Living a Marginal Existence

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CHICAGO 2022

October 28, 2022

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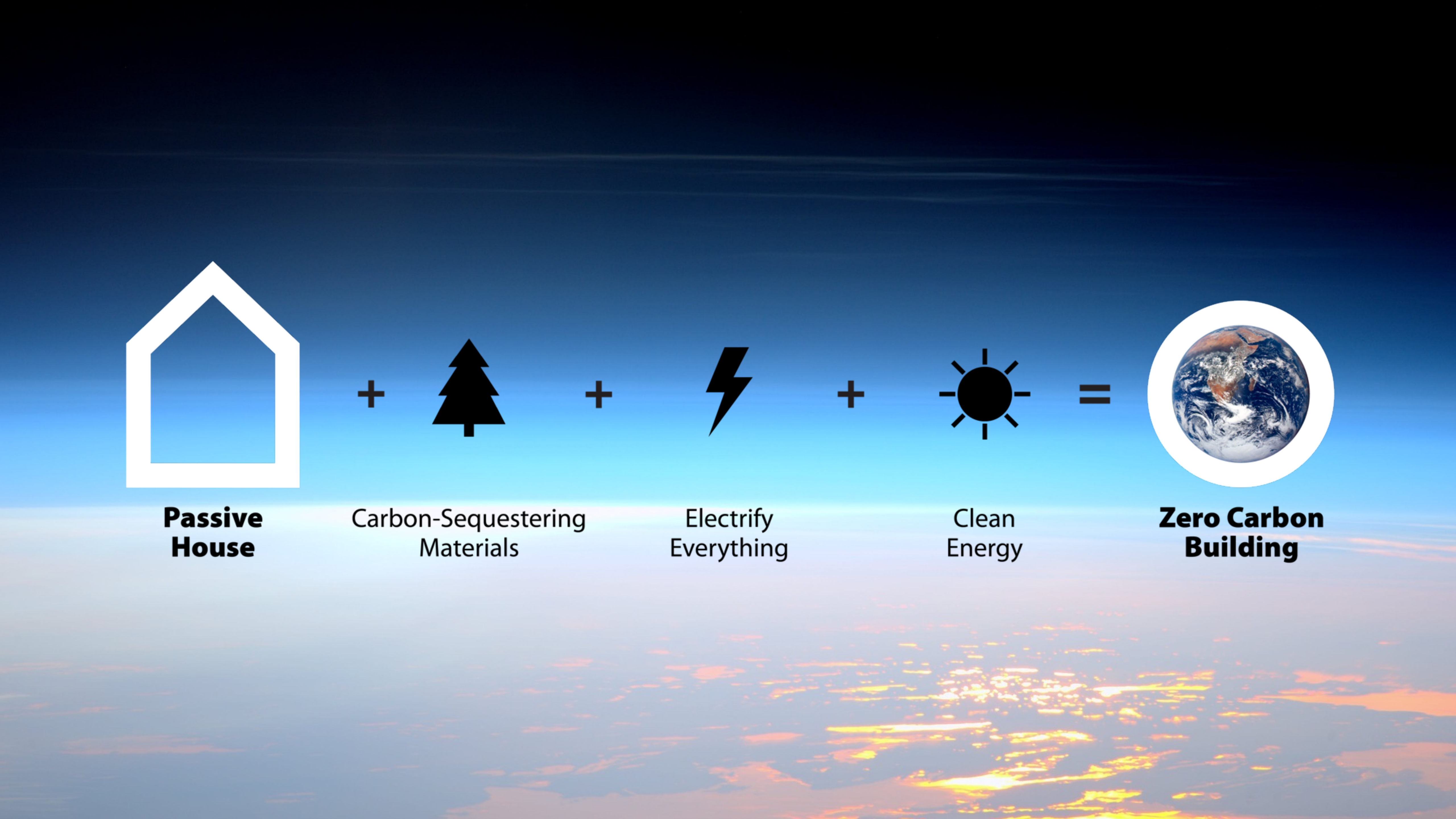
Passive House and Embodied Carbon reduction aren't tradeoffs.

