constraints that was set. At the same time, we selected some of the performance results of the testing to validate similar conditions that are relevant to this project. We briefly discuss them in this section.

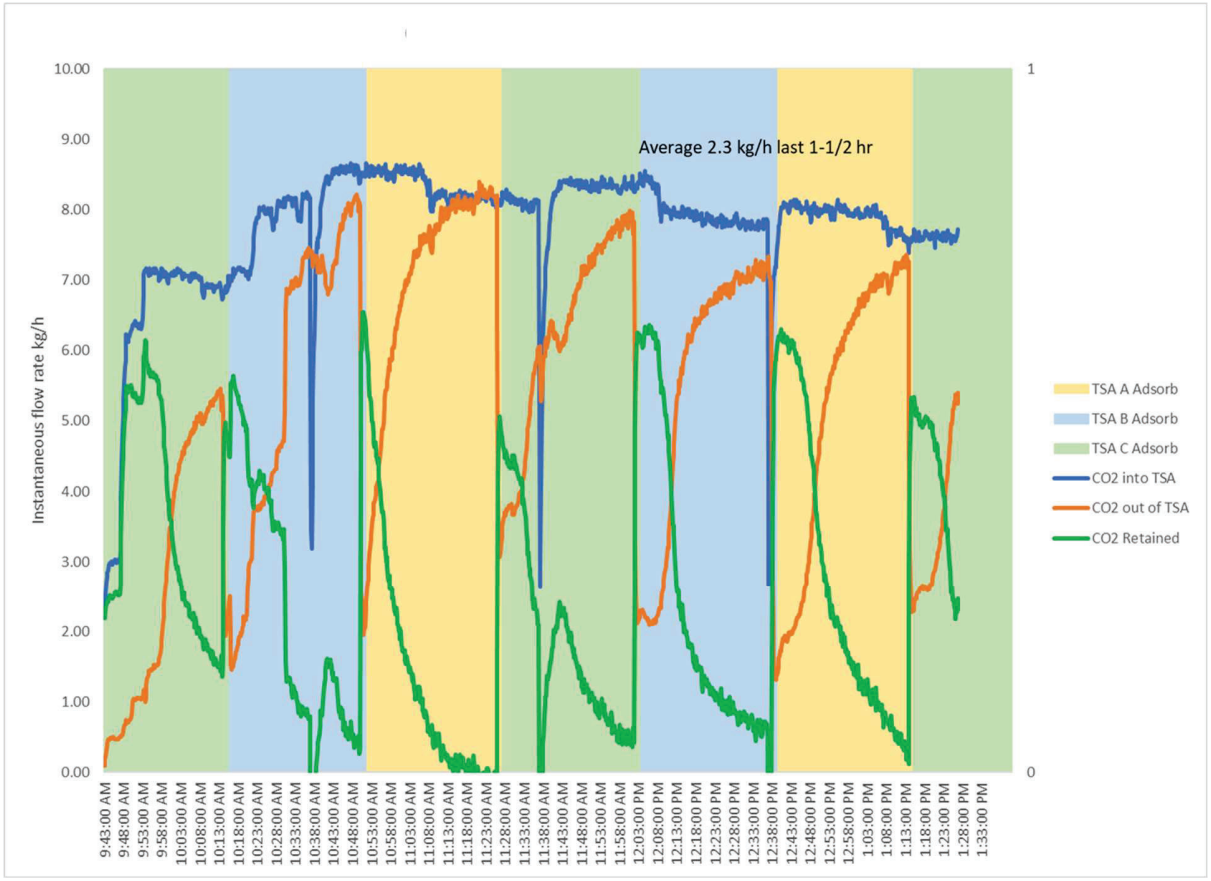

Figure 21 CO_2 balance in adsorption tanks

Figure above, represents the flow rate of CO_2 in the streams into (blue line) and outlet (orange line) of the adsorption tanks. The inlet is the processed exhaust stream right after the dryer, with the aim to remove the CO_2 from it. And the outlet is the air stream that is released to the environment, and ideally we do not want to see any CO_2 in this stream. The amount of CO_2 retained by

the adsorbents in the tank is calculated as the difference between the amount of CO_2 in the inlet and outlet, which is shown by the green line.

The three vertical bands (green, blue, orange) indicates which tank (TSA A, B, and C) is in the adsorption part of its cycle. We can observe that CO_2 is being captured (retained) and regenerated from all three TSAs in each cycle. At the same, it appears that the TSAs are not fully regenerated since we detect CO_2 in the outlet from the very beginning of each cycle, and we keep losing CO_2 in the air that is vented to the environment. This is attributed to multiple causes. First, we are using an indirect heating system in the prototype, which heavily limits the regeneration efficiency. Especially knowing that the thermal conductivity of the adsorbents are extremely low, which creates high temperature gradients. Knowing this obstacle, we have used direct heating technology for the designs presented in this project (check Figure 4). Other contributing factors that adversely affect the CO_2 recovery are high ambient temperature during the tests, and the large size of the exhaust gas source (compressor) for this test which was higher than the maximum capacity of our prototype. Finally, figure below provides the mass concentration of the CO_2 in the inlet and outlet (air to the environment) of the TSAs during the same run.

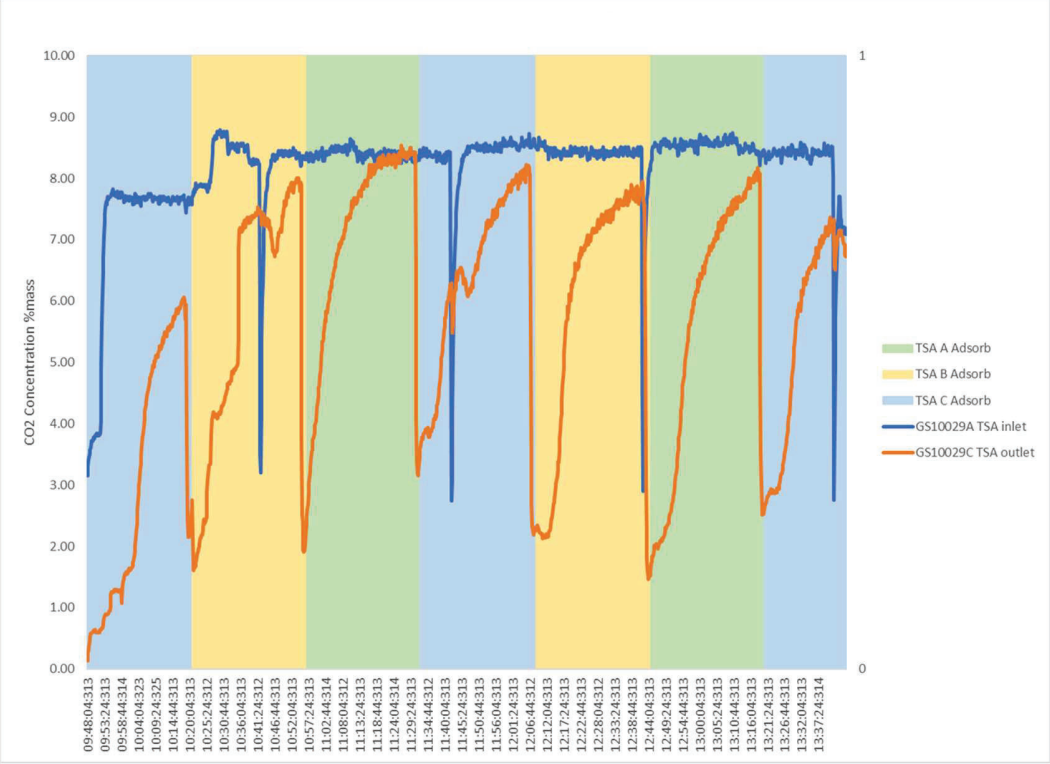

Figure 22 CO_2 concentration in streams to and from TSAs during adsorption

Follow up of the previous point, the figure below shows the readings from 4 thermocouples inside TSA B during the test of 38-minute adsorption cycle. The thermocouples are distributed vertically along the height of the tank. These thermocouples are distances about 2 inches from the surface of the tube bundle that is used for indirect heating with water as thermal fluid.

