Documentation of Support by the National Renewable Energy Laboratory to TVA 2025 Integrated Resource Plan

Garvin Heath, Christopher Skangos, Noah Frey, Lauren Sittler, Brian Gentry, Tapajyoti Ghosh, Caitlin Murphy and Merve Olmez-Turan

National Renewable Energy Laboratory

Technical Report
February 2025

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08GO28308

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Suggested Citation
Heath, Garvin, Christopher Skangos, Noah Frey, Lauren Sittler, Brian Gentry, Tapajyoti Ghosh, Caitlin Murphy and Merve Olmez-Turan. 2025. *Documentation of Support by the National Renewable Energy Laboratory to TVA 2025 Integrated Resource Plan*. Golden, CO: National Renewable Energy Laboratory.

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This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Support for the work was also provided by the Tennessee Valley Authority under Agreement IAG-23-23526-0. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Acknowledgments

We thank colleagues at the Tennessee Valley Authority for their guidance and assistance: Hunter Reed, Alex Britt and Trystan Knowles.

List of Acronyms

CCS	carbon capture and storage
CH_4	methane
CO_2	carbon dioxide
DOE	U.S. Department of Energy
GHG	greenhouse gas
GWP	global warming potential
H_2	hydrogen
IPCC	Intergovernmental Panel on Climate Change
IRP	Integrated Resource Plan
ISO	International Organization for Standardization
LA100	Los Angeles 100% Renewable Energy Study
LCA	life cycle assessment
LCI	life cycle inventory
LiAISON	Life-cycle Assessment Integration into Scalable Open-source Numerical models
N_2O	nitrous oxide
NGCC-CCS	natural gas combined cycle with carbon capture and sequestration
NREL	National Renewable Energy Laboratory
OSTI	Office of Scientific and Technical Information
premise	PRospective EvironMental Impact AsSEssment
SMR	small modular reactor
TVA	Tennessee Valley Authority

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1 Introduction

The National Renewable Energy Laboratory (NREL) was contracted by the Tennessee Valley Authority (TVA) to support TVA's independent estimation of life cycle GHG emissions associated with their portfolios evaluated in their 2025 Integrated Resource Plan (IRP). TVA desires to follow an approach developed and used by NREL for more than a decade, most recently in the Los Angeles 100% Renewable Energy Study (LA100) (Cochran and Denholm 2021; Nicholson et al. 2021).[1] NREL's approach quantifies all greenhouse gas (GHG) emissions attributable to a choice in electricity generation technology, which is well suited to the goal of an IRP in supporting decisions regarding which resources to use for electrical capacity and generation. This appendix describes the motivation for using NREL's approach, which differs from traditional GHG emissions accounting; the scope of NREL's support of TVA; the verification of TVA's replication of NREL's approach; the methods developed specifically for the TVA IRP that differ from those previously documented for LA100; and NREL's independent validation of results achieved by TVA for select IRP cases.

1.1 Why Estimate Life Cycle GHG Emissions?

The traditional approach to estimate carbon dioxide (CO_2) emissions from combustion is to multiply activity data (generation by a particular technology) by a CO_2 emission factor (EF) for that technology (i.e., g CO_2/kWh). However, such an estimation scheme does not consider several other components of GHG emissions attributable to electricity generation. In the traditional approach:

- Only emissions from the combustion of fossil fuel energy are counted, whereas emissions from upstream fossil fuel extraction and processing are disregarded.
- Only CO_2 emissions are considered, whereas other GHG emissions (e.g., methane [CH_4], nitrous oxide [N_2O]) are ignored. This omission might be particularly important for CH_4 released in coal mining, oil production, and natural gas production and transport, as well as any emissions of non-CO_2 GHG emissions released through combustion processes.
- A focus on combustion-only emissions does not consider the implications of GHG emissions from equipment manufacturing and construction, operations and maintenance activities, and plant decommissioning, which can be usefully categorized into four life cycle stages:
    - Plant construction (called "upstream" in life cycle assessment [LCA] literature)
    - Plant operating emissions, which are further disaggregated into:
        - Emissions associated with fuel combustion for electricity generation
        - All other emissions during plant operation, e.g., maintenance activities, including those associated with obtaining the fuel (called the "fuel cycle")
    - Plant decommissioning (or "downstream").

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[1] For the full report, see https://maps.nrel.gov/la100/#home-1. For the chapter on GHG emissions, see https://www.nrel.gov/docs/fy21osti/79444-8.pdf.

Most renewable electricity technologies have no or limited operational GHG emissions (with the exception of biopower[2]). A more comprehensive evaluation of the impact of capacity expansion scenarios requires evaluating GHG emissions across the full life cycle of each technology by intentionally employing accepted procedures from the field of LCA (e.g., International Organization for Standardization [ISO] 14040). A schematic of the relevant life cycle phases for electricity generation technologies is shown in Figure 1. NREL's LCA-based approach is tailored to enabling fair comparisons of GHG emissions attributable to choices being made today among various combinations of electricity generation technologies that will be used decades into the future.

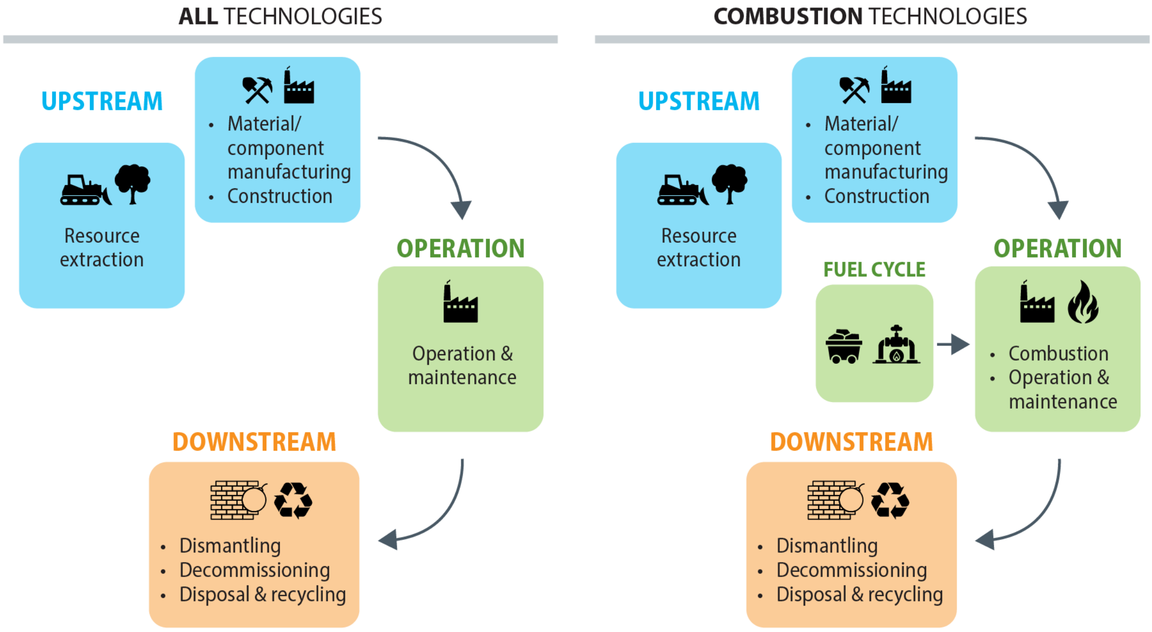

Figure 1: The three major phases of the life cycle, and constituent components, for electricity generation technologies using renewable energy sources and those combusting fuels (both fossil and others like hydrogen or biomass). Nuclear technologies have a fuel cycle but don't use combustion. *Image by Liz Craig, NREL.*

1.2 NREL's Expertise in This Area

To support the assessment of non-combustion emissions, for more than a decade, NREL conducted a comprehensive and systematic review of the LCA literature to create a database of

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[2] The combustion of biomass emits CO_2 and other GHGs; however, because the carbon emitted during combustion is absorbed during photosynthesis in feedstock production, these emissions cancel when summed over the life cycle. The impacts of combustion-only CO_2 emissions reported in this chapter assume no net emissions from biopower facilities, consistent with a recent U.S. Environmental Protection Agency policy decision on the programmatic treatment of biomass and the forest products industry (Pruitt 2018), which treats biogenic CO_2 emissions resulting from the combustion of biomass from managed forests at stationary sources for energy production as carbon neutral. Nevertheless, there are non-cancelling GHG emissions from biopower systems outside of the biomass production and combustion processes associated with component manufacturing and construction, operations and maintenance, and, often, feedstock production. All these GHG emissions were accounted for here in the life cycle estimates; however, unaccounted for altogether in NREL's prior LCA Harmonization studies are potential GHG emissions associated with changes in land use directly or indirectly induced by the cultivation of a biomass feedstock.

GHG emissions factors disaggregated by the four life cycle stages noted on page 1. These estimates were compiled under NREL's seminal LCA Harmonization project (NREL 2024).[3] The results of the LCA Harmonization study were first featured in the Intergovernmental Panel on Climate Change (IPCC) *Special Report of the Intergovernmental Panel on Climate Change* (Sathaye et al. 2012) and in a special issue of the *Journal of Industrial Ecology* on the meta-analysis of LCAs that centered on the results of this study.[4] Note that the LCA Harmonization study did not focus only on renewable technologies; seminal reviews of fossil fuel-based generation technologies (Whitaker et al. 2012; Heath et al. 2014) as well as nuclear technologies (Warner and Heath 2012) have also been completed.

Results from the IPCC special report and the *Journal of Industrial Ecology* special issue articles (e.g., Whitaker et al. 2012; Warner and Heath 2012) were then used to analyze capacity expansion scenarios in a series of flagship reports for the U.S. Department of Energy (DOE), starting with the *Renewable Electricity Futures Study* (NREL 2012) and later including updates for most renewable technologies, such as the Wind Vision (DOE 2015a; 2015b), Hydropower Vision (DOE 2016a; 2016b), and GeoVision (DOE 2019a; 2019b). As mentioned, LA100 (Nicholson et al. 2021) was the most recent application of the results of the LCA Harmonization study, which added two storage technologies (lithium-ion batteries and hydrogen fuel cells).

1.3 Approach

The approach to estimating changes in GHG emissions attributable to the future utilization of electricity generation technologies combines three key outputs of a capacity expansion model (fuel combustion CO_2 emissions, electricity generation, and capacity additions/decommissions) with literature-based estimates of life cycle GHG emissions for TVA assets. The collected literature went through several rounds of strict screening for robustness of methodology, transparency of reporting, and technology relevance to be considered in the analytical phases of the LCA Harmonization project. NREL's most recent application of this systematic literature review approach supports TVA's IRP and is described in Sections 3.3 and 3.4 of this paper. (Additional information about the screening process for the LCA Harmonization project is detailed in the *Renewable Electricity Futures Study*, Appendix C [NREL 2012].) Of approximately 3,000 references screened throughout the history of the LCA Harmonization project, about 300 have been used as the basis to compute life cycle GHG emissions factors.

The references passing the LCA Harmonization project's systematic review were then further analyzed to develop GHG emissions factors for each life cycle phase. Following are descriptions of the definitions of each phase and our analytical approaches:

- *One-time upstream emissions* include emissions resulting from raw materials extraction, materials manufacturing, component manufacturing, transportation from the manufacturing facility to the construction site, and on-site construction. These emissions occur once during the lifetime of a generation unit. Emissions factors used in the analysis of this life cycle stage are median estimates taken from the results of the LCA Harmonization project.

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[3] See https://www.nrel.gov/analysis/life-cycle-assessment.html.