Passive House reduces a building's total emissions, even by 2030,

while *also* decarbonizing winter heating peaks.

Choosing low-embodied carbon materials also reduces emissions.

…so let's do both.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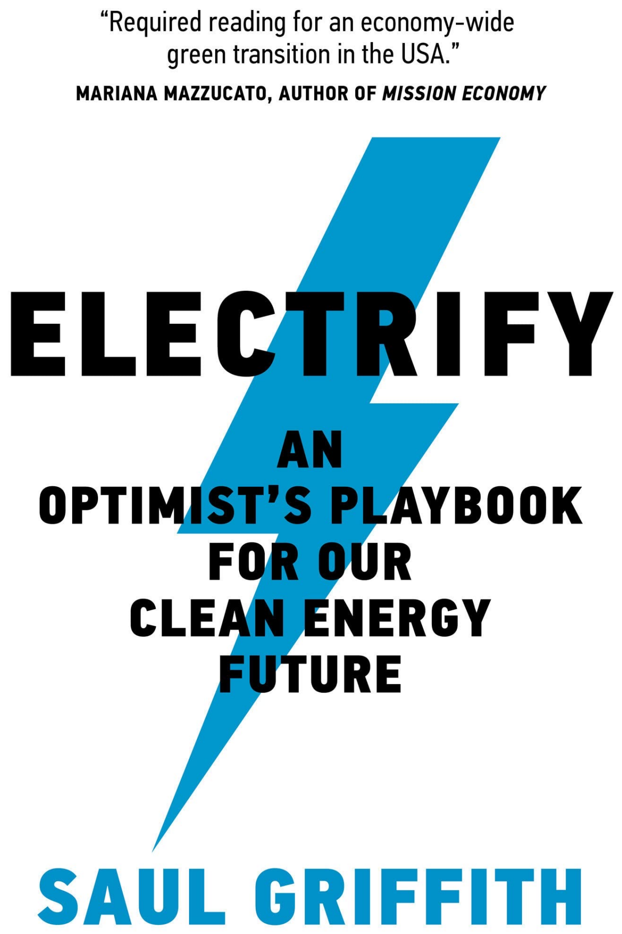
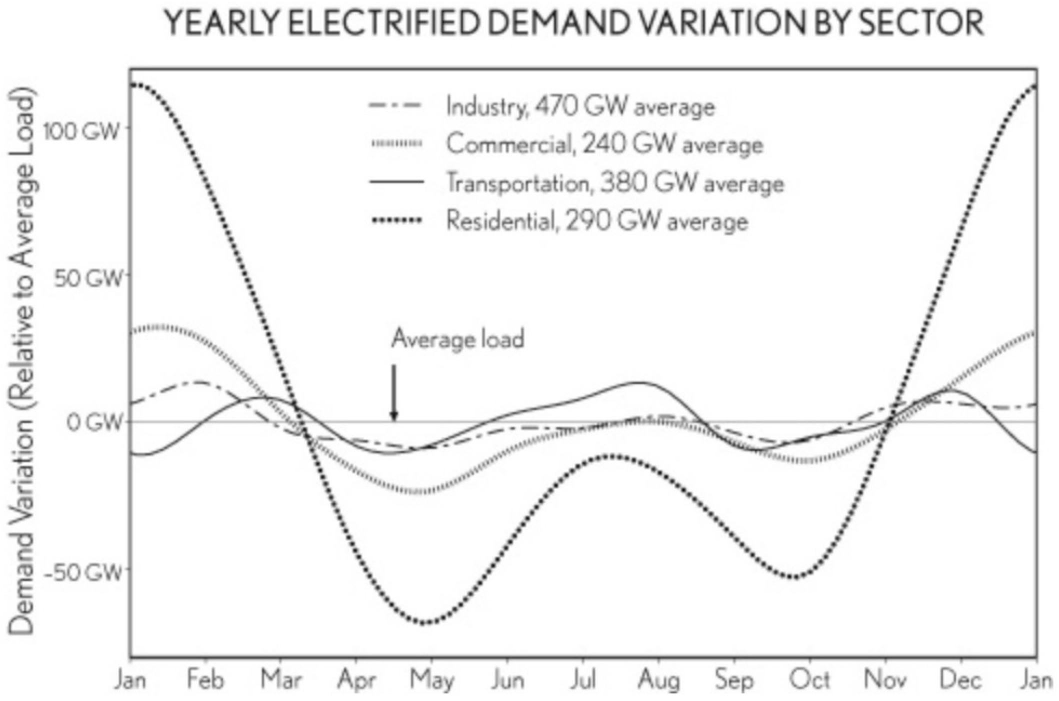
Passive House
Carbon-Sequestering Materials
Electrify Everything
Clean Energy
Zero Carbon Building