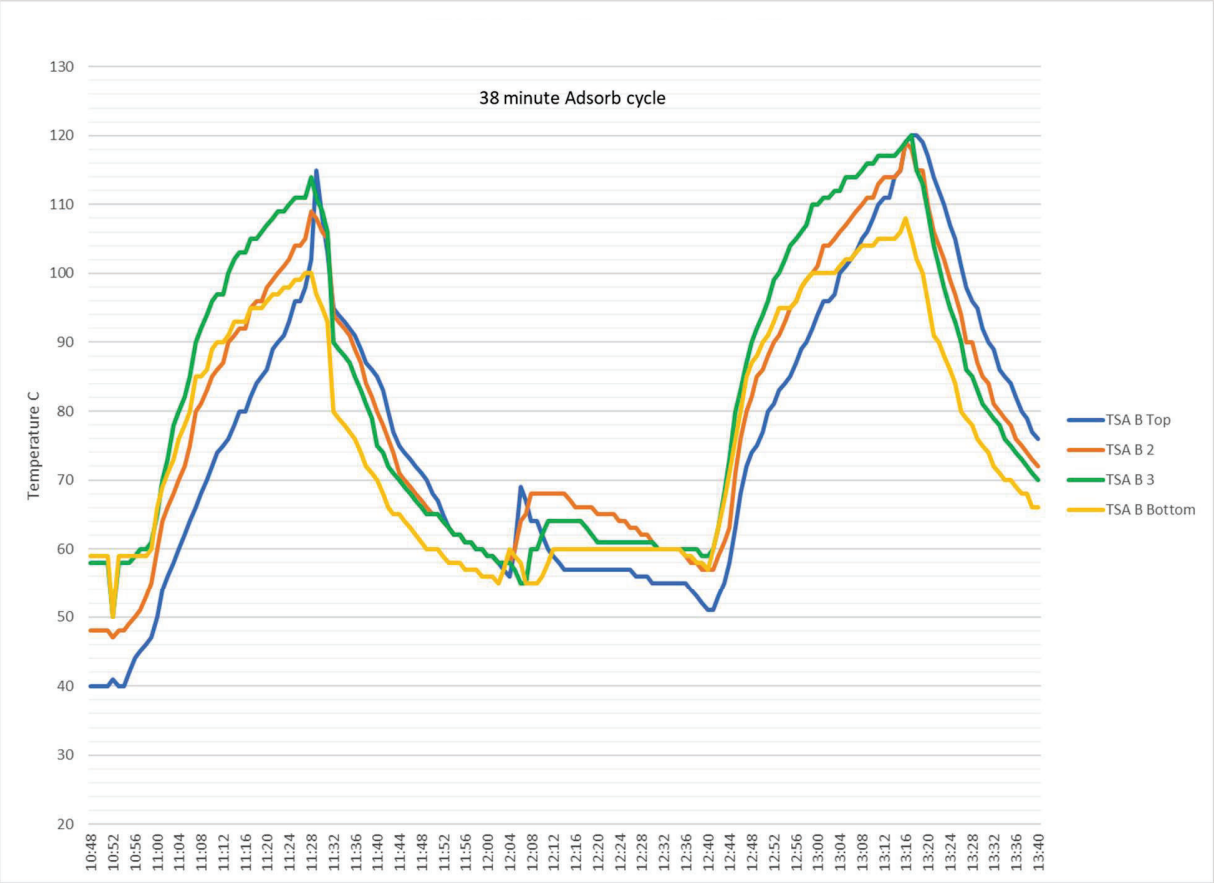

Figure 23 TSA B - adsorbent temperature

During regeneration we are incorporating indirect heating using water that recovers heat from the exhaust gas at the beginning of the process and prior to the dryers. For adsorption, the cooling of the adsorbents is assisted by direct cooling and simply flowing the cold exhaust gas stream that enters the tank for CO_2 capture. As a result we observe a sharper Temperature change for adsorption compared to regeneration. Since this measure has direct correlation with heat transfer rate, we can conclude that shifting to direct heating and cooling technology can significantly improve the performance of the system. This affects variety of targets such as intake capacity, CO_2 capture rate, energy efficiency, etc.

Another important observation is the limit of the temperature level for both adsorption (115 °C – 120 °C) and regeneration (55 °C – 60 °C). The main cause for the adsorption temperature limit are the higher ambient temperature at the day of testing and the fact that some part of the cooling is done indirectly by using cooling water. This reiterates the importance of the ambient temperature as discussed earlier in this report. While we have limited data regarding the effect of ambient temperature on the performance of the systems designed in this project, further investigation is required to better understand the dynamics and extent of this parameter.

On the other hand and in the case of regeneration, the main limiting factor is the incorporation of the indirect heating. To extend further, lets have a look at the temperature of the water (thermal fluid) that is used as heating source during regeneration, figure below.

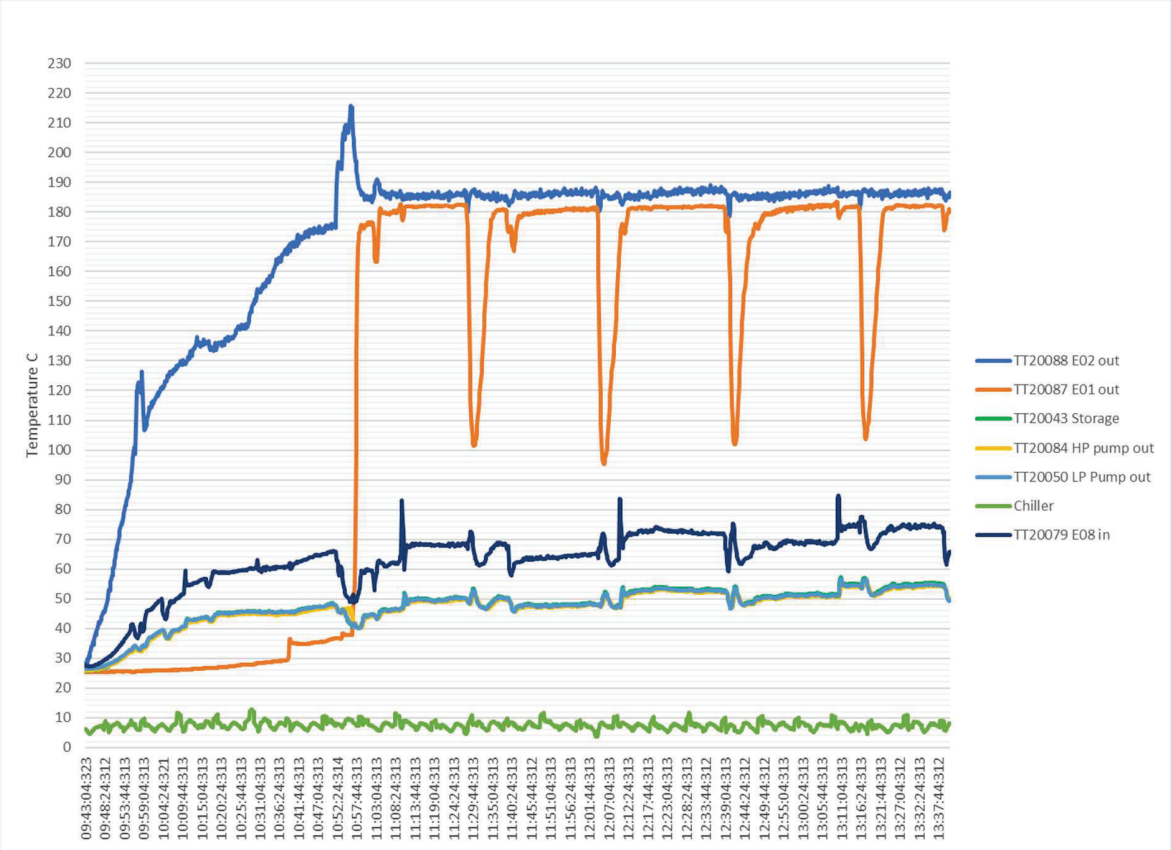

Figure 24 Thermal fluid (water) temperatures throughout the system

E01 out and E02 out shows the temperature of the water at the outlet of heat exchangers that are used to recover the heat in the exhaust gas at the beginning of the process. We can see that they reach well above 180 °C, yet the temperature in the TSA peaks at 120 °C. This is a challenge, since for