[4] See https://onlinelibrary.wiley.com/toc/15309290/2012/16/s1

- *Ongoing non-combustion operational emissions* occur during the operating phase and include fuel cycle emissions (where applicable) and emissions resulting from non-combustion-related operations and maintenance activities. These emissions occur each year the plant operates. Emissions factors used in the analysis of this life cycle stage are median estimates taken from the results of the LCA Harmonization project.
- *Ongoing combustion emissions* result from combustion at the power plant (where applicable) for the purpose of electricity generation. These emissions occur each year the plant operates. TVA's capacity expansion model directly calculates CO_2 emissions from combustion. In this work, emissions of non-CO_2 GHG emissions from combustion are also considered (differing from prior, analogous NREL research like LA100).
- *One-time downstream emissions* include emissions resulting from facility decommissioning, disassembly, transportation to the waste site, and the ultimate disposal and/or recycling of the generation assets and other site materials. These emissions occur once during the lifetime of a generation unit. Emissions factors used in the analysis of this life cycle stage are median estimates taken from the results of the LCA Harmonization project.

One-time emissions (upstream and downstream) are related to the embodied emissions of a generation unit, which are largely determined by the unit's size (capacity). Capacity additions and subtractions of all technologies are tracked by TVA's capacity expansion model. Multiplying literature-estimated, technology-specific, one-time upstream (downstream) GHG emissions normalized per kilowatt of installed (retired) capacity by the capacity changes reported by TVA's capacity expansion model yields an estimate of GHG emissions associated with the addition (retirement) of that technology's capacity.

Ongoing, non-combustion GHG emissions factors are assigned by technology type. Estimates of GHG emissions associated with the fuel cycle and other ongoing, non-combustion-related activities are derived by multiplying literature-estimated, ongoing, non-combustion-related GHG emissions normalized per kilowatt-hour by the TVA model-estimated generation.

Summing GHG emissions over all years, life cycle phases, technologies, and generators yield estimates of cumulative life cycle GHG emissions for each TVA IRP case.

1.4 NREL's Tasks Performed to Support TVA's IRP

TVA's results reported in the main body of this report are considered the IRP's results, not those reported in this appendix. NREL was contracted to help TVA ensure that their methods and their model is consistent with that of NREL's, as outlined in Section 1.3. This appendix summarizes NREL's limited role in supporting TVA's estimates of life cycle GHG emissions for the IRP cases.

NREL was contracted to support TVA's independent estimation of life cycle GHG emissions in the following ways:

1. Verify that TVA's life cycle GHG estimation model follows the approach developed by NREL, including verification that:
    A. All emissions factors for the three non-combustion life cycle phases are the same as those developed by NREL.

    B. The structure of the mathematical approach to estimating life cycle GHG emissions is consistent with that developed by NREL.

2. Add four additional capabilities to NREL's life cycle GHG emissions modeling approach in support of TVA's IRP. These capabilities have been added to both the NREL and TVA life cycle GHG emissions models to:

    A. Disaggregate the CO_2-equivalent GHG emissions calculated using NREL's life cycle emissions factors into individual mass emissions estimates for each of the three major GHGs (CO_2, CH_4 and N_2O). This was done to support the economic valuation of the emissions of each GHG.

    B. Account for hydrogen generated through electrolysis powered solely by renewable energy (aka green hydrogen) for its use in combined cycle plants blended with natural gas.

    C. Add a new technology featured in TVA's IRP—nuclear small modular reactors (SMRs).

    D. Update the review of published life cycle GHG emissions estimates for a technology potentially important within the context of TVA's IRP: natural gas with carbon capture and storage (CCS).

3. Validate the estimates of life cycle GHG emissions from TVA's model by independently estimating life cycle GHG emissions using NREL's model. This was done for two selected cases chosen to represent the range of technology options within the overall IRP framework.

The remainder of this appendix follows NREL's scope as outlined here.

2 Verification of TVA Model

2.1 Syncing the Models

NREL verified the outputs of TVA's LCA model by matching and entering TVA's capacity expansion model inputs into NREL's model for each technology type and for each life cycle phase—construction, operation, and decommissioning. TVA's capacity expansion model expresses the capacity that was built, operating, and retired per year from 2024–2050. It covers the following technologies:

- Coal supercritical: higher-efficiency coal power plant
- Coal subcritical: traditional coal power plant
- Combined cycle: natural gas-fueled power plant
- Combined cycle with CCS: natural gas-fueled power plant with low carbon emissions
- Hydrogen combined cycle: power plant burning a blend of natural gas and hydrogen
- Combustion turbine: natural gas-fueled power plant to quickly meet peak demand
- Diesel: diesel engine power plant
- Hydro: utility-scale hydroelectric dam
- Nuclear: conventional utility-scale nuclear power plant
- Nuclear SMR: SMR technology, smaller capacity than conventional utility-scale nuclear

- Pumped hydro: hydroelectric energy storage technology
- Solar: utility-scale solar power plant
- Wind: utility-scale wind power plant
- Landfill gas: biogas used from landfill off-gas
- Biomass: biomass waste combusted to generate electricity
- Battery: utility-scale battery energy storage technology
- Market: purchased electricity to meet demand

NREL estimated upstream (installations) and downstream (decommissioning) GHG emissions for each technology by multiplying installed/decommissioned capacity (in MW) by emission factors (in g GHG/MW), as described in Section 1.3. The emissions from installations were placed in the year before a facility was commissioned, whereas the emissions for decommissioning were assigned to the year following the plant's final year of operation. Combustion and non-combustion emissions during each plant's operating years were tabulated using the TVA-generated CO_2 emissions and the monthly generation per technology per year, respectively.

NREL calculated the emissions of each plant per phase (upstream, downstream, and non-combustion) using the emissions factors shown in Table 1. Combustion emissions are output directly from the capacity expansion model and are appropriately added for each year per technology. NREL converted each phase's emissions into its CO_2 equivalent using the latest 100-year global warming potentials (GWPs) from the IPCC's 6th Assessment report, as summarized by the USEPA (Ingwersen, 2023).

Table 1. Emissions Factors for Each Phase and Technology

Data from Nicholson et al. (2021) with updates for NGCC-CCS, Hydrogen, and SMR

Electric Power Technology	One-Time Upstream GHG (CO_2 equivalent), g/kW	Ongoing Annual Non-Combustion GHG (CO_2 equivalent), g/kW-hr	One-Time Downstream GHG (CO_2 equivalent), g/kW
Coal supercritical	867,240	10	67,100
Coal subcritical	708,246	4.9	67,100
Natural Gas combined cycle	100,000	62	4,070
Natural Gas combined cycle with CCS	1,400,000	110	4,300
Natural Gas combustion turbine	64,790	70	2,600
Hydrogen combined cycle	100,000	Fuel Cycle: 28.5[a] O&M: 0.4	4,070
NG/H_2 fuel blend combined cycle	100,000	Fuel Cycle: $28.5(X_{H2})$[a] + $92(X_{NG})$[b] O&M: 0.4	4,070
Diesel	1,021	97	18
Hydro	1,100	1.9	0
Nuclear	483,552	12	175,000
Nuclear SMR	810,000	12	190,000
Pumped hydro	310	1.8	7
Solar	1,630,000	9.4	37,800
Wind	619,000	0.74	14,000
Landfill gas	64,790	38	2,600
Biomass	1,960	6	35
Battery	527,000	0	98,900
Market	NA	62	NA

[a] Pipeline hydrogen leakage is assumed to be 1.59% by energy content and calculated separately

[b]. Where "X" is the percentage of mmBtus supplied

2.2 Model Verification

NREL successfully aligned TVA's model inputs for emissions factors across all included technologies and LCA phases with NREL's methods, which are exemplified in the LA100 study (Nicholson et al. 2021). Further, TVA's methods and calculations (formulas) were verified to align with NREL's; thus, the TVA model was verified.

3 Additional NREL Model Capabilities

To align with the technologies being considered within TVA's IRP, NREL's LCA model had to be expanded in several ways. To support the use of social cost calculations, we required mass emissions of each GHG. Previously, NREL's LCA model reported results only as CO_2-equivalents, so a method was developed to disaggregate to the constituent GHGs (CO_2, CH_4, N_2O).

In another model expansion, we added technologies not previously considered by NREL's LCA model. First, NREL added accounting for the production of hydrogen used for combustion. Second, NREL added nuclear SMR technology. Third, NREL updated the life cycle GHG emissions estimates for natural gas combined cycle with CCS.

3.1 GHG Disaggregation Method and Results for Each Technology

To support the analysis of social costs stemming from the emissions of individual GHGs, it was necessary to disaggregate the LCA Harmonization study's CO_2-equivalent emissions factors (in gram CO_2e per kWh or per kW, depending on the phase) into the three primary constituent pollutants: CO_2, CH_4, and N_2O. NREL disregarded other pollutants that negligibly contributed to GHG emissions.

It was beyond the scope of the TVA IRP to go back to the original studies underlying the median estimates of the per-phase life cycle GHG emissions and extract their per-GHG emissions factors; therefore, we developed an alternative method. The premise of this alternative approach was to use a single, reputable source of life cycle inventory (LCI) data for electricity generation technologies to estimate the proportional contribution (to CO_2e) of each of the three main GHGs and then apply the proportion to the LCA Harmonization study median per-phase GHG emissions factors to obtain the per-GHG emissions factors. A single data source was desired so that the underlying LCA methods were common for all technologies. NREL sought proportional contributions because even if one LCA might differ in its estimate of magnitude of life cycle GHG emissions, the proportional contribution of each GHG is likely to be more stable.

Experts in LCA at NREL examined potential data sources offering detailed GHG emissions factors for each of the four phases of electricity generation technologies. NREL prioritized sources that could provide such detailed breakdowns with a high level of confidence. Our ideal solution was to identify a single source of LCI data; in the end, a few exceptions were made, described in the following. Given its extensive technological detail and coverage of a wide range of technologies, Ecoinvent 3.8 (Wernet et al. 2016) was chosen as the foundational dataset for the analysis.

NREL expanded the Ecoinvent dataset using premise (PRospective EvironMental Impact AsSEssment) (Sacchi et al. 2022), an open-source tool for prospective LCA, supplementing the original database with LCI data for several new power generation technologies. Due to its significance and the absence of data in Ecoinvent, LCI information for nuclear power plant decommissioning was sourced from the literature (Gibon & Menacho, 2023). The updated database was exported using the code-based LCA framework Life-cycle Assessment Integration into Scalable Open-source Numerical models (LiAISON) (Ghosh & Lamers, 2023) and imported into Activity Browser (Steubing et al. 2020), a graphical user interface employing Brightway2

(Mutel, 2017) for conducting emissions analysis. The sequential steps for disaggregating GHG emissions factors are outlined as follows.

First, for each power generation technology, the LCI dataset was separated into four phases: construction, non-combustion operations, combustion processes (where applicable), and the end of life of the power plant. Second, an LCA was performed for each phase with a functional unit of 1 kWh of generated electricity. (Note that the estimate of the proportion of CO_2e emissions contributed by each emitted GHG is not dependent on the choice of functional unit—kWh or kW—because the parameters required to convert between the two [i.e., capacity, capacity factor, and lifetime] themselves do not depend on emissions ratios of different GHGs). Using the emissions inventory explorer, we obtained the total CO_2, CH_4, and N_2O emissions quantities. Using global warming potentials for these emissions, the ratio for emissions factor disaggregation was obtained as follows:

$$R_i = \frac{Q_i . W_i}{\sum_j Q_j . W_j}$$

where R_i is the disaggregation ratio for the i^{th} emission, Q_i is the quantity of the i^{th} emission, W_i is the midpoint indicator weight (global warming potential) for the GHG footprint for the i^{th} emissions, and i and j belong to the set of three pollutants: CO_2, CH_4, and N_2O. Once these ratios were obtained, the aggregated GHG emissions factor (E) from the LCA Harmonization study was multiplied by the R_i value to estimate the disaggregated emissions factor (E_i) for the respective pollutants.

$$E_i = E . R_i$$

Table 2 lists the estimated proportions for each of the three considered GHGs for each technology and phase.

Data were not available to disaggregate GHGs for each of the TVA-analyzed technologies; therefore, assumptions were made to fill in missing values using those for other technologies that were deemed close proxies, as noted in the table.