Winter Peak





8.6 Modeled seasonal variations by energy sector if loads were almost completely electrified.

Griffith, S. (2022). Electrify: An optimist's playbook for our Clean Energy Future. The MIT Press.

But What About Embodied Carbon?

Common Assumptions About Embodied Carbon and [redacted] Decarbonization

Did you account for the smaller EC and refrigerant leaks from smaller systems in a low load building?

1. [redacted] higher EC and often higher overall emissions [redacted]

What about the "Time Value of Efficiency?"

2. The [redacted] dictates that 2030 is the important time horizon, not [redacted]

Not according to the EPA!

3. If my [redacted] near-zero emissions, then building energy use isn't [redacted]

Operational and Embodied Carbon Emissions Estimator

Operational
& Embodied Carbon Emissions Estimator
BETA
October 2022

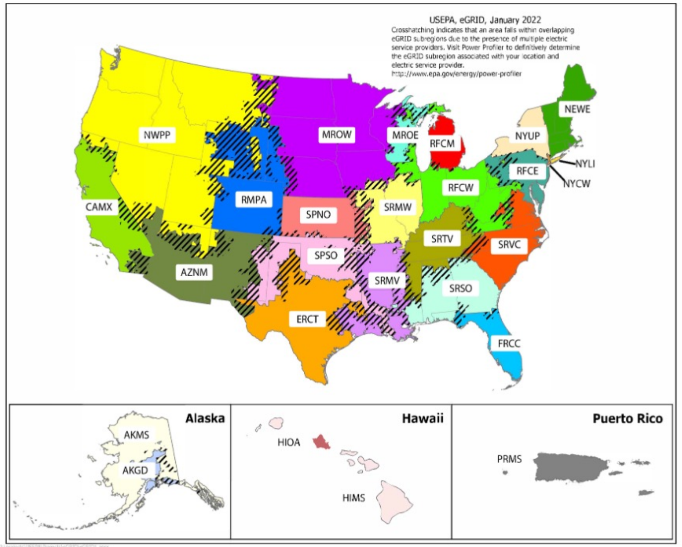
Emission Factors	Units	Case 1	Case 2	
Electricity	lb CO_2e/MWh	936	936	0%
Natural Gas	lb CO_2e/MWh	681	681	0%
				0%

Building Inputs	Units	Case 1	Case 2	
Floor Area	ft²	10,000	10,000	0%
EUI	kBTU/ft².yr	30.0	15.0	-50%
Energy Use Per Year	kWh/yr	87,925	43,962	-50%
Space Heating Fraction	%	50%	25%	-50%
Gas Fraction of Heat	%	0%	0%	0%
Electric Fraction of Heat	%	100%	100%	0%
Heat Gas Emissions	lb CO_2e/yr	0	0	0%
Heat Electricity Emissions	lb CO_2e/yr	41,149	10,287	-75%
Heat Emissions Total	lb CO_2e/yr	41,149	10,287	-75%
Non-Heat Electricity Emissions	lb CO_2e/yr	41,149	30,862	-25%
Total Operational Emissions	lb CO_2e/yr	82,298	41,149	-50%
				0%