regenerating the Zeolites in the TSA, we need temperatures at least above 150 °C. Therefore, we believe that the adsorbents are not properly regenerated during these cycles. Based on our previous data, we know that by increasing the cycle time to 48 minutes, we still observe the ~120 °C temperature peak during regeneration. While the water temperature levels allow us to easily reach temperatures above even 160 °C in the TSA tank, the heat transfer is very inefficient due to the low thermal conductivity of adsorbents. Confirming the necessity of shifting from indirect to a mainly direct heating and cooling system.

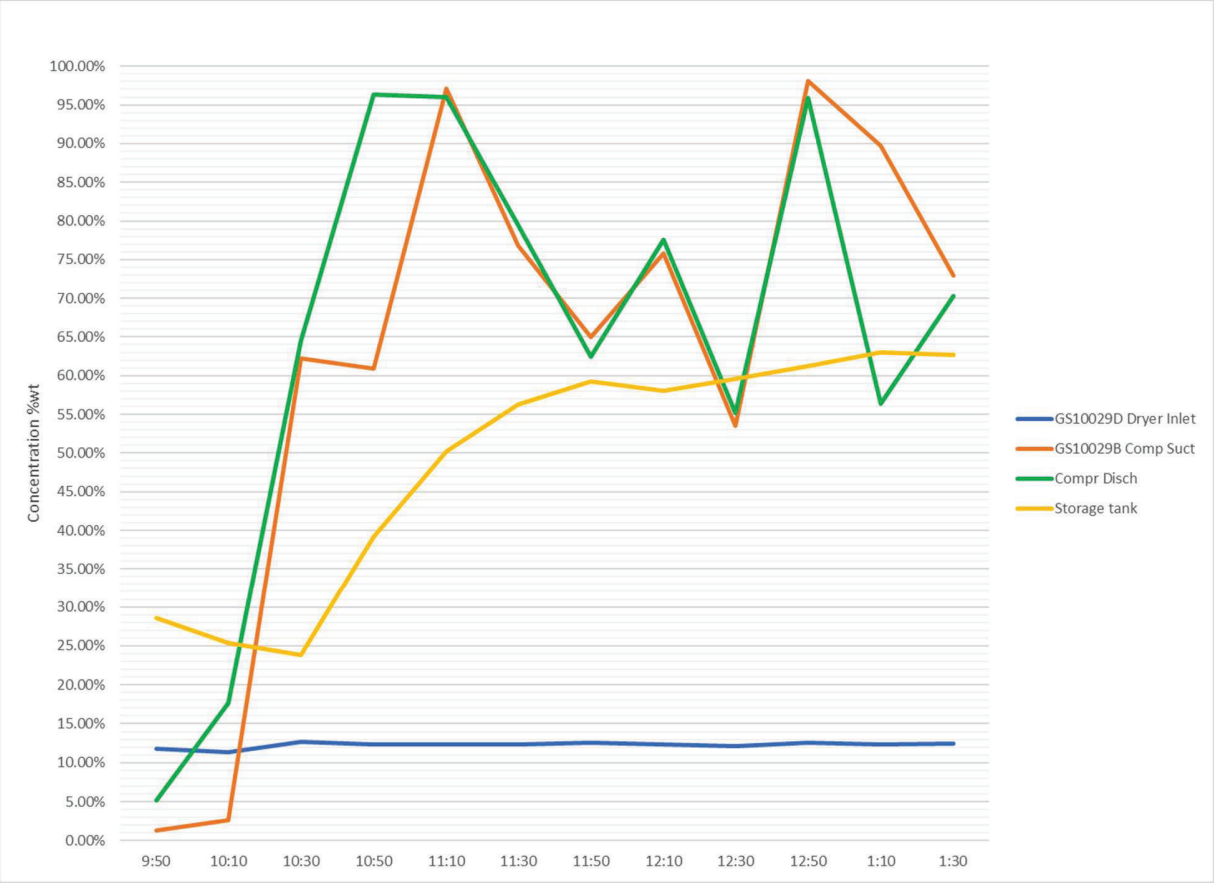

Figure 25 CO_2 concentration measurement

The combination of higher exhaust inlet to the system and high ambient temperature, affects the concentration of the capture CO_2 as shown in Figure 26. We can see the trend in the measured CO_2 wt% at the inlet of the dryer (entering the MCC system), suction and discharge of the compressor (after the TSA), and storage tank. The inlet exhaust contains about 12 wt% of CO_2. While the captured CO_2 shows higher concentrations, it has high fluctuations with a peak at 98 wt%. It is important to mention that this prototype does not purge the TSA prior to releasing the CO_2 in the regeneration phase. Therefore,

the trapped air in the tank is in the mixture of captured gas, and therefore, resulting in high impurities. This causes the major contribution to the low concentration of only 63 wt% CO_2 in the storage tank. By fine-tuning the purge time, we will reach concentration of +97 wt% in the storage tank. This change has been incorporated in all of our designs since the beginning of this year, and prior to the start of this project. The total amount of captured CO_2 during this test about 7 kg at a rate of 4.7 kg/hr. During which the inlet stream to the MCC was 90-100 kg/hr at ~12 wt% concentration of CO_2. See figures below.

