Lawrence Livermore
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LLNL Multimodal CO_2 Transport Cost Model (2024):
Description and User's Manual

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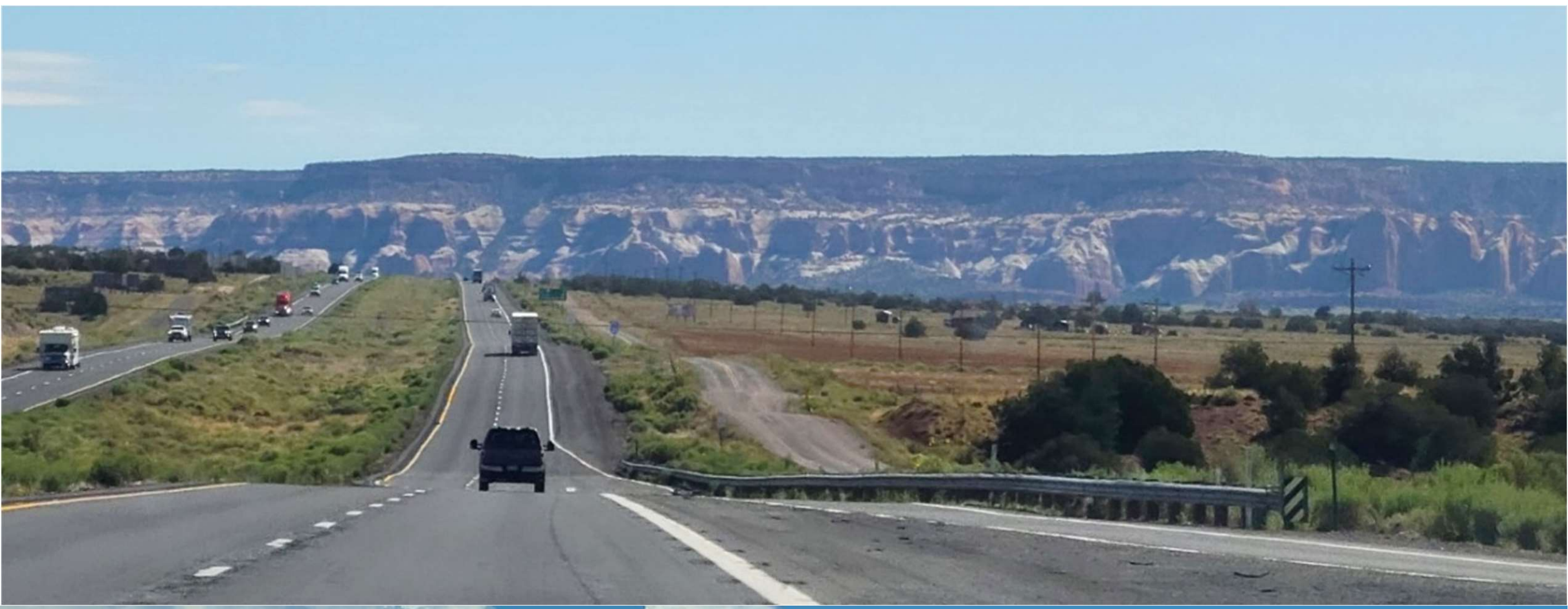

Disclaimer

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Open-Source Software License for Excel Spreadsheet

There is an Excel spreadsheet file that accompanies this document. This spreadsheet is released and made available under the BSD 3 open-source software license.

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Acronyms and abbreviations

ABS	American Bureau of Shipping
AR6	Sixth Assessment Report
ASME	American Society of Mechanical Engineers
BLS	Bureau of Labor Statistics
BOG	Boil-Off Gas
CAPEX	Capital Expenditure
CCS	CO_2 Capture and Storage
CDR	Carbon Dioxide Removal
CFR	Code of Federal Regulations
CO_2e	Carbon Dioxide Equivalent
COTS	Commercial Off The Shelf
DOD	Department of Defense
DOE	Department of Energy
eCFR	Electronic Code of Federal Regulations
EIA	Energy Information Administration
FECM	Fossil Energy and Carbon Management
FINEX	Financial Expenditure
GAO	Government Accountability Office
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
IRS	Internal Revenue Service
ISO	Independent System Operator
KPI	Key Performance Indicator
LCA	Life Cycle Accounting
LCO2	Liquified CO_2
LLNL	Lawrence Livermore National Laboratory
LPG	Liquified Petroleum Gas
MuMoCoCo	Multi-Modal CO_2 transport cost model
NETL	National Energy Technology Laboratory
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
OPEX	Operating Expenditure
PPI	Producer Price Index
RTO	Regional Transmission Organization
sCO_2	Supercritical CO_2
STB	Surface Transportation Board
STCC	Standard Transportation Commodity Code
TPC	Total Plant Cost
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WACC	Weighted Average Cost of Capital

1. Model Introduction and Orientation

Under direction of the United States Department of Energy (DOE) Office of Fossil Energy and Carbon Management (FECM), Lawrence Livermore National Laboratory (LLNL) has developed a life cycle accounting (LCA) inclusive technoeconomic model for the transport of carbon dioxide by truck and rail in the US. This model is called the Multimodal CO_2 Cost Model, or MuMoCoCo. This open source, Microsoft Excel-based tool estimates capital, operating, and financing costs based on bottom-up engineering and logistics design. The intended use is as a screening tool for carbon management projects to complement the FECM/NETL CO_2 pipeline cost estimation tool (CO_2 Transport Cost Model, also known as CO2_T_COM) (Morgan et al., 2023). The manual aims to assist users in understanding not only how to use MuMoCoCo, but also the assumptions, model structure, strengths, and limitations of the model. Section 1 covers the structure and use of the model. Sections 2–4 and the appendices provide details on the assumption, data, calculations, and methods of the model.

1.1. Software Overview

MuMoCoCo consists of five macro-enabled sheets: “Read Me”, “User Interface”, “Calculations”, “FINEX”, and “Options”.

- The “Read Me” sheet provides a brief overview of the model and license information.
- The “User Interface” sheet takes drop-down input selection and automatically updates the key performance indicators (KPIs) and the cost waterfall graph as outputs on the same sheet. An overview of the inputs and outputs is provided in Section 1.1.2 of this document. Most users are expected to interact only with the ‘User Interface’ sheet.
- The “Calculations” sheet contains all of the bottom-up engineering and logistics design, lifecycle emissions calculations, and all the data used in the calculations. Sophisticated users wishing to personalize calculations or add functionality will likely do so in the “Calculations” sheet; details are provided in Sections 1.1.3 and 2.
- The “FINEX” sheet, described in more detail in Sections 1.1.4 and 3, determines the financing costs and the break-even revenue for a given project design.
- The “Options” sheet provides the inputs for the drop-down menus in the ‘User Interface’ sheet. This sheet is described in Section 1.1.5.

As a general rule, users should limit their interaction with MuMoCoCo to input selection in the “User Interface” sheet—naïve alteration to the “Options”, “Calculations”, or “FINEX” sheets may cause unintended and difficult-to-identify errors. That being said, the model is self-contained and open source so that more sophisticated users can alter it to meet their needs. To the extent possible, this document attempts to provide guidance on where alterations can be safely made and where particular care should be taken.

1.2. “Read Me” sheet

The “Read Me” sheet provides a brief overview of the model and its usage. License, copyright, and attribution details are also provided in this sheet.

1.3. “User Interface” sheet

The “User Interface” sheet allows the user to select inputs to match their project and receive an instant calculation of the KPIs and costs (Figure 1). The sheet is set to automatically recalculate any time an input is changed—there are no buttons or keystrokes required to run the model. However, it is necessary that macros are enabled.