Table 2. Disaggregation Percentages for Emissions Factors by Technology

	One-Time Upstream			Combustion			Non-Combustion			One-Time Downstream[a]		
Electric Power Technology	**CO_2**	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**
Coal supercritical	94%	6%	1%	100%	0%	0%	51%	47%	2%	97%	2%	1%
Coal subcritical	92%	7%	1%	99%	0%	1%	54%	45%	2%	97%	2%	1%
Combustion turbine	93%	6%	1%	99%	0%	1%	51%	49%	1%	97%	2%	1%
Combined cycle	94%	5%	1%	99%	0%	1%	51%	49%	1%	97%	2%	1%
Combined cycle with CCS	97%	2%	1%	95%	0%	5%	56%	44%	0%	97%	2%	1%
Solar	89%	10%	1%	0%	0%	0%	90%	5%	5%	97%	2%	1%
Hydro	95%	4%	1%	0%	0%	0%	95%	4%	1%	97%	2%	1%
Pumped hydro	95%	5%	1%	0%	0%	0%	95%	5%	1%	97%	2%	1%
Battery	91%	8%	1%	0%	0%	0%	0%[g]	0%[g]	0%[g]	97%	2%	1%
Wind	92%	7%	1%	0%	0%	0%	95%	4%	1%	97%	2%	1%
Nuclear	99%	0%	1%	0%	0%	0%	92%	6%	2%	95%[d]	4%[d]	1%[d]
Nuclear SMR	99%[b]	0%[b]	1%[b]	0%	0%	0%	92%	6%[b]	2%[b]	95%[b]	4%[b]	1%[b]
Biomass	92%	8%	0%	0%[e]	0%[e]	0%[e]	96%	3%	1%	98%	1%	1%
Landfill gas	92%	6%	1%	0%[e]	0%[e]	0%[e]	96%	4%	1%	97%	2%	1%
Hydrogen Combined cycle[h]	93%[c]	6%[c]	1%[c]	0%[f]	0%[f]	0%[f]	92%	7%	1%	97%	2%	1%

[a] The only technology with an Ecoinvent unit process for the downstream life cycle phase was "hard coal IGCC." Biomass and all other technologies are assumed to have the same proportional contribution by GHG as the coal IGCC, except for nuclear, which we obtained from a source as noted in table note d.

[b] Nuclear SMR is assumed to have the same proportional GHG emissions as "nuclear."

[c] A hydrogen combustion turbine is assumed to have the same proportional GHG emissions as a natural gas-fired "combustion turbine" for this life cycle phase.

[d] From Gibon and Menacho (2023)

[e] As per US EPA (Pruitt, 2018), the combustion of biomass is assumed to be net carbon neutral, i.e., the amount of carbon sequestered in the biomass is the same as that which is released to the atmosphere from combustion.

[f] Only NOx emissions are emitted in the combustion of H_2, which were not considered as a GHG in this analysis. NOx is defined as oxides of nitrogen, which includes nitrogen monoxide (NO) and nitrogen dioxide (NO_2). NO_2 should not be confused with N_2O, nitrous oxide, which is a GHG.

[g] There were no operation phase non-combustion emissions present in the Ecoinvent unit process.

[h] Due to the green hydrogen production assumptions, hydrogen co-fired combined cycle utilizes a total life cycle disaggregation percentage for both H_2 and NG ongoing non-combustion phase. Values used for the NG portion were 91%, 8%, and 1% for CO_2, CH_4, and N_2O, respectively.

The Ecoinvent unit processes assumed for each of the analyzed technologies reported in Table 2 are noted in Table 3. The cell entries are the exact names defined in Ecoinvent (Wernet et al. 2016).

Table 3. Ecoinvent Unit Process Correspondence

Technology	Upstream and Downstream	Combustion and Non-Combustion
Coal supercritical	Construction, hard coal IGCC power plant 450 MW[a]	Electricity production, hard coal, ultra-supercritical
Coal supercritical	Hard coal power plant construction, 500 MW	Electricity production, hard coal, subcritical
Combustion turbine	Market for gas power plant, 300 MW electrical	Electricity production, natural gas, conventional power plant
Combined cycle	Market for gas power plant, combined cycle, 400 MW electrical	Electricity production, natural gas, combined cycle power plant
Combined cycle with CCS	Market for gas power plant, combined cycle, 400 MW electrical + CCS construction	Electricity production, at natural gas-fired combined-cycle power plant, post, pipeline 200 km, storage 1,000 m
Solar	Market for photovoltaic plant, 570 kWp, multi-Si, on open ground	Electricity production, photovoltaic, 570 kWp, open ground installation, multi-Si
Hydro	Market for hydropower plant, reservoir	Electricity production, hydro, reservoir, alpine region
Pumped hydro	Market for hydropower plant, reservoir + 5 22-KW pumps	Electricity production, hydro, pumped storage
Battery	Market for battery, Li-ion, rechargeable, prismatic	Note: b
Wind	Market for wind turbine, 2 MW, land-based	Electricity production, wind, 1–3-MW turbine, land-based
Nuclear	Nuclear power plant construction, boiling water reactor 1,000 MW	Electricity production, nuclear, boiling water reactor
Nuclear SMR	Note: c	Note: c
Biomass	Market for heat and power co-generation unit, organic Rankine cycle, 1,000 kW electrical[d]	Heat and power co-generation, wood chips, 6,667 kW, state of the art
Landfill gas	Heat and power co-generation unit construction, 160 kW electrical, components for electricity only	Electricity production, at biomass-fired IGCC power plant
Hydrogen combustion turbine	Note: e	Heat and power co-generation, biogas, gas engine

[a] This is one of two technologies where the downstream Ecoinvent unit process differs from the upstream. In this case, the downstream unit process is “dismantling, hard coal IGCC power plant 450 MW.”

[b] There were no operation phase non-combustion emissions present in the Ecoinvent unit process.

[c] Nuclear SMR is assumed to have the same proportional GHG emissions as “nuclear.”

[d] The downstream unit process for biomass differed from the upstream, and it is “dismantling, BIGCC power plant 450 MW.”

[e] A hydrogen combustion turbine is assumed to have the same proportional GHG emissions as a natural gas-fired “combustion turbine” for this life cycle phase.

3.2 Hydrogen Life Cycle Emission Factor Development

When hydrogen (H_2) is combusted, no greenhouse gas is emitted.[5] However, the production of H_2 always has some embodied GHG emissions. There are many pathways to produce hydrogen; in TVA's IRP, hydrogen usage is assumed to be only "green" H_2, i.e., hydrogen produced through electrolysis powered by 100% renewable energy sources. Thus, there are no GHGs directly emitted in the H_2 production process; yet there are GHGs emitted in the life cycle of the renewable technologies used to produce green H_2.

For H_2 that is combusted to generate electricity, NREL developed an emission factor for the ongoing, non-combustion phase of a combined cycle plant[6] based on the embodied GHG emissions proportional to the mix of renewable technologies that would be expected to produce the green H_2 purchased by TVA. This method also considers leakage of hydrogen once produced. NREL's approach also accounts for different ratios of blending H_2 with natural gas that evolve over time within certain IRP cases.

The below subsections describe the approach NREL developed to account for embodied H_2 emissions.

3.2.1 Proportional Contribution to Green H_2 Production from Renewable Technologies

Leveraging NREL's hydrogen production expertise and in consultation with TVA, NREL selected solar photovoltaic (PV), land-based wind, and short-duration batteries (e.g., 2-hour and 4-hour lithium-ion batteries) as candidate technologies that could be combined to produce green hydrogen within the TVA region.[7] NREL then used a robust least-cost optimization approach, based on cost and performance characteristics for each technology specific to the TVA region, to determine a typical mixture of these three technologies to produce green hydrogen at the scale of future TVA demand.

NREL's approach for estimating the typical generation mix of PV, wind and batteries relies on the Regional Energy Deployment Systems (ReEDS) model (Ho et al. 2020). The ReEDS capacity expansion model simulates the evolution of the U.S. electricity system at a regional scale through 2050. ReEDS is a linear optimization model that identifies the least-cost mix of resources that meet regional electricity demand and policy requirements across the contiguous United States. In each simulated future year, ReEDS co-optimizes the investment, retirement, and operation of all electricity generation, storage, and transmission technologies. To properly

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[5] Combustion of H_2 does not emit the three main GHGs – CO_2, CH_4 and N_2O. Combustion of H_2 does emit NO_2, which is an indirect GHG, but this effect is not considered in NREL's LCAs.

[6] Note that at present, no IRP case utilizes hydrogen in combustion turbines. Thus, the discussion will focus explicitly only on combined cycle plants, though analogous methods and results are directly applicable to combustion turbine use of hydrogen.

[7] TVA assumes the green hydrogen will be produced using a similar mixture of renewable resources that are available within its region, coupled with battery storage.

bound the ReEDS model for this analysis on green hydrogen production, several decisions were made:

- Hydrogen production strictly originated from the technologies that were pre-defined as investment options (PV, land-based wind, and short-duration batteries),
- Hydrogen was produced via proton exchange membrane (PEM) water electrolysis,
- All hydrogen produced is behind-the-meter (i.e., not grid connected), and
- Hydrogen was not transported outside of the demand area where it was produced.

TVA-forecasted hydrogen demand profiles from 2025-2050 were integrated along with TVA's utility boundaries to calculate the optimal, least-cost mix of electricity supply for hydrogen production via electrolysis. Based on 30 ReEDS simulations, NREL found a representative proportional generation mix of 45% PV, 45% wind, and 10% lithium-ion battery. For reference, the levelized cost of hydrogen (LCOH) leading up to the 2032 target of 30% hydrogen blending (see section 3.3.4 below), LCOH values within the TVA region range from \$4.10 per kg to \$7.60 per kg. When accounting for the 45V incentive, this value would be reduced to \$1.10 to \$4.60 per kg in 2032. The large variation reflects regional differences in the cost of hydrogen production, primarily due to differences in the wind and solar resource, including the strength (capacity factor) and timing (hourly generation profile) of electricity production.

3.2.2 Green H_2 Ongoing, Non-combustion Emissions

The ongoing, non-combustion phase for green hydrogen is composed of three components:

1. Green H_2 fuel cycle (production of the fuel by renewables)
2. Operation and maintenance of the plants burning the green H_2
3. Leakage of H_2 once produced and prior to combustion

The estimation of emission factors for each of these components is presented below.

3.2.2.1 Green H_2 Fuel Cycle Emission Factor

To build in flexibility to the LCA model's capability to accommodate differing generation ratios of PV, wind and lithium-ion batteries, a generic formula was developed for the green H_2 fuel cycle emission factor as shown in Equation 1:

$$\begin{aligned} H2\ Fuel\ Cycle\ Emission\ Factor \\ &= (Total\ Life\ Cycle\ PV\ EF * PV\ Generation\ \%) \\ &+ (Total\ Life\ Cycle\ Wind\ EF * Wind\ Generation\ \%) \\ &+ (Total\ Life\ Cycle\ Li\_ion\ Battery\ EF * Li\_ion\ Battery\ Generation\ \%) \end{aligned}$$

Equation 1

In this formula, the total life cycle GHG emission factor of each of the three renewable resources is used instead of per phase emission factors. This is a simplifying assumption, justified for two reasons. First, NREL assumes that an analyst would not know when a PV, wind or battery resource used to produce the green H_2 sold on an open market was constructed or decommissioned. Second, because the life cycle GHG emissions from renewables is small (relative to fossil sources), NREL asserts such differentiation is not influential to accurate accounting of life cycle GHG emissions of the TVA system under IRP cases.