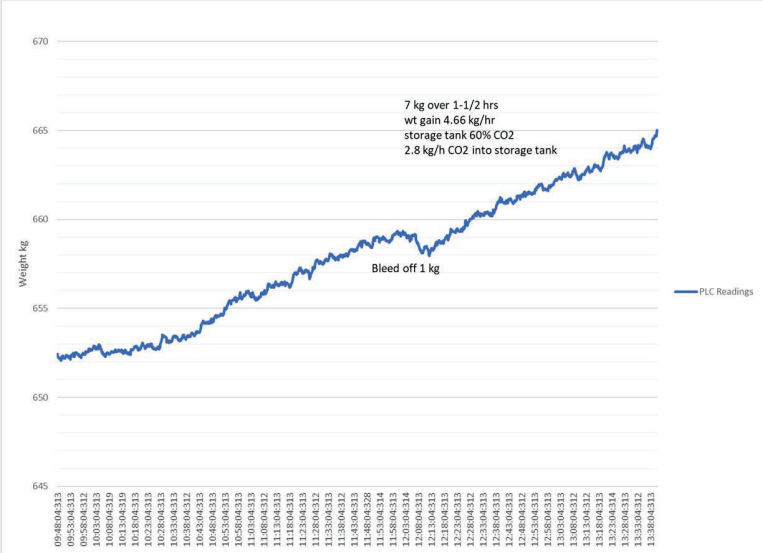

Figure 27 Storage tank's weight

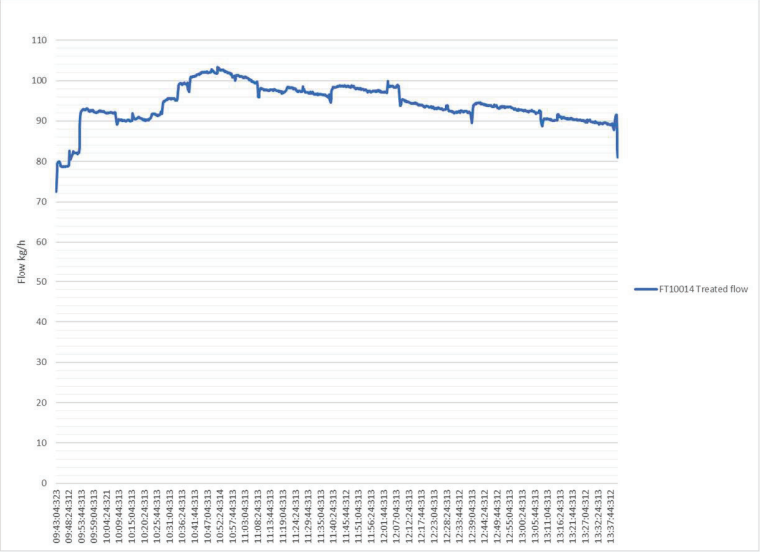

Figure 28 Treated exhaust flow rate

Finally, the performance of the vacuum pump has been tested as shown in Figure . We can consistently reach vacuums below 25 kPa as expected. This is enough vacuum level to remove most of the CO_2 with a direct heating configuration.

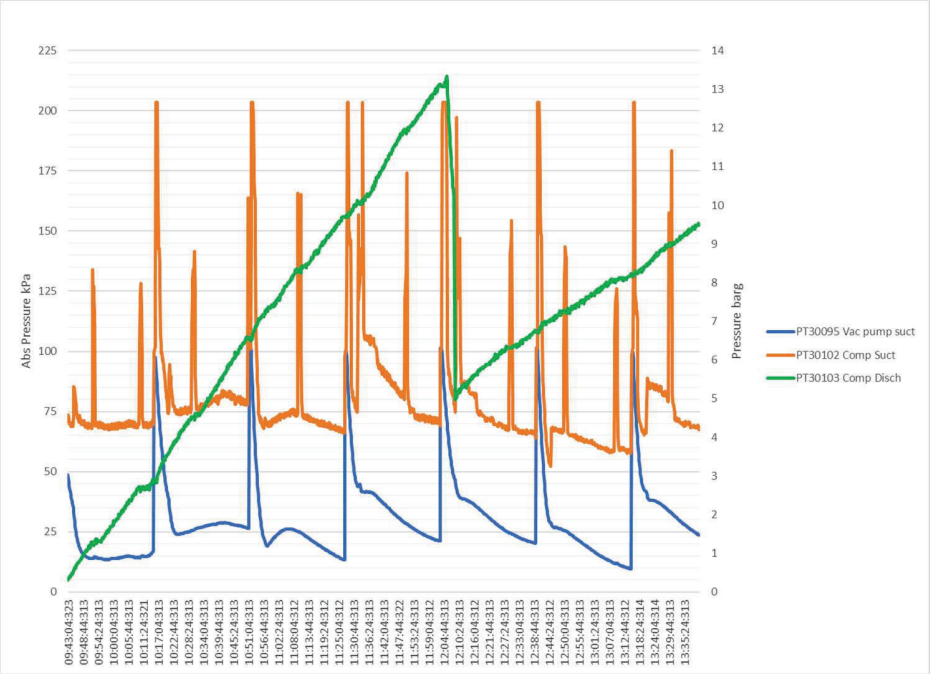

Figure 29 TSA vacuum level

While we summarized the major learnings and validation points from the tests during the visit, there are more detailed points and learnings that can be discussed. Especially regarding the improvements in the designs in this report, compared to the prototype that Scania team visited. And specifically in the case of Design B, which appears to overcome the main challenges of integrating a CO_2 capture system on trucks. It shows the potential for much higher net capture rates and better levelized cost of capture. While the Design is based mostly based on reasonable assumptions and off-the shelf systems, the concept is very novel and we believe that Qaptis is currently the only company developing such system. Therefore, it requires further investigation and development. We can get better insight by comparing the performance of the Design B with other candidates for CO_2 capture on-board of the truck, such as amine-based systems. If the Design B is a competitive system, further investigation can be helpful to evaluate this concept through more detailed development.

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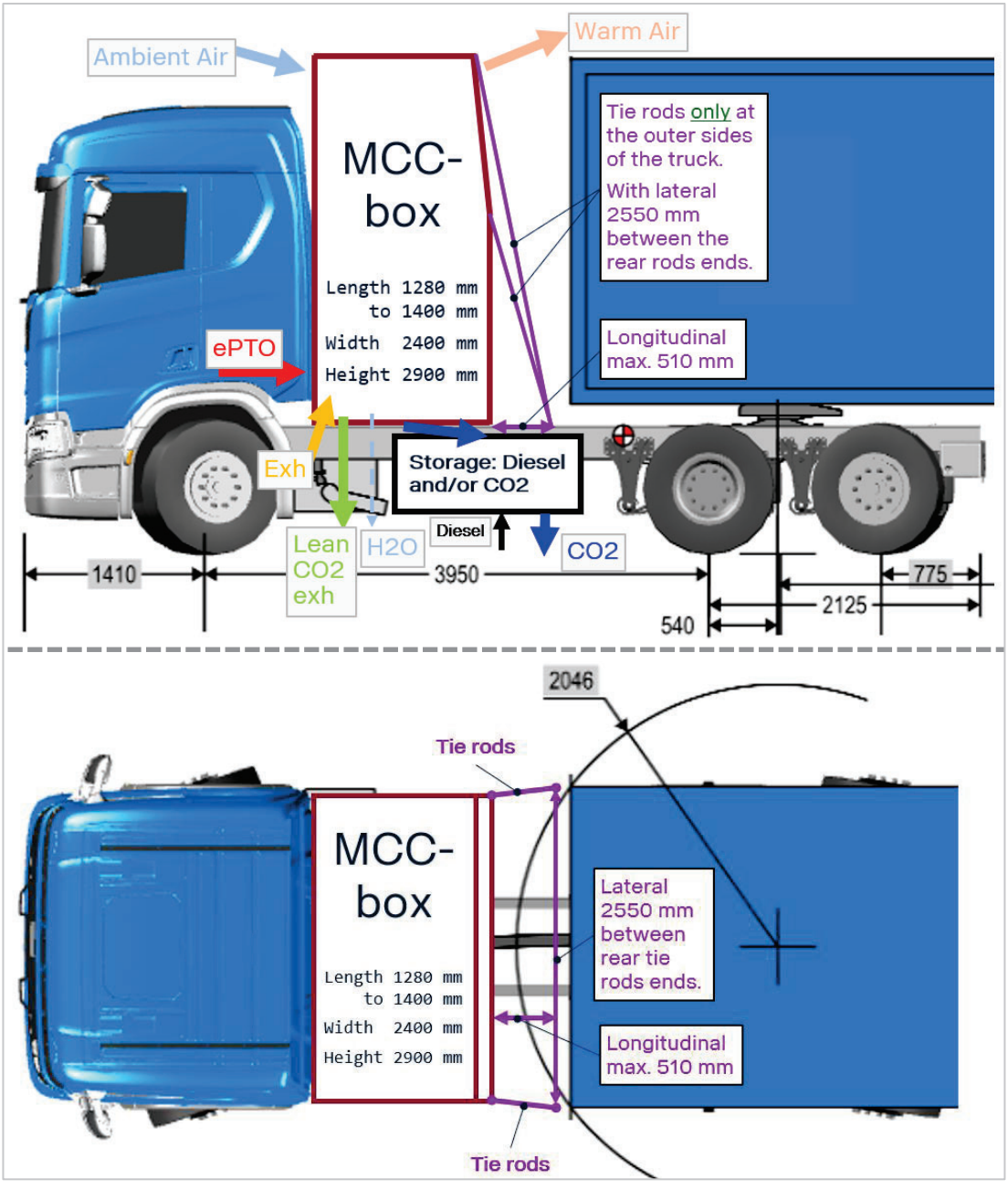
ANNEX A – DESIGN SPECIFICATIONS

Antonius KIES, Scania-EDTP. Jonas ASPFORS, Scania-ENPR. 2025-03-12

Mobile Carbon Capture (MCC) system “Qaptis”: Specifications

European long-haul tractor A6x2*4, legal CO2 subgroup 10-LH. Axle distance (AD) 3950 mm. Distance between MCC-box rear and trailer front according to ISO 1726, see here endnote [i].