User Inputs		
Size (kt-CO2/y)		300
Distance (mi)		100
Geographical Scale	State	
Location	California	
Transport Mode	Truck	
Container Type	Tanker	
Rail Transit Time Method	NA	
Rail Transit Time (h)	NA	
Truck Long Haul Solution	Intermediate Storage	
Buffer Storage Estimate Method	Calculated	
Buffer Storage Time (h)		4
Include Liquefaction Costs?	Yes	
Include Reconditioning Costs?	Yes	
Electricity Source	Grid	
Grid Decarbonization Pathway	Linear Reduction	
Grid Net Zero Year	2045	
GHG accounting	CO2e	
Fuel Economy Pathway	Historical Trends	
Negotiated Rail 'Base Rate' Reduction	NA	
Water content (ppm-mol)		500
CO2 Pressure (bar)		15
Operating Period (y)		30
Construction Period (y)		2
Construction Start Year		2024
FINEX Parameters	Calculated	
IRR		9.63%
Depreciation Period (y)		10
Capitalization (% equity)		45%
Cost of equity (IRROE)		10.77%
Cost of debt (interest rate)		3.91%
Project Contingency Factor		13.6%

Results Summary		
Net CO2 Transport Efficiency	97.3%	
	Net Cost	Gross Cost
Total	$65	$63
CAPEX	$6	$6
OPEX	$43	$42
FINEX	$16	$16
Cost details	Net	Gross
Delivered CO2 over project (net tonnes)	8755674	9000000
Liquefaction equipment	$1.89	$1.84
Buffer Storage (upstream)	$0.60	$0.59
Trucks	$1.64	$1.59
Flatbed Trailers	$0.00	$0.00
LCO2 Containers	$0.46	$0.45
Intermediate storage	$0.00	$0.00
Buffer Storage (downstream)	$0.57	$0.56
Reconditioning equipment	$0.53	$0.52
CAPEX	$5.69	$5.54
Electricity	$17.04	$16.58
Fuel	$5.12	$4.98
Makeup Water	$0.14	$0.13
Base rate	$0.00	$0.00
Fuel surcharge	$0.00	$0.00
Maintenance	$6.23	$6.06
Insurance, Permits, Fees	$2.14	$2.09
Labor	$12.61	$12.27
End of life	($0.40)	($0.38)
CAPEX+OPEX	$48.58	$47.26
FINEX	$16.33	$15.89
CO2 emissions	$0.00	$1.76
Total	$64.90	$64.90
IRR	9.6%	
Contingency	13.6%	

Emissions details	Net (%)	Gross (t-CO2/y)
Electricity	1.1%	3369
Fuel	1.6%	4654
Materials	0.0%	122
Boil-Off Gas	0.0%	0
Total	2.7%	8144
Net CO2 transport efficiency	97.3%	
Scheduling details		
Truck arrives every	40	minutes
Adds	36	trucks per day
Train arrives every	NA	NA
Train length	NA	NA

Figure 1. Inputs (peach-colored cells) and automatically updated costs and key performance indicators (green-colored cells) provided by the model.

All inputs are color-coded peach. Inputs can only be made via drop-down menu selection. As there are nested design choices, some selections will alter the input choices in other cells. The model makes default selections when such changes occur to maintain calculation integrity. When 'calculated' input values are selected by the user, their values do not automatically update in the user selection pane; to see these values, click on the drop-down list for the value of interest and the calculated value will be displayed.

It is recommended that selections are made from the top down, but this is not required. Large changes in the project design (e.g., changing from truck to rail) may require more time for the model to recalculate than minor alterations (e.g., increasing distance from 200 to 210 miles). Alteration or movement of the inputs will impact model integrity. Users wishing to make such modifications must check sheet-specific code (i.e., right click the sheet tab and select ‘View Code’) along with standard calculation and macro interdependencies. The input parameters and available options are summarized in Table 1.

Table 1. Input parameters available to users

Input	Type	Minimum	Maximum	Spacing
Size	Quantity (kt-CO_2/y)	10	1,000	1
Distance	Quantity (miles)	5	3,000	5
Geographic scale	Selection	National, Regional, State		
Location	Selection	1 country, 5 regions, 50 states		
Transport mode	Selection	Truck, rail		
Container type	Selection	Tanker, intermodal		
Rail transit time method	Selection	Calculated, User supplied (only applicable for rail)		
Rail transit time	Quantity (hours)	4	720	4
Truck long haul solution	Selection	Intermediate storage, Two drivers		
Buffer storage estimate method	Selection	Calculated, User supplied		
Buffer storage time	Quantity (hours)	0	720	4
Include liquefaction cost	Selection	Yes, No		
Include reconditioning cost	Selection	Yes, No		
Electricity source	Selection	Grid (only option)		
Grid decarbonization pathway	Selection	Ignore[1], Linear reduction		
Grid net zero year	Year	2030	2100	1
GHG accounting	Selection	CO_2 only, CO_2e		
Fuel economy pathway	Selection	Historical trends, current fleet average, EPA limits (truck only)		
Negotiated rail base rate reduction	Percentage (rail only)	0%	100%	1%
Water content	Quantity (ppm-mol)	0	50,000	10
CO_2 pressure	Quantity (MPa)	15 (only option)		
Operating period	Years	1	50	1
Construction period	Years	1	10	1
Construction start year	Year	2024	2050	1
FINEX parameters	Selection	Calculated, User supplied		
IRR	Percentage	1.00%	50.00%	0.25%
Depreciation period	Years	3	50	1
Capitalization	Percentage	0%	99%	1%
Cost of equity	Percentage	0.00%	100.00%	0.25%
Cost of debt	Percentage	0.00%	100.00%	0.25%
Project contingency factor	Percentage	0%	100%	1%
Notes- 1: this holds grid carbon intensity at current levels				

The results are color-coded green in four sections:

1. Results summary,
2. Cost details,
3. Emissions details, and
4. Scheduling details.

Costs and emissions are provided in terms of both gross and net CO_2 transported, the latter including direct and indirect emissions of the transportation chain. In addition to the numeric values, a cost waterfall graph automatically updates for the more visually inclined user (Figure 2). The results and the graph may be deleted or altered without impacting the model's calculation integrity.

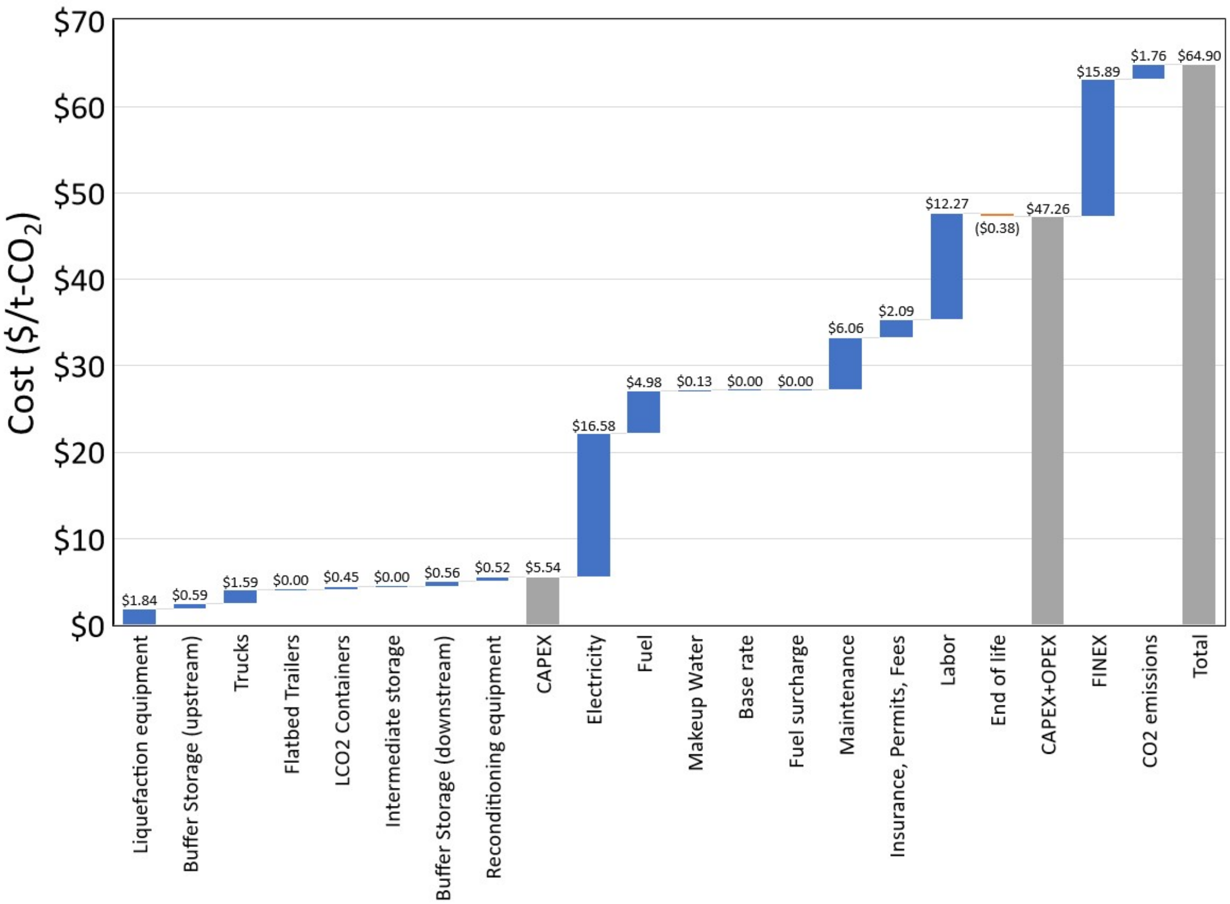

Figure 2. Cost waterfall chart that automatically updates as inputs are changed.