Heat Pump Inputs	Units	Case 1	Case 2	
Heat Pump Capacity	Tons	10.0	5.0	-50%
Floor Area/Capacity	ft²/Ton	1,000	2,000	100%
Heating Equipment Emission (IU/OU)	lb CO_2e/Ton	1,552	1,552	0%
Total Heat Equipment Emissions (no refrigerant)	lb CO_2e	15,521	7,760	-50%
Refrigerant Charge	lb/Ton	3.50	3.50	0%
Total Refrigerant Charge	lb	35.00	17.50	-50%
Refrigerant Type	Select	R-410A	R-410A	
User Specified GWP	GWP	0	0	0%
Refrigerant GWP	GWP100	2,088	2,088	0%
Refrigerant GWP	GWP20	4,340	4,340	0%
Total Refrigerant GWP100	lb CO_2e	73,063	36,531	-50%
Total Refrigerant GWP20	lb CO_2e	151,900	75,950	-50%
Refrigerant Leakage Rate	%	5%	5%	0%
Average Heat Pump Life	Years	15	15	0%
End-of-life recovery of remaining refrigerant	%	20%	20%	0%
Last year of refrigerant "top-off" before EOL	Years	12	12	0%
Percentage of refrigerant lost during lifetime	%	143%	143%	0%
Mass of refrigerant lost during lifetime	lb	50.1	25.0	-50%
Lost Refrigerant GWP100	lb CO_2e	104,479	52,240	-50%
Lost Refrigerant GWP20	lb CO_2e	217,217	108,609	-50%
Average Leakage Rate	lb/yr	3.34	1.67	-50%
Avg Annual Leaked Refrigerant GWP100	lb CO_2e	6,965	3,483	-50%
Avg Annual Leaked Refrigerant GWP20	lb CO_2e	14,481	7,241	-50%
Heat Pump COP	COP	3	3	0%
Electric Fraction of Heat	kWh/yr	43,962	10,991	-75%
HP Emission per kWh GWP100	lb CO_2e/kWh	0.0528	0.1056	100%
HP Emission per kWh GWP100	g CO_2e/kWh	24.0	47.9	100%
HP Emission per kWh GWP20	lb CO_2e/kWh	0.1098	0.2196	100%
HP Emission per kWh GWP20	g CO_2e/kWh	49.8	99.6	100%
				0%

Gas to Heat Pump EUI Correction	
Original EUI	30.0
EUI Space Heat Fraction	50%
Space Heat EUI	15
Gas Efficiency	90%
Heat Demand EUI	13.50
Heat Pump COP	2.0
Heat Pump EUI	6.8
New Building EUI	**21.8**
New Heating Fraction	31%

eGRID Subregion Lookup		EF
Zip Code	83702	lb CO_2e/MWh
Subregion 1	NWPP	936
Subregion 2	--	--
Subregion 3	--	--
https://www.epa.gov/egrid/power-profiler#/		



Operational and Embodied Emissions Estimator

0%

PV System Inputs	Units	Case 1	Case 2	
Fraction of EUI covered by PV	%	0%	0%	0%
PV Gen per kW	kWh/yr	1,000	1,000	0%
PV Size	kW	0.0	0.0	0%
Upfront PV Emission per kW	lb CO_2e/kW	1,323	1,323	0%
Upfrong PV Emission Total	lb CO_2e	0	0	0%
PV Lifespan	Years	30	30	0%
Total PV Generation	kWh	0	0	0%
PV Emission per kWh	lb CO_2e/kWh	0.0000	0.0000	0%
PV Emission per kWh	g CO_2e/kWh	0.0	0.0	0%
				0%

Battery System Inputs	Units	Case 1	Case 2	
Days of Storage	Days	0	0	0%
Average Daily Demand	kWh/day	241	120	-50%
Average Power Draw	Watts	10,037	5,019	-50%
Storage Capacity	kWh	0	0	0%
Storage Emission per kWh	lb CO_2e/kWh	165	165	0%
Storage Emission Total	lb CO_2e	0	0	0%
				0%