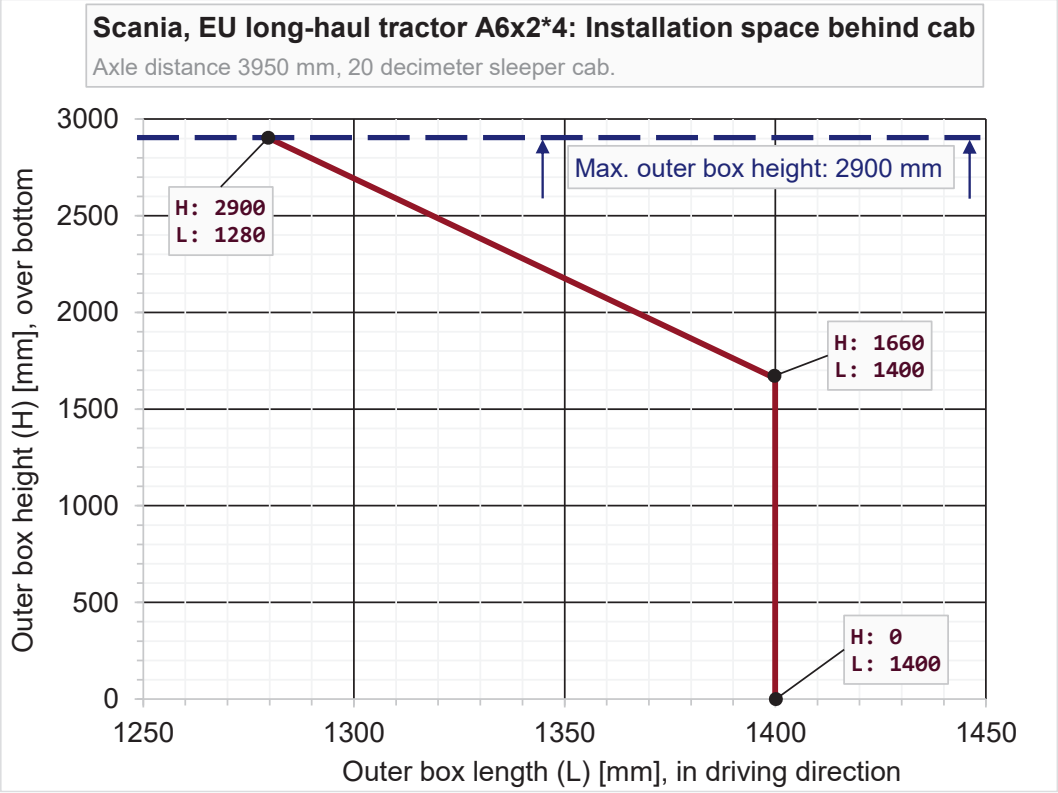


A6x2*4 of AD 3950 mm offer over the present bestseller A4x2 of AD 3750 mm big advantages for installation space behind the cab (A4x2 of AD 3750: Max. additional length ca. 320 to 440 mm (0.32 to 0.44 meters)). Via frame lengthening, an A4x2 can be retrofitted to an A6x2*4 of AD 3950 mm, hence the box size is also applicable for potential retrofits of A4x2.

Installation space behind the cab, for the MCC-system excl. combi-tanks

Outer MCC-box dimensions

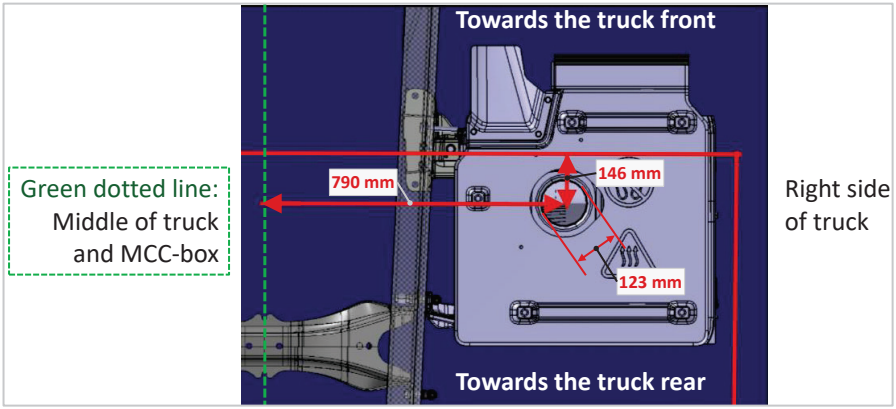
- Length (longitudinal) 1280 to 1400 mm(1.28 to 1.40 meters). In driving direction



- Width (lateral) 2400 mm (2.40 meters)
- Height (vertical) 2900 mm (2.90 meters)

The MCC-box has the following inputs and outputs

- In: The exhaust gases will come from the silencer placed at the right frame side of the vehicle. The connection has an inner diameter of 123 mm. Its center is positioned 146 mm backwards the box's front and 790 mm right of the lateral middle of the box.



From the silencer's exhaust outlet, there must be a minimum 300 mm straight pipe/hose taking bends, thermal expansion and vibrations, which goes into the box.

- In: PTO mechanical (or electrical connection from generator/inverter)
- In/out: CAN communication between vehicle and Carbon Capture Control Unit (CCCU).
- In: Ambient air mass flow into the box for cooling of radiators etc. (any impact on aerodynamics needs to be considered in addition to cooling performance and parasitic losses)
- Out: Cooling Air exiting from the box to the ambient
- Out: Cleaned "Lean CO2" exhaust gas
- Out: Water outlet pipe (emptying strategy needs to be discussed)
- Out: Captured CO2 flow to installation space on side 1 and/or side 2
- 24 V_{DC} supply for control units etc., not for power supply.
- 8 bar compressed air available if needed (optional)

The exact positions and dimensions of inlets and outlets need to be investigated further and are for the moment out of the scope of this work.

The bottom of the MCC-box shall be fixed to the vehicle frame.

This MCC-box shall include

- Complete machinery for CO2 extraction and conditioning
  - Exhaust cooler
  - Optional exhaust dryer
  - Packed towers for CO2 extraction
  - Vacuum pump
  - CO2 compressor
  - CO2 chiller
  - Heat exchangers
  - Heat transfer fluid circuitry
  - Heat insulation towards the cab and towards the exhaust aftertreatment.
  - High voltage (> 48 V_{DC}) electrical circuitry, with a buffer battery.
  - Fans, blowers, and pumps
  - Outlet for lean exhaust.
- Rack and support frames
- Mountings onto the truck frame
- Outer shell

The MCC-box will be covered at the sides and on top with air deflectors. The box shall not be mechanically connected to the cab, which needs to be tilted for repair and maintenance.

Demand on passive safety: In case of a standardised crash, the MCC-box shall be compressed by minimum 150 mm (0.15 meters) and function as buffer zone. I. e. in longitudinal direction the interior of the MCC-box shall not be completely rigid.

Noise emission needs to be considered both for comfort and for noise legislation.

The MCC-box shall not include the tanks for diesel and CO2.