1.4. "Calculations" sheet

The "Calculations" sheet is the repository for all the constants, data, engineering design, logistics design, life cycle accounting, cost analysis, and references used in the model. The sheet contains a macro that automatically calculates boil-off gas (BOG) timing and rate when relevant selections are altered. User selections from the "User Interface" sheet are color-coded blue. Alteration of these cells will break connection with the "User Interface" sheet, leading to erroneous results; these cells should not be changed directly on the "Calculations" sheet.

While it is generally not recommended for users to make alterations to the "Calculations" sheet, project-specific information can be directly input into cells without an inherent degradation of model performance—with the previously noted exception of cells tied to the "User Interface" sheet. However, substantial caution is required as the model contains many interdependencies and apparently straightforward alterations can lead to unexpected and obscure errors elsewhere in the model. Details on the "Calculations" sheet are provided in Section 2.

1.5. "FINEX" sheet

The "FINEX" sheet is where the cost of financing, net present value, break-even CO_2 price, and other values related to project finance are calculated. The sheet contains a macro that automatically solves for the break-even CO_2 price. Most users will not need to access this sheet as the typical parameters altered when determining the cost of financing are provided as input selections in the "User Interface" sheet.

Values pulled from the user's input are color-coded blue. Direct alteration of these values in the "FINEX" sheet will not prompt the macro to rerun and will not update the results. Such alterations will also eliminate the connection between the "User Interface" and "FINEX" sheet, eliminating the functionality of any subsequent drop-down selections. It is highly recommended that the "FINEX" sheet not modified except by sophisticated users who have thoroughly evaluated sheet code, the macros, and interdependent calculations. Further details about the "FINEX" sheet are provided in Section 3.

1.6. "Options" sheet

The "Options" sheet is where inputs for the "User Interface" sheet are stored. These values are not dependent on any other values in the model.

Users wishing to change the numeric value of input options may do so by changing them in the "Options" sheet. However, we remind the user that this is a screening tool with high uncertainty. The level of discretization provided was chosen to have a negligible impact on process KPIs and cost relative to the inherent uncertainty of this screening tool. Further, the ranges selected for each value were meant to cover all reasonable possibilities. Model efficacy outside of these ranges has not been assessed. One numeric value (pressure of liquid CO_2, or LCO2) is not currently an adjustable parameter. Though future updates are planned to include different LCO2 pressures, changing this value in the current version of the model may cause fatal errors.

Non-numeric options are not amenable to simple alterations. These are classifications representing distinct branches on the design tree. Sophisticated users adding new functionality may insert new selections in the "Options" sheet and update the data validation selection for relevant inputs on the "User Interface" sheet. Two non-numeric selections currently only have one option (Country: USA; Electricity source: Grid).

1.7. Using MuMoCoCo

Download the latest version of MuMoCoCo from the DOE CODE hub (https://www.osti.gov/doecode/biblio/123930) and review any comments on code updates, modifications, and corrections. Open the file and make sure macros are enabled. After reviewing the "Read Me" tab, proceed to the "User Interface" and select inputs from the peach-colored input section. Results are automatically updated in the green tables and the graphs on the same sheet.

2. System Design

MuMoCoCo generates an engineering-based, bottom-up design of a user-defined CO_2 transportation project. This design is then used to calculate the net CO_2 transported via life cycle accounting (LCA). The design is also the basis for estimating the capital, operating, and financing costs of implementing the CO_2 transport project. Transportation options are limited to trucks and rail in the United States. Designs are based on commercial off the shelf (COTS) equipment, verified models of existing systems and processes, and limitations set by regulations.

2.1. System boundaries and assumptions

System boundaries for MuMoCoCo include all activities necessitated by the CO_2 transport project design. This includes the physical means of transportation, buffer storage at each of the transport chains, liquefaction of CO_2 received from a supplier, and reconditioning of liquefied CO_2 to injection conditions. The inclusion of buffer storage, liquefaction, and reconditioning in the model was done to avoid inadvertent exclusion of these sub-systems when modeling a complete carbon management process. Users who do not wish to include these subprocesses may choose to exclude them via the “User Interface” sheet. Doing so will remove all CAPEX, OPEX, FINEX, and emissions impacts of these processes from the CO_2 accounting and cost estimation.

Carbon dioxide is assumed to be delivered to the transport project at 100% purity at standard temperature and pressure. Removal of water from CO_2 is included as an option, but purification of other contaminants is not considered in the current version of MuMoCoCo; future iterations may include this functionality. The liquefaction equipment is assumed to produce LCO2 at 1.5 MPa and -28 °C. The reconditioning equipment is assumed to generate supercritical CO_2 (sCO_2) at 10.5 MPa and 10 °C. These values were chosen to match the allowed operational ranges of COTS LCO2 transport equipment.

The life cycle accounting of CO_2 includes direct emissions (e.g., diesel burning in trucks) and indirect emissions (e.g., CO_2 from electricity usage). The model allows for the inclusion of non-CO_2 greenhouse gases (GHG) as CO_2 equivalents (CO_2e) via application of the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) 100-year Global Warming Potential (GWP) factors. Recycling of materials (e.g., steel) is not considered in the LCA.

2.2. Engineering calculations

All engineering calculations were based on bottom-up designs using COTS equipment and processes to the extent possible. Some processes and equipment, though widely used in industry, are decidedly not available “off the shelf” (e.g., the liquefaction and reconditioning systems). For such equipment, models used extensively in industry or validated with commercial project data were used for design. All detailed design data and equations are included in the “Calculations” sheet of MuMoCoCo and are not repeated here. This section aims to provide the general assumptions and logic that lay at the foundation of the traceable calculations contained in the model. For detailed explanation of engineering calculations and methods, the user is pointed to the in-text references.

2.2.1. Dehydration

The model assumes dehydration to 70 ppm-mol is required to meet specifications for CO_2 contacting surfaces in the transport chain recommended by the American Bureau of Shipping (ABS, 2024, p. 15). Users may wish to apply the more stringent lower value of 30 ppm-mol recommended by ABS. The allowable water limit could be modified in cell B264 of the "Calculations" sheet. The molecular sieve design of Roussanaly et al., (2018) was adopted for the dehydration system. The model does not attempt to estimate the mass or footprint of the dehydration system, it is assumed to utilize area available at the CO_2 capture site.

2.2.2. Liquefaction

The liquefaction system design used the model of Deng et al., (2019), an ammonia-refrigeration type compression and liquefaction system. MuMoCoCo limits the user selection to delivery pressure to 15 MPa to match the current transport containers used in industry. However, design data for alternative delivery pressures is provided in the "Calculations" sheet. Users could use this information to explore the CAPEX and OPEX implications of different liquefaction system designs but are warned that current commercial LCO2 containers may not be certified for the assumed pressure and temperature conditions. The model does not attempt to estimate the mass or footprint of the liquefaction system, it is assumed to utilize area available at the CO_2 capture site.

2.2.3. Reconditioning

A transcritical pumping-based system for reconditioning LCO2 to sCO_2 was assumed. While other pathways are possible (e.g., regasification with compression, compression with dense fluid pumping), the transcritical pumping pathway generally has the lowest CAPEX and energy consumption when starting from LCO2 (Taher, 2022). The design of Roussanaly et al., (2021) was utilized. The model does not attempt to estimate the mass or footprint of the reconditioning system, it is assumed to utilize area available at the injection site.

2.2.4. Buffer storage

Storage of LCO2 after liquefaction and before reconditioning was assumed to buffer against logistics delays in the transport of LCO2 from the source to sink. The total buffer capacity was based on the inherent risk of the transport vector and project particulars (see Section 2.3 for more details). Single buffer tank capacity was limited to 110 m^3; the number of tanks was adjusted to meet the total required capacity. While larger buffer tanks exist, according to discussions with vendors, the 110 m^3 is a general size limit for what can be transported over the road in the US. This assertion is corroborated by comparing the ~40.8 t weight limit of US highways with the total mass to transport a 110 m^3 vessel of ~39.5 t (i.e., day cab tractor truck ~7.2 t, trailer ~3.0 t, estimated mass of a 110 m^3 LCO2 buffer tank ~29.2 t). Larger sizes would require either specialized transport or on-site fabrication; both options would incur additional costs that are highly case-specific and difficult to model accurately.

A double-wall, vacuum-sealed style buffer tank was assumed, designed to meet the temperature and pressure conditions of LCO2 following standards set by the American Society of Mechanical Engineers (Towler & Sinnott, 2022, Chapter 14). A 304L stainless steel pressure vessel was used for the inner tank while the carbon steel was used for the outer shell. Perlite was assumed as the insulation material. Each buffer storage tank was outfitted with a LCO2 transfer system including a tower, filling package, and a discharge package as described in Rostam-Abadi et al., (2004). Per discussions with vendors of LCO2 transfer equipment, the fill and discharge rates were set to 3.47 and 3.78 kg/s, respectively.