Building Envelope Inputs	Units	Case 1	Case 2	
Number of Floors	Stories	3	3	0%
Roof Area	ft²	3,333	3,333	0%
Slab Area	ft²	3,333	3,333	0%
Net Wall Area	ft²	5,889	5,889	0%
Window to Wall Ratio (WWR)	%	15%	15%	0%
Window Area	ft²	1,039	1,039	0%
Triple Pane Windows	Y/N	NO	YES	
Glass Upgrade Emissions	lb CO_2e	0	2,773	100%
Roof Insulation Upgrade	R-Value	0	0	0%
Roof Insulation Type	Select	EPS foam board / R 4.0/inch avg [BEAM Avg | US & CA]	EPS foam board / R 4.0/inch avg [BEAM Avg | US & CA]	
Roof Insulation Upgrade Emissions	lb CO_2e	0	0	0%
Slab Insulation Upgrade	R-Value	0	0	0%
Slab Insulation Type	Select	EPS foam board / R 4.0/inch avg [BEAM Avg | US & CA]	EPS foam board / R 4.0/inch avg [BEAM Avg | US & CA]	
Slab Insulation Upgrade Emissions	lb CO_2e	0	0	0%
Wall Insulation Upgrade	R-Value	0	0	0%
Wall Insulation Type	Select	EPS foam board / R 4.0/inch avg [BEAM Avg | US & CA]	EPS foam board / R 4.0/inch avg [BEAM Avg | US & CA]	
Wall Insulation Upgrade Emissions	lb CO_2e	0	0	0%
Total Envelope Upgrade Emissions	lb CO_2e	0	2,773	100%

Whole Building Emissions	Units	Case 1	Case 2	
Output from BEAM or 3rd Party (no upgrades)	lb CO_2e/ft²	30	30	0%
Total Building Emission Before Upgrades	lb CO_2e	300,000	300,000	0%

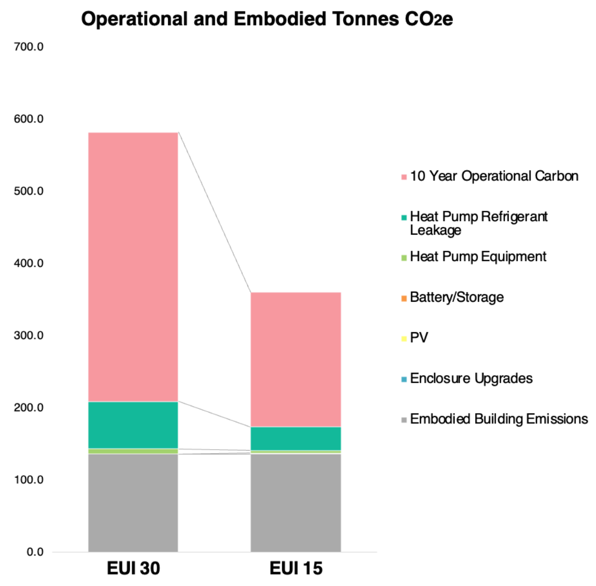
Operational and Embodied Emissions Estimator

Slab Insulation Type	Select	avg [BEAM Avg | US & CA]	avg [BEAM Avg | US & CA]	
Slab Insulation Upgrade Emissions	lb CO_2e	0	0	0%
Wall Insulation Upgrade	R-Value	0	0	0%
Wall Insulation Type	Select	EPS foam board / R 4.0/inch avg [BEAM Avg | US & CA]	EPS foam board / R 4.0/inch avg [BEAM Avg | US & CA]	
Wall Insulation Upgrade Emissions	lb CO_2e	0	0	0%
Total Envelope Upgrade Emissions	lb CO_2e	0	2,773	100%

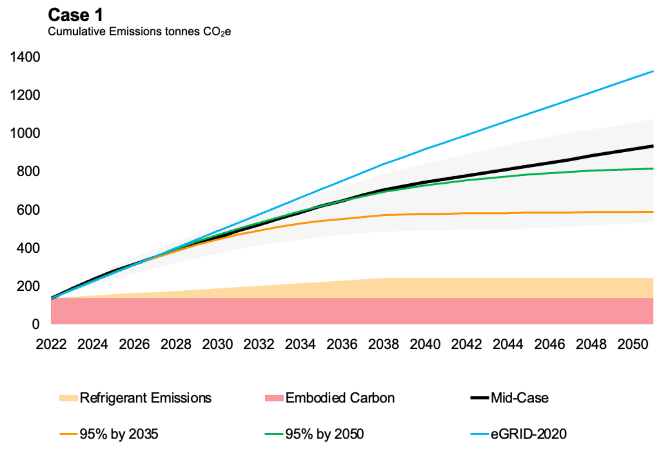
Whole Building Emissions	Units	Case 1	Case 2	
Output from BEAM or 3rd Party (no upgrades)	lb CO_2e/ft^2	30	30	0%
Total Building Emission Before Upgrades	lb CO_2e	300,000	300,000	0%