The renewable technology production mix determined applicable for the TVA region was used to quantify embodied emissions from the hydrogen fuel cycle: per above, 45%, 45%, and 10% of solar PV, wind, and lithium-ion batteries, respectively. These percentages were then applied against the total life cycle emission factor values, of 43 g CO_2e/kWh, 13 g CO_2e/kWh, and 33 g CO_2e/kWh, respectively, which were developed in the LCA Harmonization study and most recently documented in the LA100 study (Nicholson et al. 2021). The TVA region-specific mixture of PV, wind and batteries yields a weighted average emission factor of 28.5 g CO_2e/kWh.

3.2.2.2 H_2 Operation and Maintenance Emission Factor

The ongoing non-combustion emission factor for hydrogen combustion requires quantification of GHG emissions associated with plant operation and maintenance (O&M). For this analysis, NREL made the simplifying assumption that O&M for a hydrogen-fueled CC plant would be approximately the same as for a similar plant burning natural gas as their fuel, and that likewise, a plant burning blended H_2 and natural gas would also be approximately the same.[8] These assumptions are adopted also because there is no published LCA that has reported a detailed analysis of O&M for plants using similar combustion technology on different fuels.

Most natural gas LCAs do not separately report O&M GHG emissions; it is usually reported grouped with other activities. NREL identified one study – Cutshaw et.al (2023) – that separately reported O&M GHG emissions from a combined cycle plant, estimating GHG emissions of 0.4 g CO_2e/kWh which is assumed applicable for both H_2 and natural gas-fired (and blended) CCs.

3.2.2.3 H_2 Leakage Rate

An emission concern for hydrogen fuel production and utilization is hydrogen leakage. Part of NREL's method for quantifying hydrogen fuel's ongoing, non-combustion emission factor involved estimating the hydrogen leakage rate during green H_2 production, pipeline transport, storage and local distribution. The state of knowledge of these emission rates is still evolving, without a strong empirical basis currently. Referencing best available literature (Cooper et al., 2022; Esquivel-Elizondo et al., 2023; Fan et al., 2022; Mills, 2022) NREL identified all that disaggregated H_2 leakage for different supply chain stages and assessed the range of estimated hydrogen leakage rates. Table 4 summarizes the central tendency for upper and lower bounds for hydrogen leakage rates found in current literature.

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[8] As an aside, note that NREL makes the same assumption for H_2 combusted in a Combustion Turbine.

Table 4. Range of Hydrogen Mass Leakage Rates along Supply Chain Stages Relevant for Combustion of Hydrogen for Electricity Generation

Supply Chain Stage	Upper Bound Leakage (Mass %)	Lower Bound Leakage (Mass %)	Source(s)
Green Hydrogen Production	4%	2%	Fan et al., 2022
Pipeline Transport & Storage	2%	1%	Fan et al., 2022; Cooper et al., 2022
Local Distribution	0.44%	0.17%	Fan et al., 2022; Cooper et al., 2022

To develop a best (point) estimate for H_2 leakage applicable to TVA's IRP cases, NREL reviewed TVA's assumptions regarding H_2 production. TVA's set of *Net-zero Regulation* and *Net-zero Regulation Plus Growth* IRP cases adopt the Department of Energy's H_2 Earthshot (*Hydrogen Shot*) goals and milestones to determine hydrogen pricing. DOE assumes that strict policies and regulations have been enacted to support hydrogen fuel's integration into the energy sector. NREL extended the pricing assumptions regarding policies and regulations to leakage regulation and mitigation strategies to develop a point estimate of hydrogen leakage from each of the above supply chain stages. Below in Table 5 are the values used to calculate a total life cycle leakage rate for the production of green hydrogen within TVA's *Net-Zero Regulation* and *Net-Zero Regulations Plus Growth* cases.

Table 5. Point Estimate Hydrogen Mass Leakage Rates along TVA IRP-Relevant Supply Chain Stages

Supply Chain Stage	Hydrogen Leakage (Mass %)
Green Hydrogen Production	3%
Pipeline Transport & Storage	1.5%
Local Distribution	0.26%
Total:	4.76%

Note that the leakage percentage is on a mass basis; conversion to energy content or volume basis can be accomplished using the following constants (Table 6):

Table 6. Hydrogen Properties

Property	**Value**	**Source**
Energy Density of Hydrogen	120 MJ/kg	*Hydrogen Storage*. (n.d.).
Hydrogen Density	0.08376 kg/m^3	Lanz, 2001
Hydrogen Energy Density in MMBTU	0.1137 MMBTU/kg	

NREL then converted the selected leakage rate from a percent by mass, 4.76%, to a percent by energy. Using hydrogen's energy density in MMBTU of 0.1137 MMBTU/kg, the converted leakage contribution was found to equal 0.571% by energy.

3.2.3 Final Emission Factors for H_2-Fueled Combined Cycle Plants

Prior to considering blends of H_2 and natural gas, life cycle emission factors for the three applicable life cycle phases must be developed (recalling that combustion of H_2 emits none of the three major GHGs) for Combined Cycle plants fueled solely by hydrogen: upstream, ongoing non-combustion, and downstream phases.

3.2.3.1 Upstream/Downstream

The onetime upstream and downstream emission factors for a H_2 Combined Cycle are assumed to be essentially equivalent to their natural gas counterparts, as reported in the LA100 study (Nicholson et al. 2021).[9] These values, in grams CO_2e/kW, are listed in Table 7.

Table 7. Upstream and Downstream Life Cycle GHG Emissions for Hydrogen-powered Combined Cycle Plants

Electric Power Technology	**One-Time Upstream GHG (CO_2 equivalent), g/kW**	**One-Time Downstream GHG (CO_2 equivalent), g/kW**
Hydrogen Combined Cycle	100,000	4,070

3.2.3.2 Ongoing Non-Combustion

For determining the ongoing non-combustion emission factor for hydrogen-fueled combined cycle plants, NREL developed Equation 2 to incorporate the three components of GHG emissions detailed in section 3.3.3.

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[9] As an aside, note that NREL assumes the same equivalence is true for Combustion Turbines.

$$H_2\ Ongoing\ Non\text{-}Combustion\ EF\ (\frac{g\ CO2e}{kWh}) = (H_2\ Fuel\ Cycle\ EF + H_2\ O\&M\ EF) * (1 + H_2\ Leakage\ Rate)$$

Equation 2

First, the renewable technology production mix determined applicable for the TVA region was used to quantify embodied emissions from the hydrogen fuel cycle. Refer to section 3.2.2.1 for full description and calculation.

Second, the emissions contribution of hydrogen combustion plant O&M was assumed to be identical to that of O&M for natural gas fuel systems. Thus, the value from Cutshaw et.al (2023) of 0.4 g CO_2e/kWh was applied.

Third, for the hydrogen leakage rate, the determined average leakage rate percent across the total hydrogen life cycle for the given TVA scenarios was referenced: 4.76% by mass, and 1.58% by energy. Refer to section 3.2.2.3 for full description and derivation.

Using Equation 2, the total ongoing non-combustion hydrogen emission factor was found to be 29 g CO_2e/kWh.

3.2.4 H_2/NG Blended Fuel Cycle Emission Factors

TVA’s Net-zero Regulation IRP cases have assumed a phased shift from natural gas to hydrogen-blended fuel for the combined cycle fleet, based on regulatory requirements. Given forecasted hydrogen demand in H_2-relevant IRP cases, and the determined volumetric fuel blend of H_2/NG per year from 2024-2050, NREL developed Equation 3 for the ongoing fuel cycle emission factor.

$$Blended\ Fuel\ Cycle\ EF = (H_2\ Fuel\ Cycle\ EF * H_2\ Blend\ \%) + (NG\ Fuel\ Cycle\ EF * NG\ Blend\ \%)$$

Equation 3

where:

$$1 = (H_2\ Blend\ \%) + (NG\ Blend\ \%)$$

Equation 4

First, the associated hydrogen fuel cycle value was determined by the weighted average of renewable energy technology generation associated with producing green hydrogen; 28.5 g CO_2e/kWh. For the natural gas fuel cycle emission factor, the latest LCA study reporting the natural gas fuel cycle disaggregated from other components of ongoing, non-combustion -- Cutshaw et.al (2023) – was referenced to determine the value associated with natural gas extraction, processing, and transport for a combined cycle system with no carbon capture and sequestration: 92 g CO_2e/kWh.

Finally, the volumetric blending percentages for the H2/NG fuel cycle were determined by TVA's scenario assumptions. The blending percentage profile from 2024-2050 can be seen in Table 8.

Table 8. TVA IRP H_2 Blending Assumptions, 2024-2050

Year	Volumetric Percent NG In blend	Volumetric Percent H_2 in Blend
2024	100%	0%
2025	100%	0%
2026	100%	0%
2027	100%	0%
2028	100%	0%
2029	100%	0%
2030	100%	0%
2031	100%	0%
2032	70%	30%
2033	70%	30%
2034	70%	30%
2035	70%	30%
2036	70%	30%
2037	70%	30%
2038	4%	96%
2039	4%	96%
2040	4%	96%
2041	4%	96%
2042	4%	96%
2043	4%	96%
2044	4%	96%
2045	4%	96%
2046	4%	96%
2047	4%	96%
2048	4%	96%
2049	4%	96%
2050	4%	96%

3.3 SMR Life Cycle GHG Emissions

NREL conducted a literature review to estimate life cycle emissions factors for each life cycle phase for small modular nuclear reactors (SMRs). SMRs are reactors with a nameplate capacity less than 300 MW (International Atomic Energy Agency 2023). SMR technology has existed since the early 2000s with the introduction of the Multi-Application Small Light Water Reactor (MASLER/WR), which was furthered by NuScale furthered into the small modular reactor ("The

Story Behind America's First Potential Small Modular Reactor," n.d.). Today, the World Nuclear Association has listed dozens of SMR models that are under development ("Small Nuclear Power Reactors - World Nuclear Association," n.d.). For our analysis, we looked at three different models of SMRs: integrated pressurized water reactors (iPWRs) in Carless et al. (2016), a high temperature helium cooled reactor and gas turbine technology with modular helium reactor (GT-MHR) in Koltun et al. (2018), and a NuScale module from the United States in Malatesta (2021).

3.3.1 Literature Identification

Literature for SMR life cycle assessments was obtained from several citation databases as well as from a snowballing approach. In the snowballing approach, NREL identified publications that passed all screens and then either searched upstream, in the citations of that publication, or downstream, in publications that cited that paper. Four screens were applied to identify literature that met all requirements for quality, relevance, transparency, and recency. The screening process was modeled after the process used in Warner and Heath (2012). Their harmonization of LCA literature screened publications to collect and harmonize data on GHG emissions from nuclear electricity generation technologies. The life cycle processes of the nuclear systems were grouped into three categories: upstream emissions related to plant construction, ongoing non-combustion emissions related to plant operation and maintenance and the nuclear fuel cycle, and downstream emissions related to plant decommissioning.

The universe of literature evaluated was generated through searches of Scopus and OSTI, and separately by "snowballing" on identified publications. NREL developed two lists of terms: words that would indicate the presence of an LCA, and words and model names that would suggest that the technology evaluated was SMR technology. The search strings were designed to return results that contained a combination of these two categories of words.