2.2.5. Transload facilities

A transload facility is an option when logistic design calls for driver times in excess of regulatory limits (see Section 2.3.1). The truck-based transload facility design of Smith et al., (2018) was used with equipment and space limited to that required for the transfer of LCO2 intermodals between trailers or the transfer of LCO2 tanker trailers between trucks. Space requirements were based on the logistics design. It was assumed that LCO2 intermodals will not be stacked.

2.2.6. Tanker trucks

LCO2 tankers and the trucks used for their transport were based on specifications received from commercial vendors for 2023 and 2024 models available for purchase in the US market. Only diesel-based propulsion systems were assumed as this allows for projects to leverage the existing fossil fuel delivery and storage infrastructure. For long-haul trucking without transload facilities, the day cab was replaced with a sleeper cab.

All LCO2 tankers examined use a vacuum-sealed, double-wall system with Polyurethane insulation and 304L stainless steel for LCO2 contacting components. Instead of utilizing a built-in transfer system, LCO2 tankers were assumed to utilize the LCO2 transfer systems on the buffer storage tanks. Per specifications provided by vendors, the gross volume capacity of LCO2 tankers is 25 m^3.

2.2.7. Intermodal trucks

The LCO2 intermodal containers, the trailers they sit on, and the trucks used for their transport were based on specifications received from commercial vendors for 2023 and 2024 models available for purchase in the US market. Trucks were equivalent to those described previously in the section on Tanker trucks (see Section 2.2.6). It was assumed that standard flatbed trailers are adequate given the compliance of LCO2 intermodals with international intermodal design specifications.

All LCO2 intermodals examined were built on the 20’ intermodal standard. They use a vacuum-sealed, double-wall system with Perlite as the insulation. As was the case with LCO2 tankers, LCO2 contacting surfaces were 304L stainless steel and transfer equipment was not integrated into the LCO2 intermodal. Per discussions with vendors, higher volume LCO2 containers are available in Europe but the gross volume capacity of LCO2 tankers currently solid in the United States is 20.5 m^3.

2.2.8. Rail tank cars

DOT105 rail tank cars were assumed for LCO2 transport over rail. Designs were based on specifications from commercial vendors. These tank cars utilize Polyurethane insulation between a stainless steel inner pressure vessel and a carbon steel shell. The tank is integrated into the railcar. As with the truck-based systems, it was assumed that the buffer storage tanks will provide the LCO2 transfer equipment. Per DOT105 specifications, the gross volume capacity of LCO2 rail tank cars is 83.1 m^3 (49 CFR Part 179 Subpart C -- Specifications for Pressure Tank Car Tanks (Classes DOT-105, 109, 112, 114 and 120), 2023).

2.2.9. Intermodal rail

Unlike rail tank cars, LCO2 intermodals are not integrated in the railcar. Based on discussions with rail operators, four 20' LCO2 intermodals can be secured per railcar (i.e., stacked end-to-end and two high). The LCO2 intermodals are equivalent to those described in the section of Intermodal trucks (see Section 2.2.7).

2.2.10. Contingency

Contingency was estimated by separating each transport design into three broad categories: mobile equipment, stationary equipment, and buildings and construction. The contingency levels for each category were based on the data and methods of Hollmann (2014) taking into consideration whether designs were from COTS or more purpose-built designs. Users can adjust contingency rates in cells D169:D171 of the "Calculations" sheet or they can set the overall project contingency rate in the "User Interface" sheet.

2.3. Logistics

Logistics are central in determining the costs of a transportation project. For some variables impacting logistics, empirical averages and standard deviations are used to provide best estimates of the time requirements (e.g., highway speed). Other elements are limited by current technology (e.g., LCO2 transfer rate). Lastly, there are regulatorily limitations that influence logistic design (e.g., weight limitations). In all cases, the logistic design was optimized to minimize the time of transport and the number of containers being transported. The lifecycle CO_2 and cost implications do not feedback into the logistic design. The following sections provide logistic design details for each transport mode along with buffer storage.

2.3.1. Road transport

Logistics for over the road transport assumes the use of the interstate highway system. As actual routes are not considered in MuMoCoCo, travel speeds are set for each state or region by taking a weighted average of interstate lengths (US DOT Federal Highway Administration, 2024) and the average travel speeds for Class 8 vehicles on said interstates (Office of Freight Management and Operations, 2010). In a similar fashion, weigh station frequency is estimated by summing all the interstate weigh stations in the state and dividing by interstate length. Due to a lack of data, the average time at weigh stations was set to 5 minutes for all locations. National averages for all parameters were used for Alaska and Hawaii. Note that the model allows for non-sensical transport designs, such as 1,000 miles of truck transport in Hawaii. The setting of a transport distance that reflects a sensible route is considered the responsibility of the user.

The transfer of LCO2 is limited by design to between buffer storage and the transport containers and vice versa. LCO2 transfer times are set by the filling and discharge rate of the relevant valves which can be changed by users to fit their particular valves in the "Calculations" sheet cells B581:B582. LCO2 intermodals are assumed to be transferred by crane while LCO2 tankers are transferred by separating the tanker trailer from the tanker truck. Per discussions with transload operators, crane transfer, including drive up and drive out, was assumed to require 12 minutes; users may change these values in the "Calculations" sheet in cells B635:B636. Transfer of tanker trailers, including drive up and drive out, was assumed to take 6 minutes; users may change these values in the "Calculations" sheet in cells B617:B620. Filling, discharging, and container movement operations were designed to coincide with regulatorily mandated driver break periods of at least 30 minutes every 8 hours (49 CFR Part 395: Hours of Service of Drivers, 2023) and the refilling of the truck's fuel tanks; users can change this value in cell B109 of the "Calculations" sheet. Running these operations in parallel requires additional labor to cover the LCO2 and fueling operations while the driver is on break.

The filling of both LCO2 tanker trailers and LCO2 intermodals is limited by US federal regulations to a 95% of their volumetric capacity (49 CFR 173.315: Compressed Gases in Cargo Tanks and Portable Tanks., 2023). Federal regulations also limit the gross weight of vehicles traveling over the interstates to 90,000 pounds (40,823 kg) (23 CFR Part 658: Truck Size and Weight, Route Designations—Length, Width and Weight Limitations, 2023). These limits, along with the weight of the truck, trailer, and container are used by the model to determine the amount of LCO2 that can be transported in each truckload. Users can change these values in B104:B105 in the "Calculations" sheet.

The logistics design for drivers has 3 operating modes that are fundamentally connected to US regulations of driving time, commonly known as the "11/14 rule" (49 CFR Part 395: Hours of Service of Drivers, 2023). This rule, taken in concert with the previously described empirical highway speeds and LCO2 transfer activities, limits the distance a single driver can take a load and return to base. For routes below this distance, a single driver can be used. At longer distances, two options are provided for the user to select from: 1) a two-driver team, or 2) a shuttle-type system with transload facilities acting built at 11/14 rule distances acting as intermediate storage. The two-driver solution requires a sleeper cab with its additional cost and weight, along with higher labor costs. The intermediate storage option requires the building of transload facilities and slightly longer transport times to cover the transloading operations. Users select a long-haul solution in the "User Interface" sheet. Users can change the time periods allowed for driving or operation in cells B110:B111 of the "Calculations" sheet.

The number of transfer stations and operators is set by the frequency of truck arrival/departure and the time requirements of the transfer workers. The model assumes a steady frequency of truck arrivals and departures without holiday breaks. Stations and operators are rounded up to the next integer in the model.

2.3.2. Rail transport

As is the case for truck transport, the model does not consider specific routes for the movement of LCO2 by rail, but it does exclude states without rail lines. Note that this allows for non-sensical system designs, such as 1,000 miles of rail transport within Rhode Island; the setting of a transport distance that reflects a sensible route is considered the responsibility of the user. The speed of transport is based on the average speed for each rail operator in the state or region, weighted for the length of rail line they operate (GAO, 2022). Operator speeds are adjusted to account for interconnection time, congestion, and the like. The model automatically calculates the time of travel, but users can alternatively input project-specific travel times in the “User Interface” sheet.

LCO2 transfer to both rail tank cars and intermodals was assumed to occur at the buffer storage locations with transfer times set by the filling and discharge rate of the relevant valves; these can be changed by users in the “Calculations” sheet cells B581:B582. Per discussions with operators, the hook up and disconnect of transfer equipment was assumed to take 5 and 3 minutes per container, respectively. Users may change these values in the “Calculations” sheet in cells B679:B680. An alternative system design not considered in the model, but widely used in the intermodal industry, is the transfer of LCO2 intermodals by crane. This would allow for the filling and discharge of LCO2 intermodals to occur while the train is in transit to or from the buffer storage facility.