Installation space side 1 for CO2/Diesel Storage, between mudguards of front axle and first rear axle

Outer box dimensions

- Length 2500 mm (2.50 meters). In driving direction.
- Width 720 mm (0.72 meters)
- Height 750 mm (0.75 meters)

This tank-box shall include:

- Tank for diesel fuel
- Tank for CO2
- If so as combi-tank
- Rack and support frames
- Mountings to the truck frame
- Outer shell

This tank-box has the following inputs and outputs

- In: CO2 gases from MCC-box
- In/Out: Diesel supply and return line
- In: Diesel refill
- Out: CO2 outlet for emptying
- In/out: CAN Communication between CCCU and tank sensor/actuators
- 24 V supply
- 8 bar compressed air available if needed (optional)

Installation space side 2 for CO2/Diesel Storage, between silencer and mudguard of first rear axle

Outer box dimensions

- Length 1800 mm (1.80 meters). In driving direction.
- Width 770 mm (0.77 meters)
- Height 750 mm (0.75 meters)

This tank-box shall include:

- Tank for diesel fuel
- Tank for CO2
- If so as combi-tank
- Rack and support frames
- Mountings to the truck frame
- Outer shell

In-/Output same as for side 1.

Upper limit for MCC system weight

The MCC system weight shall contain

- Complete MCC-box behind the cab.
- All tanks for diesel and CO2 at max. weight. In case of average capture rates above 32 %, the tanks get heavier while driving and adding CO2 (→ ca. 3.15 kg_{CO2}/kg_{diesel}).
- All mountings.

The **MCC system weight** shall be maximum **2.90 tonnes (2900 kg)**

Note: A lightweight A6x2*4 long haul tractor without diesel tanks and with 100 Liter AdBlue tank weighs ca. 8.10 tonnes, and a tractor weight with MCC of 11.00 tonnes is the upper limit for the European market[1]. This leaves 2.90 tonnes for the MCC system with full CO2 tanks.

[1] It is assumed that diesel-MCC would get the status of “alternative fuel” and subsequently a weight bonus of 1 tonne. Compare regulation 96/53/EC: Art. 2 'alternative fuels', Annex I / item 2.2.2.

Recommendation: It was found that two big combi-tanks for the demanded range of 840 km on the KTK cycle, at a consumption of 44.4 Liter/100km with an average capture rate of 85 %, weigh maximum 1.50 to 1.60 tonnes. Hence, the MCC-box behind the cab should not weight more than 1.40 to 1.30 tonnes.

Maximum permitted pressure drop without changes to the engine

6-cylinder turbodiesel engine 500 hp

- 1300 rpm & 2730 Nm
- 1824 kg/h humid exhaust
- Tailpipe-outlet 400 °C
- Max. 50 mbar (= 5 kPa) additional pressure drop
    - Downstream tailpipe-outlet
    - No changes of engine settings required.

A higher flow resistance from the MCC system can be managed, and in this case engine calibration and turbocharger need to be adapted. If the additional consumption penalty from an electrical blower in the MCC-box can be avoided, this effort could become worth it.

Power Take Off (PTO)

PTO shaft from engine or from gearbox

- The lowest power limit for a PTO is 160 kW_{mech}, which are also available during driving.
- During driving with engaged gear, the PTO permits 1000 Nm torque, and the PTO-speed is set by the body-builder. During 1 to 2 seconds gearshifting, the PTO torque is limited to 300 Nm, what may result in the need for a buffer battery in the MCC system.
- PTOs can be retrofit into all used trucks. The retrofit becomes cheaper if the truck is already prepared for a PTO.

As an alternative, Scania takes care of the generator mounted on the PTO, and Qaptis conveys the maximum demand for electrical current, voltage and power as input to the MCC system.

One option is high voltage > 48 V_{DC} with a buffer battery, which is fed from a PTO-generator. This would facilitate regenerative braking and reduce MCC's consumption penalty. In that case, Scania would elaborate on the PTO-generator and provide the specified electrical power supply to Qaptis' MCC-system.

The Carbon Capture Control Unit (CCCU) shall communicate with the vehicle control system. At least the following signals need to be reported:

- Actual Torque [Nm] or electric power consumption [kW] extracted from PTO or ePTO
- Status of MCC-unit
- Actual CO2 Capture efficiency [%]
- State of CO2 storage [%]

Ambient conditions

- Ambient temperatures: -30 to +50 °C. Cold start mode for winter.
- Up to 3000 m altitude.
- Down to ambient pressure 700 hPa
- Down to dry air density 0.85 kg/m³

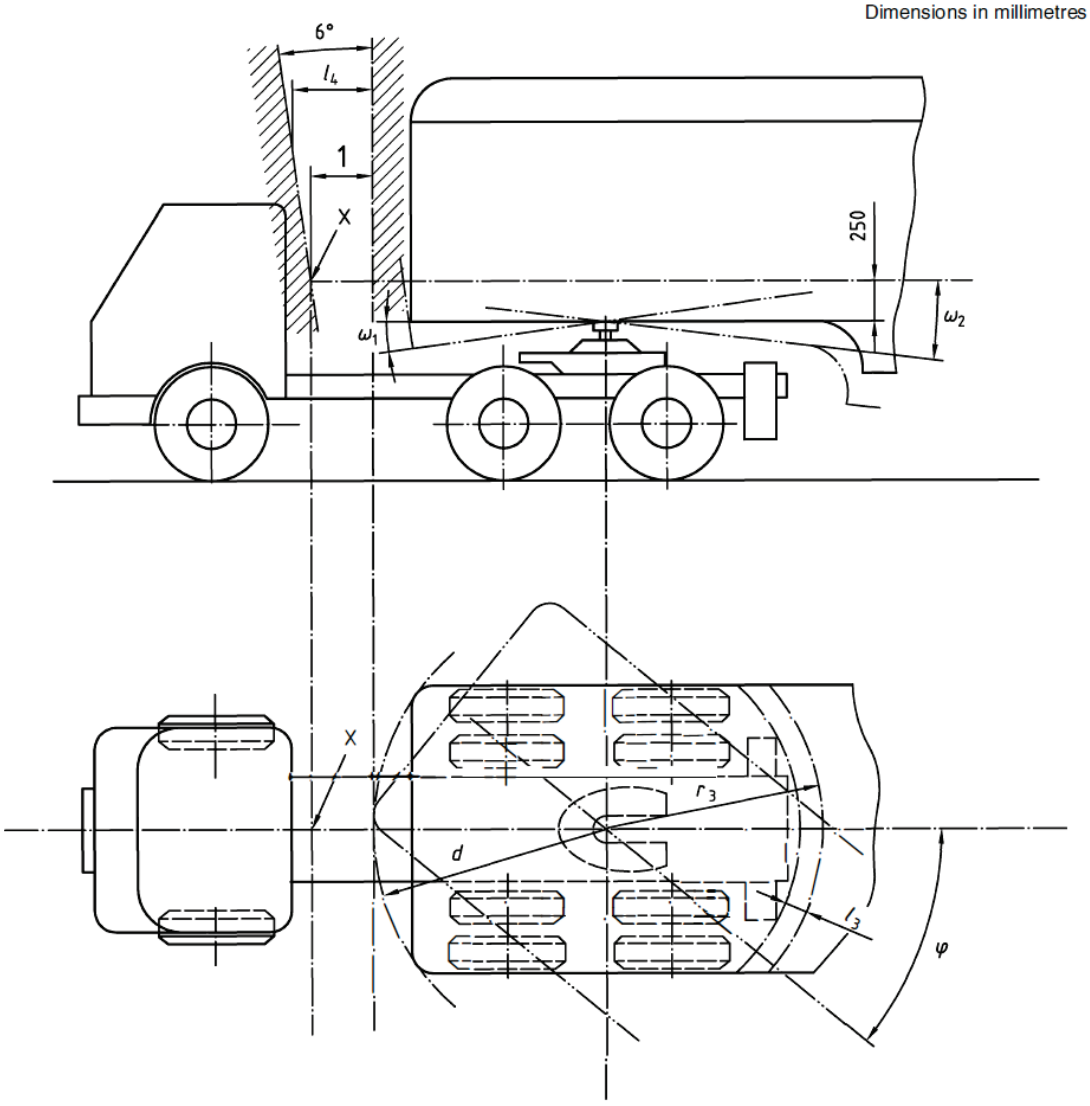
Within these ambient conditions the MCC-system shall function, if so with reduced capture rate at seldom extreme conditions. If outside these conditions the MCC-system should not function, it shall shut down in a safe manner and the driver shall be informed about the shutdown by a signal in the instrument panel.