Table 9. Keywords Used to Identify Published LCAs Focused on SMR

LCA	SMR Column 1	SMR Column 2	Additional Scopus Terms
carbon account*	MARVEL Research Microreactor *	RITM-200M*	small modular w/5 reac tor*
Carbon foot print*	ARC-100 *	MHR-100*	small w/5 modular reactor*
Carbon footprint*	KP-FHR *	KLT-40S*	small w/5 reactor*
cradle W/3 cradle	Hermes prototype *	GT-MHR*	
cradle W/3 grave	MMR-5 *	ELENA*	
LCA*	Natrium *	EGP-6*	
LCIA*	Thorcon TMSR *	BREST-OD-300*	
Life cycle analys*	VOYGR	ABV-6E*	
Life cycle assessment*	Nuscale micro *	VK-300*	
Life cycle impact analys*	FMAurar *	UNITHERM*	

Life cycle impact assessment*	FMR *	SHELF-M*	
Lifecycle analys*	PB-FHR *	RUTA-70*	
Life-cycle analys*	EM2 *	KARAT-45*	
Lifecycle assessment*	FUJI*	SVBR-100*	
Life-cycle assessment*	BWRX-300*	KARAT-100*	
Lifecycle impact analys*	Holos Quad*	HTMR100 Th-100*	
Life-cycle impact analys*	PRISM*	PBMR-400*	
Lifecycle impact assessment*	OPEN20*	AHTR-100*	
Life-cycle impact assessment*	Xe-100*	PHWR-220*	
	BANR*	AHWR-300 LEU*	
	MCFR*	i-SMR*	
	LFTR*	SMART*	
	SMR-160*	MicroURANUS*	
	Starcore	BANDI-60*	
	Westinghouse SMR*	ACPR50S*	
	Westinghouse LFR*	ACPR100*	
	IMSR400*	LandStar-I*	
	eVinci	HAPPY200*	
	SSR-W*	DHR400*	
	SSR-U*	CAP50*	
	Moltex SSR-W	CAP200 LandStar-V*	
	Aurora Powerhouse Product Line*	CAP150*	
	i-SMRP*	ACP100S*	
	LFR-TL-30*	HTR-PM*	
	THORIZON*	HTR-10*	
	STAR*	NHR200-II*	
	NUWARD*	ACP100*	
	SC-HTGR*	SNP350*	
	JIMMY*	TMSR-SF*	
	Seaborg CMSR*	CNP-300*	
	Copenhagen Atomics Waste Burner*	MoveluX*	
	U-Battery*	IMR*	

	UK SMR*	HTTR*	
	LFR-AS-200*	GTHTR300*	
	SEALER-55	4S*	
	Energy Well*	PeLUIt/RDE*	
	VBER-300*	nuclear	
	RITM-200S*	small modular reactor*	
	RITM-200N*	SMR*	

Notes: LCIA - Life Cycle Impact Assessment. An asterisk (*) acts as a truncation symbol, meaning that the search term will pick up alternate word endings. For example, the keyword “carbon footprint*” will pick up “carbon footprint,” “carbon footprints,” and “carbon footprinting.” The Scopus search has additional functionality not available on OSTI, so some search terms were used in Scopus only. In Scopus, “w/5” will return all results in which the first term occurs within five words of the second term.

NREL developed search strings to identify literature that could potentially contain an LCA on SMR. Two citation databases were searched: SCOPUS and OSTI.

Table 10. Search Strings Used in the SCOPUS and OSTI Databases

Search #	SCOPUS Search Queries	OSTI Search Queries
1	Performed on 12/17/2023 Query: **TITLE** ((lifecycle AND assessment) OR (lifecycle AND assessments) OR (lifecycle AND analysis) OR (lifecycle AND analyses) OR (life-cycle AND assessment) OR (life-cycle AND assessments) OR (lifecycle AND analysis) OR (lifecycle AND analyses) OR (life AND cycle AND assessment) OR (life AND cycle AND assessments) OR (life AND cycle AND analysis) OR (life AND cycle AND analyses) OR (footprint AND analysis) OR (carbon AND footprint) OR (carbon AND foot AND print) OR (carbon AND footprinting) OR (carbon AND accounting) OR (carbon AND emissions) OR (cradle W/3 cradle) OR (cradle W/3 grave) OR (environmental AND impact) OR (environmental AND impacts) OR (total AND cycle) OR (fuel AND cycle) OR (externalities) OR (embodied AND carbon) OR (embedded AND carbon)) AND TITLE ((small AND modular AND reactor) OR (small AND modular AND reactors) OR (smr) OR (smrs) OR	Performed on 5/21/2024 Query: ("carbon account*"OR "Carbon foot print*" OR "Carbon footprint*" OR "cradle to cradle" OR "cradle to grave" OR "LCA*" OR "LCIA*" OR "Life cycle analys*" OR "Life cycle assessment*" OR "Life cycle impact analys*" OR "Life cycle impact assessment*" OR "Lifecycle analys*" OR "Life-cycle analys*" OR "Lifecycle assessment*" OR "Life-cycle assessment*" OR "Lifecycle impact analys*" OR "Life-cycle impact analys*" OR "Lifecycle impact assessment*" OR "Life-cycle impact assessment*")AND ("MARVEL Research Microreactor * " OR "ARC-100 *" OR "KP-FHR *" OR "Hermes prototype *" OR "MMR-5 *" OR "Natrium *" OR "Thorcon TMSR *" OR "VOYGR" OR "Nuscale micro *" OR "FMAurar *" OR "FMR *" OR "PB-FHR *" OR "EM2 *" OR "FUJI*" OR "BWRX-300*" OR "Holos Quad*" OR "PRISM*" OR "OPEN20*" OR "Xe-100*" OR "BANR*" OR "MCFR*" OR "LFTR*" OR "SMR-160*" OR "Starcore" OR "Westinghouse SMR*" OR "Westinghouse LFR*" OR "IMSR400*" OR "eVinci" OR "SSR-W*" OR "SSR-U*" OR "Moltex SSR-W" OR "Aurora Powerhouse Product Line*" OR "i-SMRP*" OR "LFR-TL-30*" OR "THORIZON*" OR "STAR*" OR "NUWARD*" OR "SC-HTGR*" OR "JIMMY*" OR "Seaborg CMSR*" OR "Copenhagen Atomics Waste Burner*" OR "U-Battery*" OR "UK SMR*" OR "LFR-

	(small AND modular W/5 reactor) OR (small W/5 modular AND reactor))	AS-200*" OR "SEALER-55" OR "Energy Well*" OR "VBER-300*" OR "RITM-200S*" OR "RITM-200N*" OR "RITM-200M*")
2	Performed on 12/18/2023 Query: **TITLE** ((lifecycle) OR (life AND cycle) OR (life-cycle) OR (lifecycle AND assessment) OR (lifecycle AND assessments) OR (lifecycle AND analysis) OR (lifecycle AND analyses) OR (life-cycle AND assessment) OR (life-cycle AND assessments) OR (lifecycle AND analysis) OR (lifecycle AND analyses) OR (life AND cycle AND assessment) OR (life AND cycle AND assessments) OR (life AND cycle AND analysis) OR (life AND cycle AND analyses) OR (footprint AND analysis) OR (carbon AND footprint) OR (carbon AND foot AND print) OR (carbon AND footprinting) OR (carbon AND accounting) OR (carbon AND emissions) OR (cradle W/3 cradle) OR (cradle W/3 grave) OR (environmental AND impact) OR (environmental AND impacts) OR (total AND cycle) OR (fuel AND cycle) OR (externalities) OR (embodied AND carbon) OR (embedded AND carbon)) AND TITLE ((small AND modular AND reactor) OR (small AND modular AND reactors) OR (smr) OR (smrs) OR (small AND modular W/5 reactor) OR (small W/5 modular AND reactor))	Performed on 5/21/2024 Query: ("carbon account*"OR "Carbon foot print*" OR "Carbon footprint*" OR "cradle to cradle" OR "cradle to grave" OR "LCA*" OR "LCIA*" OR "Life cycle analys*" OR "Life cycle assessment*" OR "Life cycle impact analys*" OR "Life cycle impact assessment*" OR "Lifecycle analys*" OR "Life-cycle analys*" OR "Lifecycle assessment*" OR "Life-cycle assessment*" OR "Lifecycle impact analys*" OR "Life-cycle impact analys*" OR "Lifecycle impact assessment*" OR "Life-cycle impact assessment*")OR "MHR-100*" OR "KLT-40S*" OR "GT-MHR*" OR "ELENA*" OR "EGP-6*" OR "BREST-OD-300*" OR "ABV-6E*" OR "VK-300*" OR "UNITHERM*" OR "SHELF-M*" OR "RUTA-70*" OR "KARAT-45*" OR "SVBR-100*" OR "KARAT-100*" OR "HTMR100 Th-100*" OR "PBMR-400*" OR "AHTR-100*" OR "PHWR-220*" OR "AHWR-300 LEU*" OR "i-SMR*" OR "SMART*" OR "MicroURANUS*" OR "BANDI-60*" OR "ACPR50S*" OR "ACPR100*" OR "LandStar-I*" OR "HAPPY200*" OR "DHR400*" OR "CAP50*" OR "CAP200 LandStar-V*" OR "CAP150*" OR "ACP100S*" OR "HTR-PM*" OR "HTR-10*" OR "NHR200-II*" OR "ACP100*" OR "SNP350*" OR "TMSR-SF*" OR "CNP-300*" OR "MoveluX*" OR "IMR*" OR "HTTR*" OR "GTHTR300*" OR "4S*" OR "PeLUIt/RDE*" OR "nuclear") OR "small modular reactor*"OR "SMR*")
3	Performed on 12/29/2023 Query: **TITLE** ((lifecycle) OR (life AND cycle) OR (life-cycle) OR (lifecycle AND assessment) OR (lifecycle AND assessments) OR (lifecycle AND analysis) OR (lifecycle AND analyses) OR (life-cycle AND assessment) OR (life-cycle AND assessments) OR (lifecycle AND analysis) OR (lifecycle AND analyses) OR (life AND cycle AND assessment) OR (life AND cycle AND assessments) OR (life AND cycle AND analysis) OR (life AND cycle AND analyses) OR (footprint AND analysis) OR	

	(carbon AND footprint) OR (carbon AND foot AND print) OR (carbon AND footprinting) OR (carbon AND accounting) OR (carbon AND emissions) OR (cradle W/3 cradle) OR (cradle W/3 grave) OR (environmental AND impact) OR (environmental AND impacts) OR (total AND cycle) OR (fuel AND cycle) OR (externalities) OR (embodied AND carbon) OR (embedded AND carbon)) AND TITLE ((small AND modular AND reactor) OR (small AND modular AND reactors) OR (smr) OR (smrs) OR (small AND modular W/5 reactor) OR (small W/5 modular AND reactor) OR (mpower) OR (voyger) OR (smr-300) OR (klt-40s) OR (ap1000) OR (smmsr) OR (hwmsr) OR (abv-6m) OR (ritm-200) OR (sm-tmsr) OR (sm-msr) OR (advanced AND nuclear) OR (small W/5 reactor) OR (small W/5 reactors))	

The search dates for each query are listed in Table 10.

The SCOPUS search returned 643 pieces of literature. The OSTI search returned 1,327 publications. In addition to the search results from SCOPUS and OSTI, promising publications from a snowballing technique were also included in the universe for screening. The first paper to initially pass all screens was “The environmental competitiveness of small modular reactors: A life cycle study” (Carless, Griffin, and Fischbeck 2016). Papers published after Carless et al. that referenced the publication were included in the snowballing search. Two other publications were also used as sources in the snowballing technique: (“Embodied Emissions for Advanced Nuclear Reactors: Nuclear-IES Greenhouse Gas Model Project,” n.d.)) and (Le Boulch et al. 2024)). Rather than searching for publications that cited these two more modern papers, however, NREL collected and screened the references in these papers. The total number of papers screened, from all sources, came to 2,012.

3.3.2 Literature Screening

Four screens were used to filter papers that did not meet requirements for relevancy, quality, originality, transparency, and reporting standards. Screen 1 used bibliographic data to remove publications that were duplicates, written in a language other than English, published before 1980, less than five pages long, or in the wrong file format. Screen 2 focused on removing publications that did not meet standards for relevancy. Relevant literature was defined as literature that contained an LCA on SMR. NREL took a liberal approach during this screen, retaining publications that contained an LCA on nuclear technology that had not been ruled out as SMR. Later, in Screen 3, NREL examined the full text and removed publications containing LCAs on nuclear technology that was not classified as SMR technology. Screen 3 also focused on criteria related to methodology and reporting requirements. Screen 4 was the last screen completed before data extraction and removed any paper that did not report LCA emissions results by life cycle phase.