The filling of both LCO2 rail tank cars and LCO2 intermodals is limited by US federal regulations to a 95% of their volumetric capacity (49 CFR 173.24b -- Additional General Requirements for Bulk Packagings., 2023; 49 CFR 173.314: Compressed Gases in Tank Cars and Multi-Unit Tank Cars., 2023). Specific rail lines have gross weight limitations, the most common limit is 286,000 pounds (129,727 kg). These limits, along with the weight of the rail tanker, or railcar with four intermodals, are used by the model to determine the amount of LCO2 that can be transported per railcar. Users can change these values in B104 and B106 in the “Calculations” sheet.

The model assumes that linehaul unit trains are the preferred mode of transporting CO_2 over rail. It further assumes that dedicated tracks exist for incoming and outgoing shipments. The amount of CO_2 to be transported by each unit train is set by the frequency of arrival/departure. Unit trains are limited in the model to a length of 200 railcars (Safety Advisory 2023-03; Accident Mitigation and Train Length, 2023); users can change this length in cell B113 of the “Calculations” sheet. If this length is exceeded, the model assumes that alternative rail lines can be accessed such that unit trains are operating in parallel. For logistics designs where the train length falls below the average unit car length (i.e., 73) (Dick et al., 2021), it is assumed that the LCO2 is transported with other materials rather than utilizing unrealistically small train lengths; the logistics of these co-transported materials are not considered in the model.

The number of transfer stations and operators is set by the frequency of truck arrival/departure and the time requirements of the transfer workers. The model assumes a steady frequency of truck arrivals and departures without holiday breaks. Stations and operators are rounded up to the next integer in the model.

2.3.3. Buffer storage

Buffer storage in the model is based on the uncertainties inherent in the transport chain design. There are no considerations for buffering upstream or downstream operations. Users can override the transport-specific buffer storage needs in the “User Interface” sheet.

The quantity of buffer storage for truck transport is based on an incident where the standard interstate highway route has become temporarily unusable. A re-routing distance of 1.3 times the standard distance was assumed (Yang et al., 2018). Such an event would likely cause local congestion, so a reduction in highway speeds of three standard deviations was assumed (De Leonardis et al., 2018). The delay caused by the reduced speed and increased distance was converted to a quantity of CO_2 to be buffered based on the designed system flowrate. The detour distance correction factor and highway speed adjustment can be altered by the user in cells B923:C923 and B927:C927 of the “Calculations” sheet, respectively.,

As re-routing is generally much more complex for rail, it was assumed that a rail incident would not change the route but would decrease the speed. A three standard deviation reduction in speed from the average for the local rail line was used to determine the time delay and thus the quantity of CO_2 to be buffered (GAO, 2022). These assumptions can be altered in cells D923 and D927 of the “Calculations” sheet.

2.4. Location factors

The location of a project impacts many parameters both from a process performance perspective and cost. MuMoCoCo was built as a state-based analysis. Regional analyses are developed by aggregating the state-level factors for the relevant states. Regional definitions vary by federal agency and commodity being considered. MuMoCoCo follows the regional definitions set by the Energy Information Administration (EIA) for natural gas. Users can manually alter regional definitions by changing the region specification for each state in cells B180:B229 in the “Calculations” sheet. This method will also allow users to analysis sub-regional or cross-regional projects.

2.4.1. Boil-off gas

Boil-off gas (BOG) refers to the release of LCO2 for pressure regulation purposes. This occurs as the temperature of LCO2 increases due to heat transfer from the surrounding air and irradiation from the sun (both direct and reflected from the surroundings). Location impacts both factors. Annual averages for temperature and direct normal irradiance were used (NOAA, 2024; NREL, 2024). Seasonal variations from the average are not accounted for in the model.

2.4.2. Carbon intensity of electricity

The model assumes that projects interconnect to the local grid for the supply of electricity used in the process. As the model does not have granularity below the state level, the average consumption-based CO_2 or CO_2e emissions of electricity for each state are estimated by averaging all of the Regional Transmission Organizations (RTO) and Independent System Operators (ISO) in the state. For Alaska and Hawaii, generation-based emissions are used based on the relevant grid mix. Cells E180:E229 in the "Calculations" sheet provide the generation-based emissions for each state per the US Energy Information Administration (EIA, 2022); these not used by the model.

The model does not have the ability to add purpose-built energy generation or storage to a project. Users could directly change the CO_2 or CO_2e intensity in the cells R180:S239 in the "Calculations" sheet.

2.4.3. Cost of electricity

State-level electricity rates for industry are assumed by the model (EIA, 2023a). The model does not have the ability to add purpose-built energy generation or storage, power purchase agreements, or other electricity supply options to a project. Users could directly change the cost of electricity in the cells U180:U239 in the "Calculations" sheet.

2.4.4. Cost of diesel

Fuel costs for truck and rail transport systems were based on the 10-year average highway costs for No. 2 Ultra Low Sulfur Diesel (EIA, 2023b). Users could directly change the cost of fuel in the cells X180:X239 in the "Calculations" sheet.

2.4.5. Installation factor

State-level correction factors for installation costs were assumed in the model (DOD, 2024).

2.4.6. Labor rates

State-level annual wages from the Bureau of Labor Statistics were used for each occupation (BLS, 2024b). The overhead rate for drivers was based on the higher training, licensing, and insurance required for liquified gas drivers (Leslie & Murray, 2022). Overhead rates for all other occupations were held constant across locations and based on analogous industries (BLS, 2024a). Users could directly change labor rates in cells AC180:AC239, AE180:AF239, AH180:AH239, AJ180:AJ239, AL180:AL239, and B23:B24 in the "Calculations" sheet.

2.4.7. Land value

The cost of a land was based on pastureland values at a state level (USDA, 2023). Land acquisition was only assumed for intermediate storage transload facilities. Liquefaction, reconditioning, and buffer storage equipment were assumed to utilize land already acquired as part of the upstream and downstream processes. Users could alter land values via cells AB180:AB239 in the "Calculations" sheet.

2.4.8. Sales tax

State and federal taxes are used in the model. Projects wishing to model the impacts of tax breaks could alter the cells D180:D239 in the “Calculations” sheet.

2.4.9. Cost of truck tires, maintenance, permits, licenses, insurance, and tolls

State-level data for the ancillary costs of heavy duty trucking was based on a national survey (Leslie & Murray, 2022). These costs are not unique to liquified gas transport and so may be an underestimate. Users could alter these costs in cells BR180:BV239 in the “Calculations” sheet.

2.4.10. Interstate speed and standard deviation

Average empirical speeds for distinct interstate highways were converted to an estimate of average state-level highway speed by taking the weighted average of the interstate highway speeds and the length of each interstate highway within the state (Office of Freight Management and Operations, 2010; US DOT Federal Highway Administration, 2024). The standard deviation for highway speed was set constant for all states (De Leonardis et al., 2018). Users could alter speeds in cells AO180:BM239 and standard deviations in cells B926:C926 in the “Calculations” sheet.

2.4.11. Weigh station frequency

Weigh stations were summed for each state and divided by the relevant interstate highway length to estimate an average weigh station frequency. Users could manually alter the weigh station frequency via cells BQ180:BQ239 in the “Calculations” sheet.

2.4.12. Rail base rate and fuel surcharge

The per railcar rate paid to rail operators (i.e., base rate) was estimated at the state-level by taking the average base rate for operators in the state weighted by the miles of rail they operate within the state (STB, 2022). An analogous calculation was done to determine the fuel surcharges (STB, 2024b, 2024a). Users could change these values via cells CG180:CH239 in the “Calculations” sheet.

2.4.13. Rail speed and standard deviation

Average and standard deviation of speed for rail transport at the state level was estimated by taking the average operator performance weighted by the miles of rail they operate within the state (GAO, 2022). Users could change these values via cells CE180:CF239 in the “Calculations” sheet.

2.5. Temporal factors

All projects happen over time in a world where change is the rule rather than the exception. To address this reality, the user is given the opportunity to make judgement calls about whether or not to consider changes occurring over time external to the project. The user is also provided the option to set the period of construction and operational period of the project.

2.5.1. Inflation and cost escalations

Datasets used in the model have disparate quality in terms of the recentness of data. All cost data is updated to the construction start year set by the user. For consistency with Morgan et al., (2023), a flat inflation rate of 2.3% is assumed to update data to the project start year.

2.5.2. Evolution of carbon intensity of electricity

No preset predictions of the electrical grid are provided to users. Users can choose to leave the current system static (i.e., select 'ignore') or predict future changes in cell B18 of the "User Interface" sheet. Those choosing to predict the future can set the date of net-zero electricity generation in cell B19 of the "User Interface" sheet. The model assumes a linear decline in emissions to that date. Users wishing to model purpose-built zero CO_2 electricity could simply set the net-zero year to the start of the project. Note that delivered electricity cost is not connected to assumptions about decarbonization in the model.