[i] ISO 1726:2005. *Road vehicles - Mechanical coupling between tractors and semi-trailers - Interchangeability*. Pages 2-3

3.3 Forward-clearance-zone radius of semi-trailer

The semi-trailer's forward-clearance-zone radius, d (see Figure 2), shall not exceed 2040 mm.

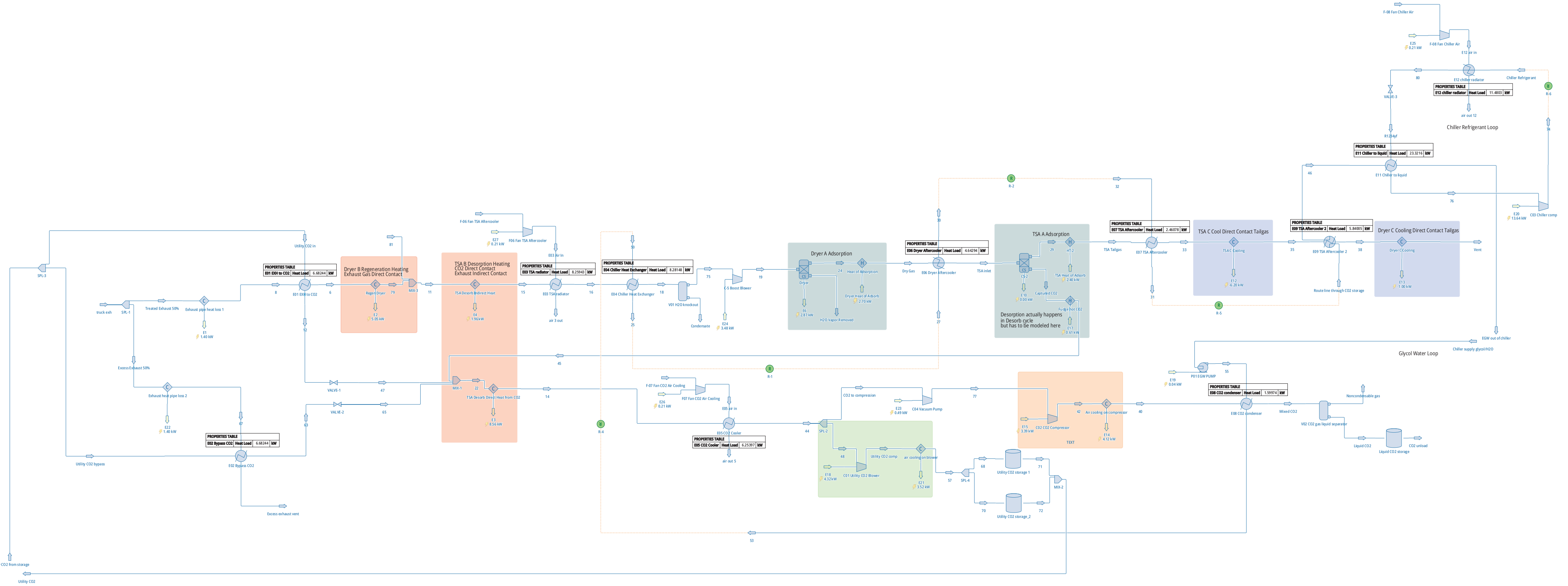
Dimensions in millimetres



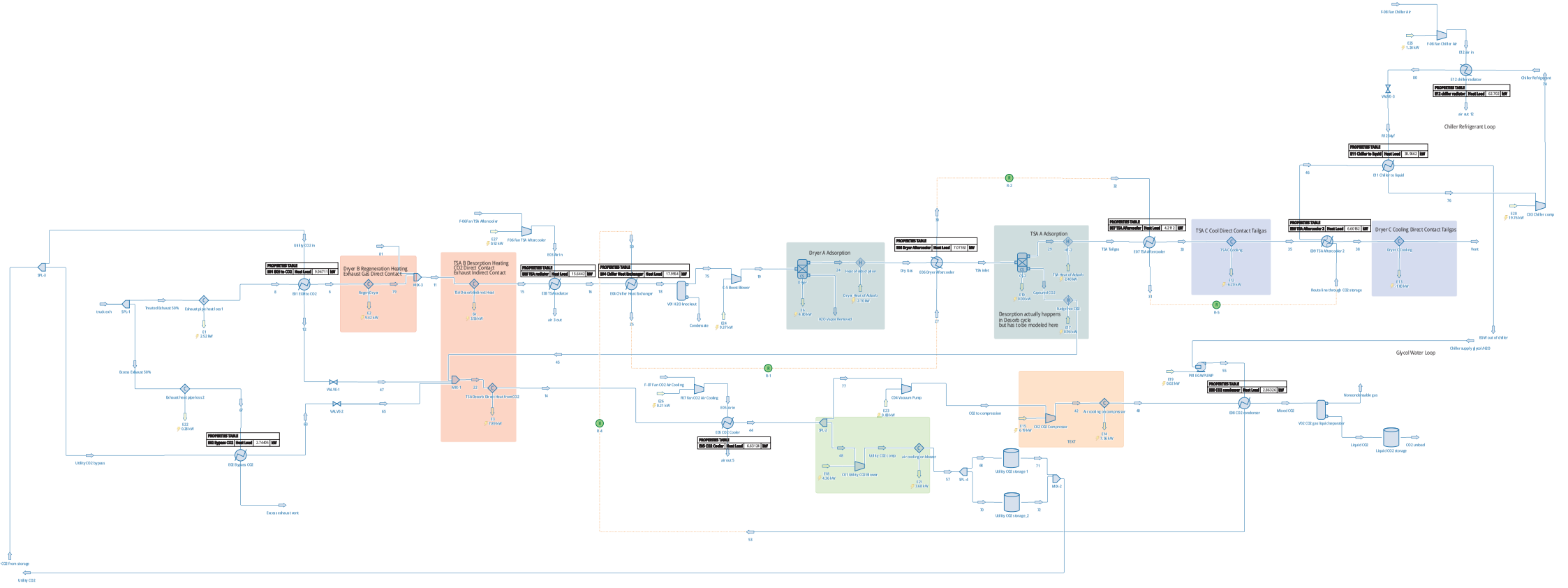
Key
1 l_4 at point X = 80 mm min

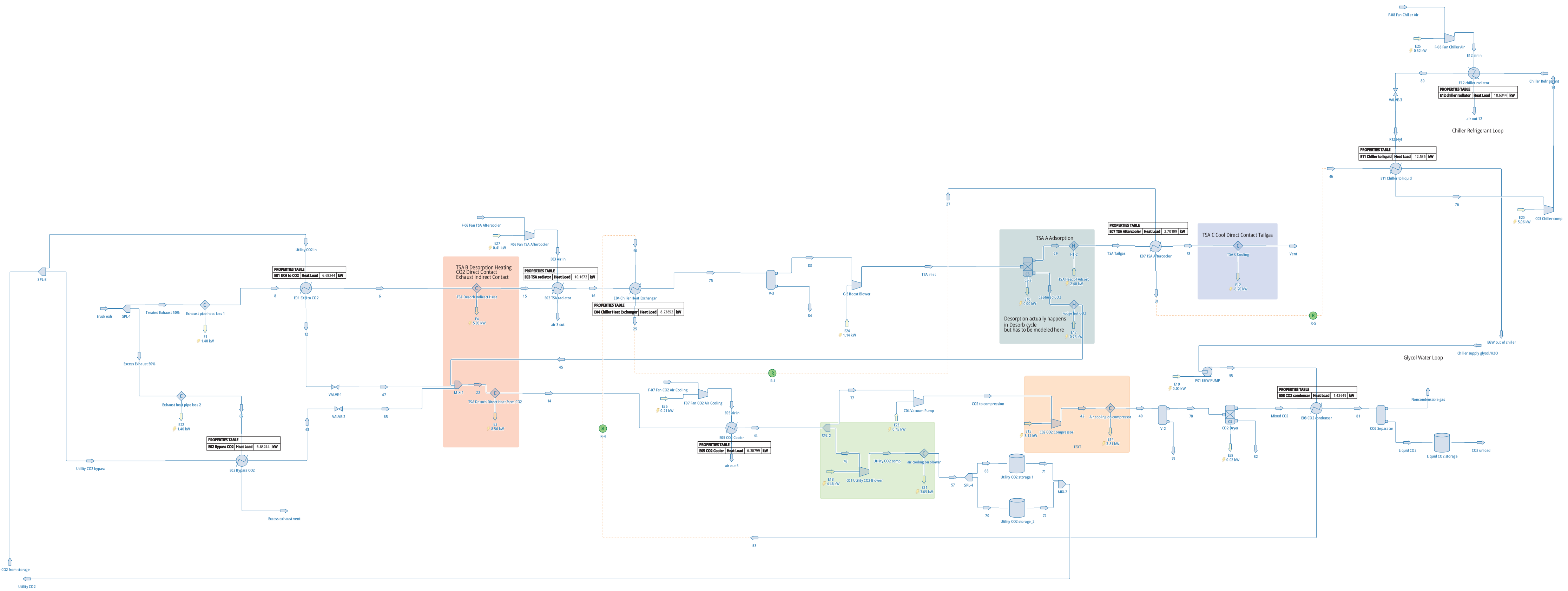
Figure 2 — Free space between tractor and semi-trailer

ANNEX B – SIMULATION FLOWSHEETS



Chiller Refrigerant Loop
Glycol Water Loop
Dryer B Regeneration Heating Exhaust Gas Direct Contact
TSA B Desorption Heating CO2 Direct Contact Exhaust Indirect Contact
Dryer A Adsorption
TSA A Adsorption
TSA C Cool Direct Contact Tailgas
Dryer C Cooling Direct Contact Tailgas
Desorption actually happens in Desorb cycle but has to be modeled here
E01 EXH to CO2
E02 Bypass CO2
E03 TSA radiator
E04 Chiller Heat Exchanger
E05 CO2 Cooler
E06 Dryer Aftercooler
E07 TSA Aftercooler
E08 CO2 condenser
E09 TSA Aftercooler 2
E11 Chiller to liquid
E12 chiller radiator
C01 Utility CO2 Blower
C02 CO2 Compressor
C03 Chiller comp
C04 Vacuum Pump
C-5 Boost Blower
V01 H2O knockout
V02 CO2 gas liquid separator
Utility CO2 storage 1
Utility CO2 storage_2
Liquid CO2 storage
CO2 from storage
Utility CO2
Excess exhaust vent


Utility CO2 in
PROPERTIES TABLE
B51 B50 to CO2 | Heat Load | 9.94711 | kW
Dryer B Regeneration Heating
Exhaust Gas Direct Contact
Regen Dryer
Q 9.42 kW
TSA B Desorption Heating
CO2 Direct Contact
Exhaust Indirect Contact
TSA B Desorb Indirect Heat
Q 3.96 kW
F-06Fan TSA Aftercooler
E27 0.58 kW
F06 Fan TSA Aftercooler
E03 air in
air 3 out
PROPERTIES TABLE
B08 TSA radiator | Heat Load | 15.6442 | kW
E03 TSA radiator
PROPERTIES TABLE
B04 Chiller Heat Exchanger | Heat Load | 17.9954 | kW
E04 Chiller Heat Exchanger
VER H20 Knockout
Condensate
E24 9.27 kW
E-5 Boost Blower
Dryer A Adsorption
Heat of Adsorption
Dryer Heat of Adsorb
Q 2.70 kW
H2O Vapor Removal
Q 4.10 kW
PROPERTIES TABLE
B06 Dryer Aftercooler | Heat Load | 7.07392 | kW
E06 Dryer Aftercooler