Table 11. Criteria Used for Screening the Identified Universe of Publications

Screen (Information Used to Screen)	Criteria
Screen 1 (Search)	1 Search criteria 1.1 Remove duplicated publications 1.2 Remove publications not written in English 1.3 Remove publications published before 1980 1.4 Remove publications that are less than five pages 1.5 Remove publications that are abstracts, posters, and PowerPoint presentations
Screen 2 (Title, Abstract, Full Text - where necessary)	2 Complete LCA on small modular reactors 2.1 Remove publications that did not evaluate SMRs as the product (A conservative approach was taken where a publication included nuclear technology that couldn’t quickly be ruled out as SMR. The reactor capacity was later checked in Screen 3.) 2.2 Remove publications that did not include an LCA (LCA results must report normalized emissions as CO_2e/kWh or CO_2e/kW)
Screen 3 (Full Text)	3 High quality, relevant, original, and transparent LCA 3.1 Remove publications that use AEI methods, do not include all life cycle phases (upstream, operations, and downstream). 3. 2 Remove publications that do not report results numerically, do not document the software or modeling technique used, do not cite data sources, and do not contain original work for all phases. 3.3 Remove publications that do not pertain to current-day SMR (reactor capacity < 300 MW(e)). 3. 4 Remove publications that do not report electricity as a product (Electricity can be an intermediate product later converted to another product).
Screen 4 (Full Text)	4 Focus emissions reported in results 4.1 Remove publications that do not report results by life cycle phase.

Notes: AEI – average economic intensity, which is a highly aggregated form of economic input-output-based LCA (see Warner and Heath, 2012)

Three publications passed all four screens. Those works were Carless et al. (2016), Koltun et al. (2018), Malatesta (2021). Life cycle emission data was extracted from the numerical results reported in these three publications. One of these papers, Koltun et al. (2018), contained LCA results for emissions savings from the recycling of materials. Results from this paper are reported as two scenarios: without recycling credits and including recycling credits.

3.3.3 Life cycle GHG emissions per phase for SMR

Results for six different scenarios were extracted from the three publications that passed all screens. The publications reported results in a variety of units. Where needed, units were converted to g CO_2e per kW for upstream and downstream emissions and g CO_2e per kWh for ongoing non-combustion emissions. Total emissions are reported in g CO_2e per kWh. Two publications from which these scenarios were extracted reported the system lifetime, capacity factor, and system capacity. NREL used these operational parameters reported in each publication to convert between g CO_2e/kW and g CO_2e/kWh. Koltun did not report the system lifetime or capacity factor. NREL assumed a lifetime of 40 years and a capacity factor of 92%, the same assumptions used in a previous nuclear reactor harmonization paper (Warner and Heath (2012)). A summary of these parameters is given in Table 12. The net reactor capacities, net system capacities, system lifetimes, capacity factors, and locations are reported in Table 12.

Table 12. System Characteristics of Each Published Scenario

Author (Year)	Reactor Net Capacity (MW)	System Net Capacity (MW)	System Lifetime (Years)	Capacity Factor (%)	Location
Carless et al. (2016)	225*	225	60	97	U.S.
Koltun et al. (2023)	285	1140 (results reported on basis of 1000)	60	90	Australia
Koltun et al. (2023)	285	1140 (results reported on basis of 1000)	60	90	Australia
Koltun et al. (2023)	285	1140 (results reported on basis of 1000)	60	90	Australia
Koltun et al. (2023)	285	1140 (results reported on basis of 1000)	60	90	Australia
Malatesta (2021)	57	684	40*	92*	Australia

Notes: Carless et. al did not specify whether the reactor capacity was net or gross. It was assumed to be net. System lifetime (years) and capacity factor were not reported by Malatesta and these were assumed based on a previously reported in Warner and Heath (2012).

Carless et. al (2016) reported emissions for all processes in units of g CO_2e per kWh. To convert upstream and downstream emissions to the units of g CO_2e per kW, we multiplied the reported upstream emissions by the lifetime electricity produced and divided by the reactor capacity as shown in Equation 5. The lifetime electricity produced was reported as 114 TWh in the publication. It was not specified as net or gross and was assumed to be net. The reactor capacity was reported as 225 MW (also not specified as net or gross and assumed to be net).

$$\frac{g\ CO_2e}{kW} = \frac{g\ CO_2e}{kWh} * \frac{lifetime\ kWh}{reactor\ net\ kW}$$

Equation 5

Koltun et. al (2023) reported emissions in units of 10^3 tons CO_2e eq. The lifetime net electricity produced was reported to be 469.5 TWh. The conversions to g CO_2e per kW and g CO_2e per kWh are shown in Equation 6 and Equation 7

$$\frac{g\ CO_2e}{kW} = 10^3 tons\ CO_2e * 10^3 * \frac{10^6\ g\ CO_2e}{ton\ \ CO_2e} * \frac{1}{reactor\ net\ kW}$$

Equation 6

$$\frac{g\ CO_2e}{kWh} = 10^3 tons\ CO_2e * 10^3 * \frac{10^6 gCO_2e}{ton\ CO_2e} * \frac{1}{lifetime\ kWh}$$

Equation 7

Malatesta (2021) reported emissions results in g CO_2e per kWh. The lifetime electricity produced was calculated using the assumed lifetime of 40 years, assumed capacity factor of 92%, and reported net capacity of 684 MW, as the lifetime electricity produced could not be located in the publication. Then g CO_2e per kW for upstream and downstream phases were calculated using Equation 8 and 5.

$$lifetime\ kWh = 40\ years * \frac{365\ days}{year} * \frac{24\ hours}{day} * 0.92 * 684{,}000\ reactor\ net\ kW$$

Equation 8

NREL grouped reported life cycle phases into the categories of upstream, ongoing non-combustion, and downstream, with all nuclear fuel cycle activities included in the ongoing non-combustion phase. CO_2e emissions for each lifecycle stage are reported in Table 13. The publication by Koltun et al. contained results for emissions that occurred due to accidents and incidents during operations as well as emissions savings for recycling credits. NREL assumed that emissions related to accidents and incidents were included in the ongoing non-combustion phase for the scenarios extracted from the Koltun paper.

Table 13. Published, Per-Phase GHG Emissions for SMR

Author (Year)	Accidents & Incidents	Recycling Credits	Upstream GHG Emissions (g CO_2e / kW)	Ongoing Non combustion GHG Emissions (g CO_2e / kWh)	Downstream GHG Emissions (g CO_2e / kW)	Total Life Cycle GHG Emissions (g CO_2e / kWh)
Carless et al. (2016)	N.R.	N.R.	4.6 x 10^{5}*	7.8	1.8 x 10^{5}*	9.1
Koltun et al. (2023)	No	No	1.9 x 10^{6}*	2.2	2 x10^{5}*	6.7
Koltun et al. (2023)	No	Yes	1.9 x 10^{6}*	2.2	6.6 x 10^{4}*	6.4
Koltun et al. (2023)	Yes	No	1.9 x 10^{6}*	16	2 x 10^{5}*	21*
Koltun et al. (2023)	Yes	Yes	1.9 x 10^{6}*	16	6.6 x 10^{4}*	21*
Malatesta (2021)	N.R.	N.R.	8.1 x 10^{5}*	37	3.5 x 10^{5}*	41*

Notes: N.R. – Not Reported. Asterisk (*) signifies that this result was calculated by NREL using system characteristics for each scenario. Values are rounded to two significant figures.

From the emissions results of the six scenarios, NREL calculated sample statistics: the minimum, maximum, and the first, second, and third quartiles (where applicable). These statistics are reported in Table 10. The median value for the total life cycle GHG emissions was 15 g CO_2e per kWh. The mean was 17 g CO_2e per kWh. In the previous nuclear harmonization paper, Warner and Heath (2012) reported both the mean published GHG emissions as well as the mean harmonized GHG emissions for LCAs on nuclear electricity generation. The published mean and harmonized mean were 25 g CO_2e per kWh and 18 g CO_2e per kWh respectively for light water reactors, 30 g CO_2e per kWh and 22 g CO_2e per kWh for pressurized water reactors, and 18 g CO_2e per kWh and 11 g CO_2e per kWh for boiling water reactors (Warner and Heath (2012)).

The total reported LCA GHG emissions in Malatesta (2021) also stand out, with a total life cycle emission factor more than twice the next smallest value. In this publication, two stages in the nuclear fuel cycle, mining and milling and conversion, contribute the majority of these LCA emissions at a combined total of 31.1 g CO_2e per kWh. In comparison, Carless et. al (2016) reported only 4.6 g CO_2e per kWh for the entire nuclear fuel cycle. Koltun et al. (2023) reported 9.87 g CO_2e per kWh for the nuclear power cycle.

Table 14. Summary Statistics of Life Cycle GHG Emissions Per Phase for SMR

Summary Statistic	Upstream GHG Emissions (g CO_2e / kWh)	Ongoing Non-combustion GHG Emissions (g CO_2e / kWh)	Downstream GHG Emissions (g CO_2e / kWh)	Total Life Cycle GHG Emissions (g CO_2e / kWh)
Minimum	0.90	2.2	0.14	6.4
First Quartile	NA	3.6	0.20	7.3
Median	2.9	12	0.40	15
Third Quartile	NA	16	0.43	21
Maximum	4.1	37	1.1	41
Count	3	6	6	6

Note: Values are rounded to two significant figures. NA = this distributional statistic was not applicable given the count of estimates.

Table 15. Summary Statistics of Life Cycle GHG Emissions Per Phase for SMR (With Units of Upstream and Downstream Phases Per kW)

Summary Statistic	Upstream GHG Emissions (g CO_2e / kW)	Ongoing Non-combustion GHG Emissions (g CO_2e / kWh)	Downstream GHG Emissions (g CO_2e / kW)	Total Life Cycle GHG Emissions (g CO_2e / kWh)
Minimum	4.6×10^5	2.2	6.6×10^4	6.4
First Quartile	NA	3.6	9.5×10^4	7.3
Median	8.1×10^5	12	1.9×10^5	15
Third Quartile	NA	16	2.0×10^5	21
Maximum	1.9×10^6	37	3.5×10^5	41
Count	3	6	6	6

Note: Values are rounded to two significant figures. NA = this distributional statistic was not applicable given the count of estimates.

For the purposes of our analysis for TVA, we adopted the median values presented in Table 15.

3.3.4 Limitations

SMR is an emerging technology, with many reactor models still under development. As such, the literature passing all screens was very sparse. In the literature that did pass, assumptions about LCA emissions were sometimes based on data for older generation nuclear technology in the absence of relevant data for SMR. Additionally, some papers that appeared to be an LCA on SMR based on title did not pass the requirements for original work or methodology reporting. The small number of scenarios and variability in the publications' results gives rise to uncertainty in the expected value for LCA emissions of SMR.

3.4 NGCC-CCS Life Cycle GHG Emissions

NREL performed a literature review of LCAs focused on natural gas combined cycle with carbon capture and storage (NGCC-CCS) systems with the goal of developing updated GHG emissions factors for each life cycle phase. The literature review was completed in two steps: first, NREL searched bibliographic databases and performed snowball sampling (defined below) to identify relevant publications; second, NREL screened the identified publications to eliminate nonapplicable studies. These steps were performed in accordance with global guidance on conducting and reporting systematic literature reviews (Page et al., 2021).

This literature review built on the foundation provided by O'Donoughue et al. (2014), who performed a systematic review and harmonization of the natural gas electricity generation LCA literature published between 1980 and 2012. Their work identified twelve results (from nine publications) in which per phase GHG emissions were reported for NGCC-CCS systems. This work also built upon a more recent systematic literature review performed within the National Petroleum Council's (NPC) *Charting the Course: Reducing GHG Emission from the U.S, Natural Gas Supply Chain* study (NPC, 2024). The NPC's review searched for natural gas supply chain LCAs published 2016-2022, inclusive of those that used the natural gas for electricity generation with CCS. However, there were no usable results for NGCC-CCS systems identified within the NPC's review. Updating the results of both of the prior literature reviews added eight results (from four publications) to their tally.