2.5.3. Evolution of fuel efficiency

The model provides future scenarios for the fuel efficiency of trucks and rail, selectable in cell B21 of the "User Interface" sheet. Selection of "current fleet average" will hold fuel efficiency steady for the full project. Selection of "historical trends" will continue the historical improvements in fuel efficiency for truck and rail, modeled as a linear reduction, over the project period (Elgowainy et al., 2018; Leslie & Murray, 2022). Selection of "EPA limits", only available for truck-based transport, will keep truck fuel efficiency at the lowest levels allowed by current regulations (EPA et al., 2016).

2.5.4. Construction period

The construction period and construction start year can be altered by the user in cells B26 and B27 of the "User Interface" sheet, respectively. The construction start year determines the dollar year that all cost calculations are reported in.

2.5.5. Operational period

The operational period can be changed in cell B25 of the "User Interface" sheet. Operations are assumed to start immediately at the end of construction.

2.6. Life cycle accounting (LCA) of CO_2

For carbon management projects, the net quantity of CO_2 transported is an important metric. Net CO_2 transport is the delivered CO_2 minus emissions from electricity consumption and materials production. Delivered CO_2 is the gross CO_2 received from the supplier minus CO_2 lost to boil-off gas (for pressure regulation) and leaks. Projects utilizing CO_2 but without a need to consider carbon intensity are more likely to find delivered CO_2 the metric of interest. The focus of MuMoCoCo is carbon management projects looking to reduce emissions or increase removals, in both cases net delivered CO_2 is the proper metric.

The model allows a user to select between CO_2 and CO_2e, the latter includes the effects of other GHGs using the IPCC AR6 100-year GWP factors.

2.6.1. Fuel consumption

Fuel consumption is limited in the model to that used to power trucks and rail, all other activities are assumed to utilize grid-provided electricity. The CO_2 intensity of fuels is the combination of the combustion emissions and the upstream emissions associated with the extraction, refining, and transport of the fuel (EPA et al., 2016; Wang et al., 2023). The baseline truck and rail fuel efficiency using the current fleet averages, including correcting for the difference in weight between loaded and unloaded conditions (Leslie & Murray, 2022; STB, 2024b). Users have the option to account for improved fuel economy over the life of a project (see Section 2.5.2).

2.6.2. Boil-off gas

The regulation of container pressure via release of CO_2 (boil-off gas: BOG) leads to a direct emission of CO_2 from the system. There are two aspects of BOG that must be modeled: 1) the period where pressure is increasing but no BOG occurs, and 2) the rate of CO_2 release once BOG has been initiated. Both processes are a function of the rate of energy ingress to the LCO2 from the environment. This energy comes from the heat of the air and solar irradiance. The model runs a heat balance to calculate the energy influx rate as a function of environmental conditions and the transport speed. That rate is used to determine the time until the internal pressure reaches the regulated release pressure of 16.2 MPa (49 CFR 179.401-1: Individual Specification Requirements, 2023). It is also used to determine the BOG rate required to maintain the regulated pressure. If the total transport time is greater than the time to BOG initiation, then the BOG rate is applied to the difference between total time and time to BOG initiation to determine the amount of CO_2 lost as BOG.

2.6.3. Electricity consumption and source

Electricity consumption in the process is assumed for the operation of the dehydration. Liquefaction, and reconditioning activities. Ancillary activities that would require electricity consumption (e.g., transfer of LCO2, crane operations) are not included in the model. Electricity consumption for the dehydration and reconditioning systems are based on the designs described in Sections 2.2.1 and 2.2.2, respectively. Electricity consumption for reconditioning is based on the methods of McCollum & Ogden (2006) and Taher (2022).

All electricity is assumed in the model to come from the local grid. Since the model granularity is limited to the state level, instances where multiple RTOs/ISOs operate in a state are handled by taking a simple average. Energy transfers between RTOs/ISOs can materially change the carbon intensity of electricity consumed in a region compared to electricity generated in a region. The model uses the consumption-based CO_2 intensity of electricity (Skone, 2019). Production-based CO_2 intensity of electricity is included in cells E180:F229 of the "Calculations" sheet for users who wish to modify the code to use that metric (EIA, 2022).

2.6.4. Materials usage

CO_2 emissions from materials were broken down into three categories: equipment covered in existing DOE complex models, concrete, and steel. Trucks and trailers fall into the first category and their materials-related CO_2 emissions and operating lifetime were based on GREET (Wang et al., 2023). The CO_2 emissions from all other equipment was based on the equipment mass with the assumption that it is primarily stainless steel, produced in the US. Transload facilities were assumed to have a 30 cm thick reinforced concrete base with 10 cm thick reinforced concrete exterior walls. Internal I-beams and a sheet metal roof were assumed to account for stainless steel usage. Users wishing to change the assumed CO_2 intensity of trucks and trailers could do so in cells B466:C466 of the "Calculations" sheet. The CO_2 intensity of stainless steel and concrete could be altered in cells B80:B83 of the "Calculations" sheet.

2.7. Capital Expenditure (CAPEX) estimates

2.7.1. Catalog items

Cost estimates for trucks, trailers, LCO2 tankers, LCO2 intermodals, and LCO2 rail tank cars were taken as the average of multiple quotes from US vendors providing materially similar products. Users can alter or add to these costs in cells B451:C464, B503:C503, B551, B555, and B559 in the "Calculations" sheet.

2.7.2. Bespoke systems

Bespoke system cost estimates include all items whose design changes with the project design; namely, the dehydration system, liquefaction system, buffer storage, transload facilities, and the reconditioning system. These CAPEX estimates are generally not amenable to alteration by users. Users do have the option to completely remove upstream liquefaction equipment and/or downstream reconditioning equipment from the analysis in cells B15:B16 in the "User Interface" sheet. Buffer storage equipment can be removed from the analysis by setting the buffer storage time in cell B14 of the "User Interface" sheet to 0 hours.

The dehydration system uses the design of Roussanaly et al., (2018) and the CAPEX estimate recommendations of Deng et al., (2019). As shown in Equation 1, the direct cost for the dehydration system, $C_{dehydratio}$, is a linear function of the kilograms of water removed per hour, $\dot{m}_{water}$. Two correction factors are applied to update from the reported euros to USD, $CF_{€\rightarrow\$}$, and for inflation from the reported year (2015) to the start of project year, $CF_{inflation}$.

$$C_{dehydration} = (\dot{m}_{water} \times 90) CF_{€\rightarrow\$} CF_{inflation} \qquad \textbf{Eq. 1}$$

CAPEX estimation for the reconditioning system uses the methods and design of Deng et al., (2019) but updates the cost trend fitting functions to lower order equations. This re-fitting exercise was shown to not impact the prediction accuracy of the method. By updating to lower order equations, model behavior becomes more predictable and sensible when extended to smaller or larger sizes. The updated fitting factors are provided in Table 2.

Table 2. Updated fitting factors used in compressor chain cost estimate

Fitting factor	Compressor stage				Refrigeration stage		Recirculation
	1	2	3	4	1	2	
	linear			power	linear		
a	2,212	798	237		1,942	778	
b	519,734	730,105	1,162,483		681,871	794,341	
c				694,467			
d				0.126			
e							287
f							270
g							29,439
h							952,751
Values have been rounded; full values available in cells B303:H310 of the "Calculations" sheet.							

The cost estimate breaks costs into the compression and refrigeration chain ($C_{compressor\ stage\ 1}$, $C_{compressor\ stage\ 2}$, $C_{compressor\ stage\ 3}$, $C_{compressor\ stage\ 4}$, $C_{refrigeration\ stage\ 1}$, $C_{refrigeration\ stage\ 2}$, $C_{recirculation\ compressor}$), the heat exchangers ($C_{HX\ ,compressor\ chain}$, $C_{HX2,compressor\ chain}$, $C_{refrigeration\ intercooler}$, $C_{HX,refrigeration}$, $C_{liquefaction\ precooler}$, $C_{liquefier}$), and flash tanks ($C_{liquefaction\ flash\ tank}$, $C_{recirculation\ flash\ tank}$). All these values are a function of the mass flowrate of CO_2 through the system, $\dot{m}_{CO2}$, and are updated from the reported cost in 2015 euros to dollars for the project start year in the same way as Equation 1.