Dry Gas
TSA Inlet
TSA A Adsorption
TSA Heat of Adsorb
Q 2.40 kW
Captured CO2
Q 0.005 kW
Desorption actually happens
in Desorb cycle
but has to be modeled here
Q 0.064 kW
PROPERTIES TABLE
B07 TSA Aftercooler | Heat Load | 4.2117 | kW
E07 TSA Aftercooler
TSA Tailgas
TSA C Cool Direct Contact Tailgas
TSAC Cooling
Q 6.20 kW
PROPERTIES TABLE
B09 TSA Aftercooler 2 | Heat Load | 6.66182 | kW
E09 TSA Aftercooler 2
Route line through CO2 storage
Dryer C Cooling Direct Contact Tailgas
Dryer C Cooling
Q 1.00 kW
Vent
F-08 fan Chiller Air
E25 1.28 kW
F-08 Fan Chiller Air
E12 air in
E13 chiller radiator
PROPERTIES TABLE
B12 chiller radiator | Heat Load | 63.702 | kW
air out 12
Chiller Refrigerant
VALVE-3
R12 cold
Chiller Refrigerant Loop
PROPERTIES TABLE
B11 Chiller to liquid | Heat Load | 38.9662 | kW
E11 Chiller to liquid
E20 19.76 kW
CO3 Chiller comp
Glycol Water Loop
EGW out of chiller
Chiller supply glycol-H2O
truck exh
Treated Exhaust 50%
Exhaust pipe heat loss 1
Q 2.52 kW
Boost Exhaust 50%
Exhaust heat pipe loss 2
Q 0.28 kW
PROPERTIES TABLE
B05 Bypass CO2 | Heat Load | 2.74405 | kW
E02 Bypass CO2
Utility CO2 bypass
Excess exhaust vent
CO2 from storage
Utility CO2
VALVE-1
VALVE-2
MIX-1
MIX-2
MIX-3
R-1
R-2
R-3
R-4
R-5
TEXT
F-07 Fan CO2 Air Cooling
R07 Fan CO2 Air Cooling
E05 air in
E05 CO2 Cooler
PROPERTIES TABLE
B05 CO2 Cooler | Heat Load | 6.83138 | kW
air out 5
E06 Q 0.21 kW
E23 Q 0.88 kW
C04 Vacuum Pump
CO2 to compression
E15 6.79 kW
CO2 CO2 Compressor
Air cooling on compressor
E 16 7.16 kW
E10 0.02 kW
P01 EGW PUMP
PROPERTIES TABLE
B08 CO2 condenser | Heat Load | 2.86326 | kW
B08 CO2 condenser
Mixed CO2
V02 CO2 gas liquid separator
Noncondensable gas
Liquid CO2
Liquid CO2 storage
CO2 unload
E18 4.36 kW
C01 Utility CO2 Blower
Utility CO2 comp
air cooling on blower
E21 3.68 kW
Utility CO2 storage 1
Utility CO2 storage_2
SPL-1
SPL-2
SPL-3
SPL-4
SPL-5
SPL-6
SPL-7
SPL-8



Chiller Refrigerant Loop
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Desorption actually happens in Desorb cycle but has to be modeled here
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TEXT