3.4.1 Literature Identification

NREL generated a series of keywords related to LCAs focused on NGCC-CCS, starting from those used in O'Donoughue et al. (2014) but tailored to NGCC with CCS (Table 16). NREL grouped these keywords into four categories: emissions, LCA, natural gas, and power. Note that natural gas combustion turbines-associated keywords were included in our search criteria because some of those studies would also have investigated NGCC, however, all results relevant to NGCT were later screened out.

Table 16. Keywords Used to Identify Published LCAs Focused on NGCC-CCS

Emissions	LCA	Natural Gas	Power
Carbon footprint*	LCA*	Natural gas	Power
Carbon foot print*	Life cycle assessment*	Shale gas	Electric*
Greenhouse gas analys*	Life cycle analys*	Fossil gas	Carbon capture
Greenhouse gas emission*	Lifecycle assessment*	Natural gaz	Carbon dioxide capture
GHG analys*	Lifecycle analys*	Shale gaz	CO_2 capture
GHG emission*	Life-cycle assessment*	Fossil gaz	CCS
	Life-cycle analys*	NG	CCUS
	LCIA*	NGCC	
	Life cycle impact assessment*	NG-CC	
	Life cycle impact analys*	NGCT	
	Lifecycle impact assessment*	NG-CT	
	Lifecycle impact analys*	NGSC	

Life-cycle impact assessment*	NG-SC
Life-cycle impact analys*	NGT
	LNG
	Methane
	CH_4
	Peaker Plant*
	Peaker*

Notes: LCIA - Life Cycle Impact Assessment, NGCC – Natural Gas Combined Cycle, NGCT – Natural Gas Combustion Turbine, NGSC – Natural Gas Single Cycle, NGT – Natural Gas Turbine, LNG - Liquefied Natural Gas, CCUS - Carbon Capture, Utilization and Storage. An asterisk (*) acts as a truncation symbol, meaning that the search term will pick up alternate word endings. For example, the keyword “carbon footprint*” will pick up “carbon footprint,” “carbon footprints,” and “carbon footprinting.”

Using Boolean operators, NREL then generated two search strings to obtain our “universe” of studies (Table 17). The first string was formatted to search SCOPUS, a large abstract and citation database. The second search string was formatted to search the Office of Scientific and Technical Information (OSTI) database, the Department of Energy’s primary search tool.

Table 17. Search Strings Used to Identify Literature in the SCOPUS and OSTI Databases

SCOPUS Search String	OSTI Search String
TITLE-ABS-KEY (("LCA*" OR "life cycle assessment*" OR "life cycle analys*" OR "lifecycle assessment*" OR "lifecycle analys*" OR "life-cycle assessment*" OR "life-cycle analys*" OR "LCIA*" OR "life cycle impact assessment*" OR "life cycle impact analys*" OR "lifecycle impact assessment*" OR "lifecycle impact analys*" OR "life-cycle impact assessment*" OR "life-cycle impact analys*") AND ("natural gas" OR "shale gas" OR "fossil gas" OR "natural gaz" OR "shale gaz" OR "fossil gaz" OR "NG" OR "NGCC" OR "NG-CC" OR "NGCT" OR "NG-CT" OR "NGSC" OR "NG-SC" OR "NGT" OR "LNG" OR "methane" OR "CH4" OR "peaker plant*" OR "peaker*") AND ("power" OR "electric*" OR "carbon capture" OR "carbon dioxide capture" OR "CO2 capture" OR "CCS" OR "CCUS") AND ("carbon footprint*" OR "carbon foot print*" OR "greenhouse gas analys*" OR "greenhouse gas emission*" OR "GHG analys*" OR "GHG emission*"))	("LCA*" OR "life cycle assessment*" OR "life cycle analys*" OR "lifecycle assessment*" OR "lifecycle analys*" OR "life-cycle assessment*" OR "life-cycle analys*" OR "LCIA*" OR "life cycle impact assessment*" OR "life cycle impact analys*" OR "lifecycle impact assessment*" OR "lifecycle impact analys*" OR "life-cycle impact assessment*" OR "life-cycle impact analys*") AND ("natural gas" OR "shale gas" OR "fossil gas" OR "natural gaz" OR "shale gaz" OR "fossil gaz" OR "NG" OR "NGCC" OR "NG-CC" OR "NGCT" OR "NG-CT" OR "NGSC" OR "NG-SC" OR "NGT" OR "LNG" OR "methane" OR "CH4" OR "peaker plant*" OR "peaker*") AND ("power" OR "electric*" OR "carbon capture" OR "carbon dioxide capture" OR "CO2 capture" OR "CCS" OR "CCUS") AND ("carbon footprint*" OR "carbon foot print*" OR "greenhouse gas analys*" OR "greenhouse gas emission*" OR "GHG analys*" OR "GHG emission*")

NREL performed both searches on March 6, 2024, and received 867 publications from the SCOPUS search and 2,206 publications from the OSTI search. Combining the results from these searches, this brought our total universe of identified publications to 3,073.

In addition to searching the bibliographic databases NREL performed snowball sampling using a smaller number of publications initially identified as meeting our screening criteria and preliminarily judged of high quality to find any publications that may had been missed in the searches. Snowballing refers to mining reference lists of highly relevant studies to identify those missed using the standard keyword search of bibliographic databases approach. To include publications that may have been missed in this or previous literature searches, NREL relaxed the criteria for publication date (Criteria 1.3 described in Table 12) for publications obtained via snowball sampling. The publications used for snowball sampling (Cutshaw et al., 2023; Navajas et al., 2019; O'Donoughue et al., 2014; Wang et al., 2022) were chosen due to their quality and relevance to the topic, and produced an additional 40 publications. The addition of these publications resulted in a final universe of 3,113 publications.

3.4.2 Literature Screening

NREL subjected our universe of publications to a series of rigorous quantitative and qualitative screens to eliminate nonapplicable studies (Table 18). These screens were iteratively refined to be as objective as possible, where all marginal studies were discussed with a second researcher to confirm objective and consistent application of the criteria. The first screen targets common bibliographic information such as language, date, page count, and publication type. NREL implemented this screen through the search tools available in OSTI and SCOPUS, respectively. Then, using the title and abstract of the publications, NREL screened out those analyses that were not complete LCAs (Screen 2A and 2B) and those that were not high quality, relevant, original, or transparent (Screen 3). Finally, using the full text of the publications, NREL screened out the LCAs that did not focus on CCS (Screen 4) or did not focus on GHG emissions (Screen 5).

Table 18. Criteria Used for Screening the Identified Universe of Publications

Screen (Information Used to Screen)	Criteria
Screen 1 (Search)	**1 Search criteria** 1.1 Remove duplicated publications 1.2 Remove publications not written in English 1.3 Remove publications published before 2022 1.4 Remove publications that are less than five pages 1.5 Remove publications that are not articles, books, book chapters, theses, dissertations, or technical reports
Screen 2A (Title and Abstract)	**2 Complete LCA on natural gas electricity generation** 2A.1 Remove publications that are comments on prior publications 2A.2 Remove publications that are not LCAs (defined here as not containing more than one life cycle phase) 2A.3 Remove publications that are not focused on natural gas 2A.4 Remove publications that do not include information on both CO_2 and methane
Screen 2B (Title and Abstract)	2B.1 Remove publications that are not on technologies whose primary purpose is to generate electricity by combusting natural gas
Screen 3 (Full Text)	**3 High quality, relevant, original, and transparent LCA** 3.1 Remove publications that do not mention ISO standard (14040 series standards; 14067 series standards) or a peer reviewed LCA model (such as SimaPRO, GaBi, Brightway, OpenLCA, NETL, GREET, Cheniere, or Saudi-ARAMCO) 3.2 Remove publications that do not report results in terms of a functional unit for their LCA 3.3 Remove publications that do not refer to tracking methane emissions from the fuel cycle

	3.4 Remove publications that do not contain independent results (e.g., merely citing another publication's results) 3.5 Remove publications that do not provide transparent reporting of methods, assumptions, and technology descriptions
Screen 4 (Full Text)	**4 Focus on carbon capture and storage** 4.1 Remove publications that do not focus on natural gas power generation technologies with carbon capture and storage
Screen 5 (Full Text)	**5 Focus on emissions** 5.1 Remove publications that do not report GHG emissions quantitatively in mass units 5.2 Remove publications that do not report results by life cycle phase (quantitatively)

Notes: ISO - International Organization for Standardization, NETL - National Energy Technology Laboratory, GREET - Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model

Of the 3,113 publications in our universe, four publications passed all screens and supplied usable results to update the GHG emissions factors for NGCC-CCS systems.

3.4.3 Life Cycle GHG Emissions per Phase for NGCC-CCS

Our screening process identified eight results from four different publications. System characteristics of each result such as capture rate, capacity, lifespan, capacity factor, and location are reported in Table 13. The system characteristics previously reported in O'Donoughue et al. (2014) and NPC (2024) are also included in Table 19.

Table 19. System Characteristics of Each Published Scenario

Author (Year)	Capture Rate (%)	System Capacity (MW)	System Lifespan (Years)	Capacity Factor (%)	Location
Cutshaw et al. (2023)	90	470	30	85	N.R.
Cutshaw et al. (2023)	95	470	30	85	N.R.
Cutshaw et al. (2023)	97	470	30	85	N.R.
Gibon et al. (2017)	90	470	30	85	N.R.
Gibon et al. (2017)	90	470	30	85	N.R.
Gibon et al. (2017)	90	470	30	85	N.R.
Lacy et al. (2015)	87	450	30	80	Mexico
Singh et al. (2011)	90	400	25	91	Norway
Audus & Saroff (1995)*	86	N.R.	N.R.	N.R.	Norway
Bernier et al. (2010)*	96	360	30	86	N.R.
Bernier et al. (2010)*	90	360	30	86	N.R.
Bergerson & Lave (2007)*	90	N.R.	30	N.R.	N.R.
Jaramillo et al. (2007)*	90	N.R.	N.R.	N.R.	N.R.
Lombardi (2003)*	85	240	15	N.R.	N.R.
James III & Skone (2012)*	N.R.	470	30	85	N.R.
Skone (2012)*	N.R.	470	30	85	N.R.
Skone (2012)*	N.R.	470	30	85	N.R.

Skone (2012)*	N.R.	470	30	85	N.R.
Odeh & Cockerill (2008)*	90	430	30	75	United Kingdom
Spath & Mann (2004)*	N.R.	510	30	80	N.R.

Notes: N.R. – Not Reported. Asterisk (*) signifies that this result was previously reported in O'Donoughue et al. (2014). Values are rounded to two significant figures. Some values previously reported in O'Donoughue et al. (2014) have been revised to correct transcription errors.

Of these system characteristics, the carbon capture rate of an NGCC-CCS system heavily influences its total life cycle GHG emissions. Specifically, the capture rate directly modulates the most important life cycle phase for NGCC-CCS systems: the ongoing combustion phase. The capture rates reported in the published scenarios ranged from 85 percent to 97 percent.

The per phase GHG emissions results from the publications that passed our screens, and the results previously reported in O'Donoughue et al. (2014) and NPC (2024), are compiled in Table 20.