Simple Graph Inputs	Case 1	Case 2	
Years	10.0	10.0	0%
Name	EUI 30	EUI 15	
Embodied Building Emissions	136.1	136.1	0%
Enclosure Upgrades	0.0	1.3	100%
PV	0.0	0.0	0%
Battery/Storage	0.0	0.0	0%
Heat Pump Equipment	7.0	3.5	-50%
Heat Pump Refrigerant Leakage	65.7	32.9	-50%
10 Year Operational Carbon	373.4	186.7	-50%
Total Embodied and Operational Carbon	582.3	360.4	-38%
Operational %	64.1%	51.8%	-19%

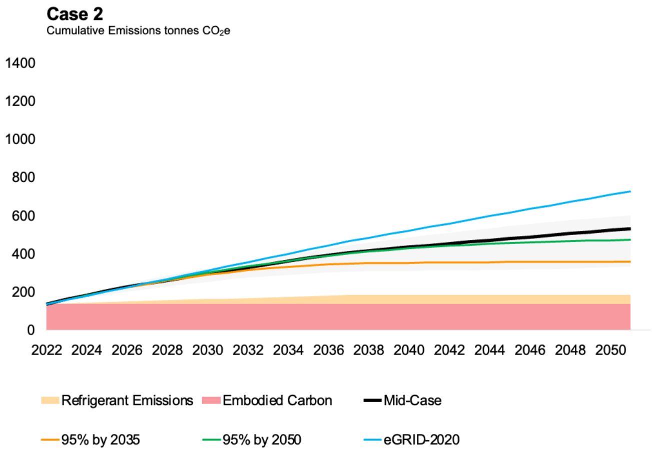
Cumulative Emissions Forecast Graph Inputs		Case 1	Case 2	
Region		NWPP	NWPP	
Cambium Emission Factor		lrmer_co2e	lrmer_co2e	
Refrigerant GWP		GWP20	GWP20	
Avg Annual Leaked Refrigerant Emissions	kg CO_2e	6,570	3,285	-50%