The cost of the first compressor stage follows Equation 2. The second and third compressor stages and the second refrigeration stage follow Equation 3. The fourth compressor stage follows Equation 4. The first refrigeration stage follows Equation 5. The recirculation compressor follows Equations 6. In Equations 2–6, the coefficients a, b, c, d, e, f, g, and h are found in Table 2 and i stands in for the specific piece of equipment. The total reference power for the compression chain, $P_{CC,reference}$, reference power for first stage of the refrigeration chain, $P_{RF1,reference}$, reference power for the recirculation compressor, $P_{RC,reference}$, the reference mass flowrate of CO_2, $\dot{m}_{CO2,reference}$, the liquid pressure, p_{liquid}, the inlet pressure, p_{inlet}, and the power increase per stage, γ, are pulled from Deng et al., (2019) Appendix A and recreated in Table 3.

$$C_i = \left(a \frac{P_{CC,reference}}{(1+\gamma+\gamma^2+\gamma^3)} \frac{\dot{m}_{CO2}}{\dot{m}_{CO2,reference}} + b\right) CF_{€\to\$} CF_{inflation} \quad \textbf{Eq. 2}$$

$$C_i = \left(aP_{(i-1)}\gamma + b\right) CF_{€\to\$} CF_{inflation} \quad \textbf{Eq. 3}$$

$$C_i = c\left(P_{(i-1)}\gamma\right)^d CF_{€\to\$} CF_{inflation} \quad \textbf{Eq. 4}$$

$$C_i = \left(aP_{RF1,reference} \frac{\dot{m}_{CO2}}{\dot{m}_{CO2,reference}} + b\right) CF_{€\to\$} CF_{inflation} \quad \textbf{Eq. 5}$$

$$C_i = \left(eP_{RC,reference} \frac{\dot{m}_{CO2}}{\dot{m}_{CO2,reference}} + fp_{liquid} + g\frac{p_{liquid}}{p_{inlet}} + h\right) CF_{€\to\$} CF_{inflation} \quad \textbf{Eq. 6}$$

Table 3. Values from Deng et al., (2019) used in compression chain cost estimate

Symbol	Meaning	Value
$P_{CC,reference}$	Reference CO_2 compression chain power	9,750 kW
$P_{RF1,reference}$	Reference first stage refrigeration chain power	1,090 kW
$P_{RC,reference}$	Reference recirculation power	200 kW
$\dot{m}_{CO2,reference}$	Reference CO_2 mass flowrate	37.3 kg-CO_2/s
p_{liquid}	Liquid pressure	27.5 bar
p_{inlet}	Inlet liquid pressure	1 bar
γ	Power increase per stage	1.092
Values have been rounded; full values available in cells B288:B296 of the "Calculations" sheet.		

The capital cost for each heat exchanger is given in Equation 7, where i is a stand-in for the specific heat exchanger, A is the heat exchanger area in m2, and j, k, and l are the fitting factors as shown in Table 4.

$$C_i = \left(j\left(\frac{\dot{m}_{CO2}}{\dot{m}_{CO2,reference}}A_i\right)^k\right) l^{p_{liquid}} CF_{€\rightarrow\$} CF_{inflation} \quad \textbf{Eq. 7}$$

Table 4. Fitting factors from Deng et al., (2019) used in heat exchanger cost estimate

Fitting factor	Value
j	12,003
k	0.603
l	1.011
Values have been rounded; full values available in cells B316:B318 of the "Calculations" sheet.	

The capital cost for each flash tank is given in Equation 8, where i is a stand-in for the specific flash tank, $t_{residence}$ is the residence time in the tank in seconds, ρ_{LCO2} is the density of LCO2 in kg/m3, and V_{liquid} is the percentage of liquid in the tank. The coefficients m, n, and o are provided in Table 5.

$$C_i = m\left(\frac{\dot{m}_{CO2}t_{residence}}{\varrho_{LCO2}V_{liquid}}\right)^n o^{p_{liquid}} \quad \textbf{Eq. 8}$$

Table 5. Fitting factors from Deng et al., (2019) used in flash tank cost estimate

Fitting factor	Value
m	70,693
n	0.562
o	1.015
Values have been rounded; full values available in cells B345:B347 of the "Calculations" sheet.	

Buffer storage CAPEX was based on the methods of Towler & Sinnott (2022), Chapter 7. This estimation is based on industrial correlations of CAPEX to the material requirements of the buffer storage tanks. The cost of the internal stainless steel pressure vessel and external carbon steel shell were calculated according to Equation 9 and then summed with the fitting factors q and r provided in Table 6. The mass of each vessel, m_{vessel}, was determined from the engineering design. The installation correction factors, $CF_{install1-7}$, are explained with values provided in Table 6. The correction factor for the location of installation, $CF_{location}$, is from DOD (2024); it is not included in the dehydration, liquefaction, or reconditioning systems.

$$C = \left(q + rm_{vessel}^{0.85}\right)\left(1 + \sum_{i=1}^{7} CF_{install\ i}\right)CF_{inflation}CF_{location} \quad \textbf{Eq. 9}$$

Table 6. Values from Towler & Sinnott (2022) used in buffer tank cost estimate

Symbol	Usage	Value
q	Fitting factor	17,400 (SS pressure vessel) 11,600 (CS shell)
r	Fitting factor	79 (SS pressure vessel) 34 (CS shell)
$CF_{installation\ 1}$	Piping	0.8
$CF_{installation\ 2}$	Equipment erection	0.3
$CF_{installation\ 3}$	Electrical work	0.2
$CF_{installation\ 4}$	Instrumentation and process control	0.3
$CF_{installation\ 5}$	Civil engineering	0.3
$CF_{installation\ 6}$	Structures and buildings	0.2
$CF_{installation\ 7}$	Insulation, paint, etc.	0.1

The transload facilities use the methodology and equipment cost estimates of Smith et al., (2018). Only a subset of equipment relevant to the envisioned LCO2 transload operations was included in the estimate, namely: land acquisition, site clearing, site earthwork, enclosed storage, employee parking, offices, loading docks, pavement under loaded trucks, truck scales, forklifts, and air compressors.

The reconditioning system CAPEX follows the methods of Bjerketvedt et al., (2020). The CAPEX estimation is a simple fitting of cost to system scale in Mt-CO_2/y, M. For project scales less than ~1.29 Mt-CO_2/y, Equation 10 is used; otherwise, Equation 11 is used. The fitting factors s, u, v, w, x can be found in Table 7.

$$C = \left(s\left(\frac{M}{u}\right)^{v}\right)CF_{€\rightarrow\$}CF_{inflation} \quad \textbf{Eq. 10}$$

$$C = (wM + x)CF_{€\rightarrow\$}CF_{inflation} \quad \textbf{Eq. 11}$$

Table 7. Fitting factors from Bjerketvedt et al., (2020) used in reconditioning cost estimate

Fitting factor	Value
s	4,561,535
u	0.993
v	0.25
w	839,851
x	3,821,096
Values are rounded; full values in cells C370:C371, B372:B374 of the "Calculations" sheet.	

2.8. Operating Expenditure (OPEX) estimates

2.8.1. Electricity

Unit electricity costs are based on the average industrial rates from all RTOs/ISOs operating in a state or region (EIA, 2023a). The model does not provide the functionality to change the electricity rates, but users could manually alter the values in cells U180:U239 in the "Calculations" sheet. Electricity consumption estimates are based on the designs of the liquefaction and reconditioning systems as described in Sections 2.2.2 and 2.2.3, respectively. Ancillary activities that typically require electricity (e.g., LCO2 transfer) were not included in the model.

2.8.2. Fuel

Unit fuel costs are based on the 10-year average highway costs for No. 2 Ultra Low Sulfur Diesel, found in cells X180:X239 in the "Calculations" sheet (EIA, 2023b). Fuel consumption was based on the assumed trajectory of fuel efficiency over the lifetime of the project as described in Section 2.6.1. Fuel costs for rail transport are included in the base rate and surcharge paid to the rail operator.

2.8.3. Labor

Labor was separated into four categories: liquefaction and reconditioning operators, LCO2 transfer operators, crane operators, trailer and intermodal wranglers, and drivers. Administrative, sales, and other assistive labor were not included in the model. Maintenance labor was included in the overall maintenance cost estimate (see Section 2.8.4).

State-level average annual salaries and overhead rates for each class of employees were pulled from federal data (BLS, 2024a, 2024b). The number of employees was based on the project scale and logistics design. No assumption of part-time or dual-purpose employees was made. Employee requirements were always rounded up to the next integer to avoid labor deficits. The annual salaries and overhead rates could be modified by the user by going to cells AC180:AC239, AE180:AF239, AH180:AH239, AJ180:AJ239, AL180:AL239, and B23:B24 in the "Calculations" sheet. The model is not amenable to modification of the required employees without thorough and careful consideration of the implications to the logistics design.

2.8.4. Maintenance, insurance, permits, and fees

Maintenance and insurance costs for stationary equipment were estimated as 4% and 1% of CAPEX on an ongoing annual basis, respectively (Towler & Sinnott, 2022, Chapter 7). The empirical correlation for maintenance does not discriminate between an in-house maintenance team or sub-contractors. Users could change these values in cells B36:B37 of the "Calculations" sheet.