Table 20. Published, Per-Phase GHG Emissions for NGCC-CCS

Author (Year)	Upstream GHG Emissions (g CO$_2$e / kWh)	Ongoing Combustion GHG Emissions (g CO$_2$e / kWh)	Ongoing Non-Combustion GHG Emissions (g CO$_2$e / kWh)	Downstream GHG Emissions (g CO$_2$e / kWh)	Total Life Cycle GHG Emissions (g CO$_2$e / kWh)
Cutshaw et al. (2023)	8.7 x 10^{-5}	38	110	N.R.	N.R.
Cutshaw et al. (2023)	8.7 x 10^{-5}	19	110	N.R.	N.R.
Cutshaw et al. (2023)	8.7 x 10^{-5}	11	110	N.R.	N.R.
Gibon et al. (2017)	12	51	73	0.019	N.R.
Gibon et al. (2017)	13	52	180	0.019	N.R.
Gibon et al. (2017)	15	54	480	0.020	N.R.
Lacy et al. (2015)	N.R.	66	110	N.R.	170
Singh et al. (2011)	20	47	99	N.R.	170
Audus & Saroff (1995)*	N.R.	N.R.	N.R.	N.R.	82
Bernier et al. (2010)*	N.R.	N.R.	N.R.	N.R.	88
Bernier et al. (2010)*	N.R.	N.R.	N.R.	N.R.	110
Bergerson & Lave (2007)*	N.R.	43	75	N.R.	120
Jaramillo et al. (2007)*	N.R.	43	59	N.R.	10
Lombardi (2003)*	0.64	65	N.R.	N.R.	65
James III & Skone (2012)*	N.R.	51	86	N.R.	140
Skone (2012)*	N.R.	47	64	N.R.	110
Skone (2012)*	N.R.	47	51	N.R.	98
Skone (2012)*	N.R.	47	110	N.R.	160
Odeh & Cockerill (2008)*	N.R.	75	130	N.R.	200
Spath & Mann (2004)*	N.R.	98	150	N.R.	250

Notes: N.R. – Not Reported. Asterisk (*) signifies that this result was previously reported in O'Donoughue et al. (2014). Values are rounded to two significant figures.

NREL then summarized these results in Table 21. The median total life cycle GHG emissions for NGCC-CCS systems is 120 g CO_2e per kWh. Median is the summary statistic that the LCA Harmonization project uses to represent the central tendency from the literature. This value is 9 g CO_2e per kWh greater than the median total life cycle GHG emissions for NGCC-CCS systems that was previously reported by O'Donoughue et al. (2014). The phase that contributes the most emissions, on average, is the ongoing non-combustion phase, with a median value of 110 g CO_2e per kWh. This is due to the emissions related to the natural gas fuel cycle and storage of CO_2.

Table 21. Summary Statistics of Life Cycle GHG Emissions Per Phase for NGCC-CCS

Summary Statistic	Upstream GHG Emissions (g CO_2e / kWh)	Ongoing Combustion GHG Emissions (g CO_2e / kWh)	Ongoing Non-Combustion GHG Emissions (g CO_2e / kWh)	Downstream GHG Emissions (g CO_2e / kWh)	Total Life Cycle GHG Emissions (g CO_2e / kWh)
Minimum	8.7×10^{-5}	11	51	0.019	65
First Quartile	8.7×10^{-5}	43	75	NA	99
Median	6.4	47	110	0.019	120
Third Quartile	14	54	120	NA	160
Maximum	20	98	480	0.020	250
Count	8	17	16	3	14

Note: Values are rounded to two significant figures. NA = this distributional statistic was not applicable given the count of estimates.

The results pulled from the publications were all reported in terms of electricity generation (g CO_2e per kWh); however, NREL is interested in the upstream and downstream emissions factors in power capacity units (g CO_2e per kW) to align with the other technologies used in this study (Table 22). To convert to power capacity units, NREL assumed a system lifespan of 30 years and a capacity factor of 85 percent. Many of the publications did not report system lifespan and capacity factor, so NREL made these assumptions to ensure the conversion to power capacity units was consistent across all studies. These specific assumptions were chosen using the modal value of the system lifespans and the capacity factors that were reported in O'Donoughue et al. (2014) and the publications screened in this study.

Table 22. Summary Statistics of Life Cycle GHG Emissions Per Phase for NGCC-CCS (With the Units of Upstream and Downstream Phases Per kW)

Summary Statistic	Upstream GHG Emissions (g CO_2e / kW)	Ongoing Combustion GHG Emissions (g CO_2e / kWh)	Ongoing Non-Combustion GHG Emissions (g CO_2e / kWh)	Downstream GHG Emissions (g CO_2e / kW)	Total Life Cycle GHG Emissions (g CO_2e / kWh)
Minimum	20	11	51	4200	65
First Quartile	20	43	75	NA	99
Median	1.4×10^6	47	110	4300	120
Third Quartile	3.1×10^6	54	120	NA	160
Maximum	4.5×10^6	98	480	4500	250
Count	8	17	16	3	14

Note: Values are rounded to two significant figures. NA = this distributional statistic was not applicable given the count of estimates.

An NGCC-CCS system that has a plant lifespan of 30 years and a capacity factor of 85 percent would run for 223,533 hours. The summary statistics reported per energy capacity for the upstream and downstream phases (shown in Table 21) were multiplied by 223,533 to achieve the summary statistics in power capacity units (shown in Table 22).

3.4.4 Limitation

Our study focused on identifying publications published starting in 2022 because prior literature would be largely captured by the National Petroleum Council (NPC, 2024) and the O'Donoughue et al. (2014) literature reviews. This resulted in a literature gap between the years of 2012 and 2016 that is not accounted for in these GHG emissions factors given the cutoff date for O'Donoghue and start date of the NPC review, respectively. NREL employed snowball sampling to fill this literature gap; however, that process is not fully systematic when used alone, and it is unlikely that NREL identified all relevant publications from 2012 to 2016. Thus, there is a possibility that some NGCC-CCS LCAs published between 2012 and 2016 are missing, and that the results reported here could differ were they to be included. Given the small change in median values for each phase of the life cycle between those reported here as compared to those reported in O'Donoughue et al. (2014), NREL believes that any omission due to the literature search gap would likely not substantially change the estimates reported here and not be biased directionally.

4 Results From Two TVA IRP Cases

Following are the results of the NREL independent validation of the TVA capacity expansion model. The NREL validation covered two distinct IRP capacity expansion scenarios: Case 1A and Case 5B, which are described in further detail in Section 4.1. This validation was done for two select cases chosen to represent the range of technology options within the overall IRP framework. Note that the validation was performed during development of the draft IRP. The magnitude of results will differ from the final IRP scenarios, however, we do not expect them to differ significantly, and the achievement of cross-validation of TVA's model to NREL's is still valid.

4.1 TVA Case Descriptions

Case 1A is a reference case scenario that reflects business-as-usual expansion with traditional technologies, least-cost planning, existing programs, no carbon regulations, increasing efficiencies, and increasing electric vehicles. (See Chapter 3 and Chapter 4 of the 2025 IRP, Volume I, for further description.) In this case, electricity demand increases at approximately 0.8% annually, and this growth in demand is largely served through the deployment of solar photovoltaics, battery, and natural gas-fired combined-cycle and combustion turbines.

Case 5B is TVA's highest load growth case and additionally assumes significant carbon regulation, load growth driven by electrification, and advancements in clean energy technologies. This scenario implements the May 2023 proposed U.S. Environmental Protection Agency GHG rules under the Clean Air Act to reduce the emissions of coal plants and operate natural gas plants with installed CCS or hydrogen fuel blends, a carbon tax initiated at $86/ton beginning in 2034 (pushing the national electric sector to net zero by 2050), and load growth at approximately 2.5% annually through 2050. This capacity expansion largely relies on battery, solar, combined cycle with carbon capture, the use of green hydrogen as a fuel, and both conventional and SMR nuclear.

4.2 TVA Case Results

The following tables report the results for draft TVA cases 1A and 5B using NREL's LCA model. The results are the aggregate annual total for each GHG, summed across all technologies commissioned, operating, or decommissioned in that year and across all four phases.

Table 23. NREL Validation of CO_2, CH_4, and N_2O Life Cycle Annual Emissions Resulting from Draft TVA Case 1A in Short Tons

Year	CO_2	CH_4	N_2O
2024	50,638,026	82,359	1,198
2025	56,050,596	76,092	1,310
2026	59,903,041	80,678	1,403
2027	50,966,000	84,927	1,233
2028	48,535,249	85,831	1,149
2029	43,847,660	86,992	1,069
2030	45,789,582	92,497	1,127
2031	43,953,036	89,117	1,098
2032	42,047,132	96,746	1,045
2033	39,568,006	94,769	987
2034	35,873,404	98,834	890
2035	35,206,239	97,243	879
2036	34,902,075	96,322	877
2037	33,179,938	91,362	840
2038	34,018,738	93,074	863
2039	33,261,550	91,504	851
2040	34,140,612	95,081	884
2041	31,872,930	87,010	813
2042	32,198,542	87,652	816
2043	34,660,643	97,177	908
2044	33,819,791	95,634	880
2045	33,948,251	96,956	893
2046	33,825,499	96,580	893
2047	32,216,265	90,136	841
2048	33,597,185	97,272	887
2049	32,580,637	94,347	869
2050	32,098,546	91,082	841

Table 24. NREL Validation of CO_2, CH_4, and N_2O Life Cycle Annual Emissions Resulting from Draft TVA Case 5B in Short Tons

Year	CO_2	CH_4	N_2O
2024	50,627,441	86,758	1,202
2025	60,774,699	83,423	1,419
2026	70,252,508	100,457	1,658
2027	65,184,506	112,937	1,584
2028	67,916,741	130,096	1,650
2029	60,750,725	135,739	1,500
2030	62,784,094	139,374	1,556
2031	64,020,137	138,435	1,604
2032	54,862,591	83,003	1,377
2033	48,408,772	95,278	1,270
2034	41,062,610	101,526	1,143
2035	34,502,759	111,125	1,024
2036	33,905,555	110,664	1,020
2037	32,845,701	109,859	1,015
2038	17,792,289	106,466	723
2039	14,216,155	96,163	647
2040	12,744,021	95,072	626
2041	12,527,301	92,888	622
2042	11,655,811	89,261	594
2043	12,148,823	90,186	615
2044	12,244,131	89,697	619
2045	12,549,060	90,844	649
2046	10,338,809	80,736	585
2047	9,073,393	73,400	538
2048	10,723,395	80,021	603
2049	10,369,764	77,181	599
2050	8,189,884	69,758	526

4.3 TVA Results Comparison

These results were compared to TVA's model results by calculating the percent difference in predicted GHG emissions. The magnitude of difference between the NREL and TVA models for Case 1A's CO_2e emissions was found to be 0.020%. Moreover, when disaggregated into their component emissions contributions, CO_2, CH_4, and N_2O emissions in Case 1A were 0.023%, 0.20%, and 0.39% respectively, showing somewhat greater discrepancy for non-CO_2 gases yet still less than 1%. For Case 5B, the magnitude of difference was found to be 0.06% in terms of CO_2e. The ranges of difference for individual GHGs were 0.05%, 0.41%, and 0.96% for CO_2, CH_4, and N_2O, respectively. While it is possible that comparisons of the two models' results may differ from the two tested, it is NREL's technical judgment that the TVA model closely replicates the results of NREL's model based on these low percent difference values in the cases tested.

5 NREL LCA Model: GLEAM

Alongside the scope of NREL's support to TVA for this IRP, NREL has been formalizing the approaches to life cycle GHG emission accounting for power sector scenarios described herein (and in the prior works noted in section 1) into a new model called GLEAM: Greenhouse Gas Life Cycle Emissions Assessment Model. GLEAM will be freely available as a Python code package hosted in a GitHub repository, and will be documented in a forthcoming NREL technical report. Once published, this report can be found by searching for "GLEAM" in NREL's Publication Database (https://research-hub.nrel.gov/en/publications/) and the model code can be found using the same search here: https://github.com/nrel.

The purpose of GLEAM is to streamline the process of estimating cumulative greenhouse gas emissions on a life cycle basis from future electricity generation scenarios. GHG emissions from future electricity generation scenarios are often produced by capacity expansion or unit commitment electric sector models; GLEAM is configured to enable interaction with formatted output from many specific models, such as NREL's Renewable Energy Deployment System (ReEDS) and Sienna, as well as private sector models such as EnCompass, and also unit commitment models such as PLEXOS. The GLEAM capability supports analyses for electric grid planning and resource investment and retirement decisions as well as research and development.

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