Costs for maintenance, tires, insurance, permits, and tolls for trucks were based on state-level empirical data and can be found in cells BR180:BV239 in the "Calculations" sheet.

2.8.5. Rail base rate and surcharges

The per railcar rate paid to rail operators was taken as the industry average for liquefied CO_2 per the 7-digit standard transportation commodity code (STCC)— excluding S342 car types. Since this data is an industry average, it was adjusted to estimate the cost from each operator based on the rates in the 5-digit STTC for compressed and industrial gases (STB, 2022, 2024a). Base rates for a state or region were estimated as the average from operators in the area, weighted by the length of rail they operate. Operator-specific fuel surcharge data is provided in STB reports, removing the need for the data adjustments applied to base rates (STB, 2024b).

2.8.6. End-of-life

The cost of decommissioning stationary equipment was estimated per standard industry handbooks as a function of the volume of the transload facilities (RSMeans, 2023). This correlation could be adjusted by the user by going to cells B1089:C1089 of the "Calculations" sheet. The upstream and downstream facility decommissioning was assumed to be covered by the upstream and downstream operators. It was assumed that stationary equipment is recycled for steel scrap at current market values (USGS, 2022). This value could be altered by users by going to cell B1169 of the "Calculations" sheet.

Per conversations with LCO2 container suppliers, container refurbishment can lead to a resale value of 90% of the original price at a price of refurbishment that scales linearly with volume. The resale value and refurbishment costs could be adjusted by the user in cells B538:G539 of the "Calculations" sheet.

3. <u>Financial Expenditure (FINEX) estimate</u>

For consistency, the financing estimate of MuMoCoCo follows that of the FECM/NETL CO_2 pipeline cost estimation tool (Morgan et al., 2023). The user is pointed to the CO_2_T_COM user manual for a detailed explanation of the financial analysis. The following sections provide information on additional features provided by MuMoCoCo.

3.1. Internal rate of return (IRR)

MuMoCoCo provides an estimate for project IRR given the CAPEX allocation of the system design. The estimate is a CAPEX-weighted average of typical IRR for mobile equipment, stationary equipment, and building and construction (Deloitte, 2013; Pettit, 2005). These values can be found in cells B159:B167 in the “Calculations” sheet. Users may set their own IRR in the “User Interface” sheet in cell B29.

3.2. Depreciation period

The model assumes a straight-line depreciation of fixed capital investment. A baseline, project-level depreciation period of 10 years is used. The user is alerted to the fact that different elements in the transport chain have different service lives per the IRS (IRS, 2023). For example, the class life is 6 years for heavy duty trucks, 15 years for railcars, 9.5 years for chemical manufacturing equipment, and the like. Also, alternative depreciation methods may be leverage by a project. Since MuMoCoCo is considered a screening level tool, a flat depreciation schedule for all items is used. Users can alter this depreciation period in cell B30 of the “User Interface” sheet. Note that this cell does not put controls on the depreciation period, allowing users to select depreciation periods that would not be acceptable under the current tax code.

3.3. Capitalization

The model uses a baseline capitalization of 45% but allows users to alter this value in cell B31 of the “User Interface” sheet. Note that no limits are put on the capitalization rate; subject matter expertise should be leveraged to reflect realistic financing designs.

3.4. Cost of equity

A baseline value of 10.77% is assumed for the minimum internal rate of return on equity. This value can be modified in cell B32 of the “User Interface” sheet. Note that no limits are put on the cost equity; subject matter expertise should be leveraged to reflect realistic financing designs.

3.5. Cost of debt

The model uses a baseline cost of debt of 3.91% but allows users to alter this value in cell B33 of the “User Interface” sheet. Note that no limits are put on the cost of debt; subject matter expertise should be leveraged to reflect realistic financing designs.

3.6. Project contingency

The model provides an estimate for the overall project contingency based on the CAPEX allocation. A CAPEX-weighted average of contingency for the mobile equipment, stationary equipment, and buildings is used (Hollmann, 2014). These values can be found in cells C169:B171 in the "Calculations" sheet. Users may set their own contingency in the "User Interface" sheet in cell B34.

3.7. Negotiating power

The base rate paid to rail operators is known to be highly dependent on the size and timeframe of a transport agreement. At the time of writing, the transport of LCO2 is small compared to other commodities (e.g., ~1/5th of liquified petroleum gas (LPG), ~1/30th of liquid petroleum products), resulting in base rates that may be unrealistically high for larger, long-term CO_2 transport projects. The model uses the current base rates as a baseline but provides the user with the opportunity to apply a reduction through negotiation with the rail operator in cell B22 of the "User Interface" sheet. Users are recommended to examine the 7-digit STCC expanded stratification report to estimate how much base rates could be reduced via negotiations; for reference, at the time of writing, the base rate for LPG is ~88% that of LCO2 (STB, 2022).

4. Limitations

While substantial effort has been made to make MuMoCoCo applicable to a wide variety of projects, many potentially material factors were purposefully excluded from the model. In most cases, these factors were excluded because they do one or more of the following:

- require technology that is not technically or commercially mature,
- rely upon highly contested views of the future,
- introduce unacceptable levels of uncertainty, or
- require models of human and societal behavior.

A short summary of identified limitations in MuMoCoCo is provided in the following subsections.

4.1. Alternative fuels and electrification of transport

The model does not provide the option for alternative fuel or battery electric heavy vehicles or rail operations. Although these options are beginning to appear on the market, their nascent nature makes their actual CO_2 emissions—both from production and use—unclear. Moreover, the infrastructure necessary to supply alternative fuels or electric charging to meet the logistics requirements of MuMoCoCo do not exist at the time of writing. The costs associated with developing such infrastructure for a single project are outside the scope of the MuMoCoCo model.

4.2. Decarbonization of materials production

The model leverages GREET estimates for the CO_2 intensity of equipment where possible and materials elsewhere. It is broadly expected that, like electricity production, heavy industry will undergo some degree of decarbonization over the coming decades. The MuMoCoCo model does not provide the user with the capability to account for such decarbonization over the lifetime of the project. This decision was made because the rate and extent of industrial decarbonization is highly uncertain at the time of writing and because much of the construction of equipment and facilities is front-loaded. The obvious exception is the heavy-duty vehicles used in truck-based transportation. However, these constitute <5% of total emissions in most scenarios. Since the reduction in emissions that could come from including industrial decarbonization is much less than the uncertainty it would introduce, it was not included in the analysis.

4.3. Behind the meter power

The model does not provide the option for behind the meter, purpose-built power. However, users could directly input the CO_2 intensity and cost of electricity for their power system as explained in Sections 2.6.3 and 2.8.1, respectively

4.4. Cost changes

Both CAPEX and OPEX costs are assumed to be flat in the model. Changes in electricity and fuel costs over the life of a project could meaningfully impact the overall project economics. Similarly, improved labor efficiency is not uncommon as industries and companies mature. Lastly, while the stationary equipment and trucks are unlikely to see major cost reductions, the scale up of domestic production of LCO2 intermodals, tankers, and rail tank cars could come with significant cost declines. As a point of reference, quotes for internationally manufactured LCO2 intermodals were as cheap as ~60% of the domestically manufactured average; this difference was primarily attributed to manufacturing scale and learning by doing.

4.5. Negotiating power

The model allows for the user to "negotiate" for lower base rates with the rail operator but does not provide such ability for other items. Notably, the purchase of many dozens of heavy vehicles or rail cars would likely provide the opportunity for lower unit cost. Such data is highly confidential and insufficient data could be acquired to set reasonable bounds on cost reduction potential. As such, such functionality was not included in the model.

4.6. Incentives

The MuMoCoCo model includes taxes in the financial model but does not include other costs (e.g., royalty payments) or incentives (e.g., 45Q tax breaks, grants). The 45Q tax incentives were excluded as these relate to the storage or utilization of CO_2. While transport is often required for storage or utilization to occur, it is not sufficient on its own to receive a tax break. Royalties, grants, and other financial instruments were considered too project-specific for the screening-level analysis service that MuMoCoCo aims to provide.

4.7. Logistics uncertainty

The MuMoCoCo model uses average rates (e.g., highway speed, filling flowrate, hookup time) in the design of transport system. A more robust design would utilize probability distributions for all of the time-dependent activities and run a Monte Carlo analysis to determine whether the design meets the system performance requirements. Such analysis was deemed unnecessary for a screening-level tool.

4.8. First/last mile of transport

In all transportation and distribution systems, the last and first mile are often disproportionally costly. The model assumes that truck-based systems have facilities that are directly off of the highway. It assumes that rail-based systems have branches or spur lines and an existing transload facility. If these assumptions are not met, substantial additional costs may be incurred by the project.

4.9. Project uncertainty

The model does not provide estimates of uncertainty for the project. This is particularly relevant for the construction phase, where permitting, public resistance, and the like may delay or halt a project.

5. References

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