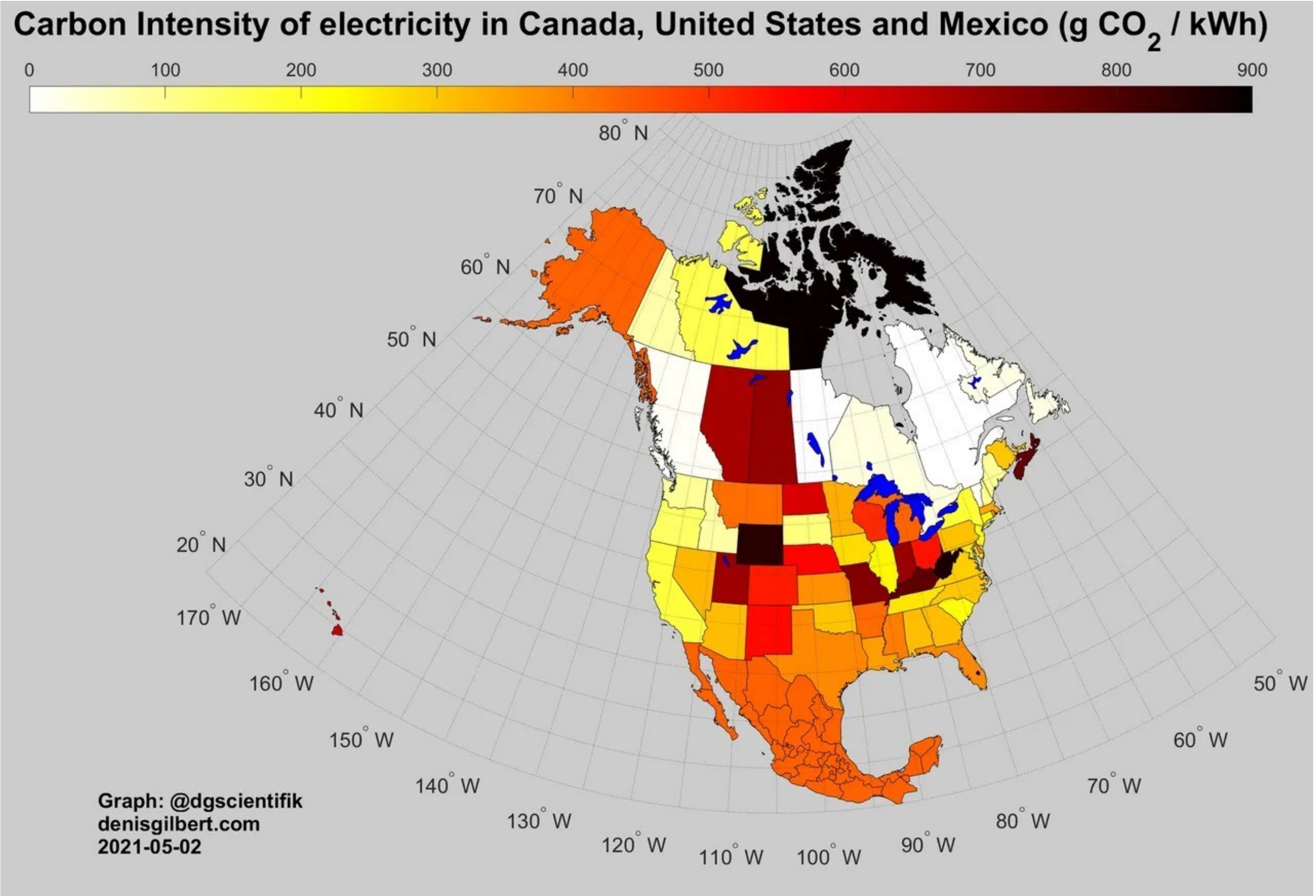
EUI 30



EUI 15

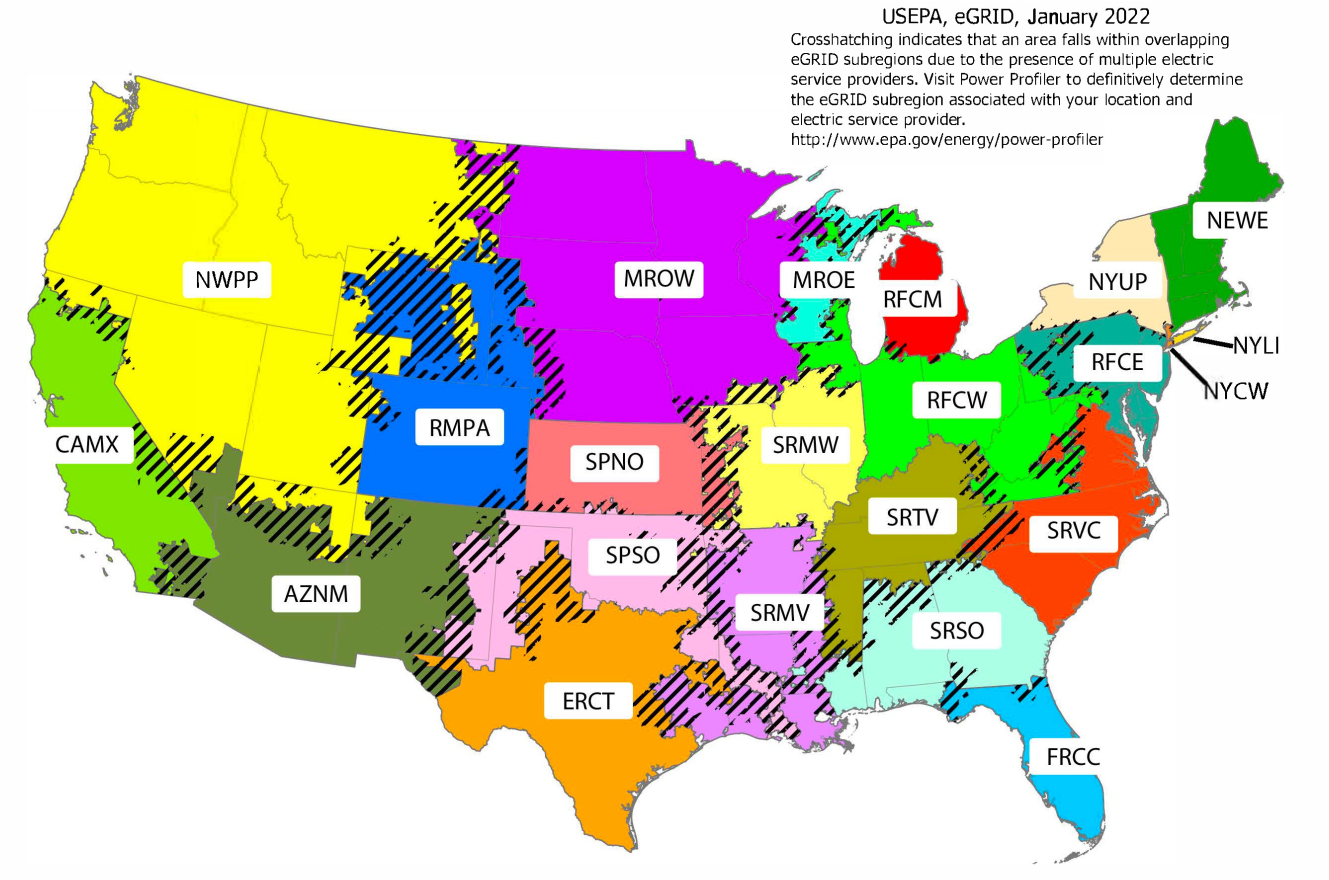


Operational Carbon Boundaries



https://denisgilbert.com/blog/f/carbon-intensity-of-electricity-in-canada-mexico-usa

Operational Carbon
eGRID subregions
Grid Interconnection & Systems Thinking



Subregions, unlike **states**, are defined using the transmission, distribution and utility service territories of power plants and therefore don't follow traditional geographic state boundaries.

https://www.epa.gov/green-power-markets/us-grid-regions

Operational Carbon
eGRID subregions

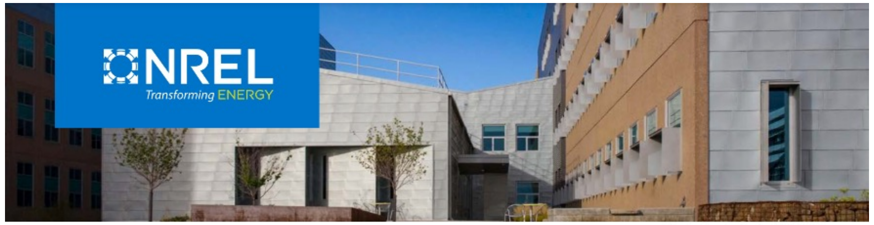


Photo by Dennis Schroeder, NREL 23201

Greenhouse Gas Emissions Accounting in Buildings

Building operations in the United States account for about 70% of electricity use, about 40% of the total U.S. primary energy consumption,[1] and about 30% of greenhouse gas (GHG) emissions.[2] Carbon dioxide (CO_2) emissions from building energy use and embodied emissions accounted for about 37% of global CO_2 emissions in 2020.[3] Thus, accurate GHG emissions accounting is critical to inform decisions for emissions reduction. This fact sheet provides an introduction to GHG emissions accounting for operation of buildings including equipment replacements and operational material purchases. It does not include embodied GHG emissions in existing buildings or from major retrofit construction activities.

What are operational activities that result in emissions and where are the opportunities to reduce emissions from commercial buildings?

The majority of GHG emissions from building activities come from combustion of fossil fuels for energy, either remotely for generation of electricity or on-site for heat and power generation. Carbon dioxide, methane, and nitrous oxide are all GHGs associated with combustion. Methane can also be released to the atmosphere from leakage in pipes, valves, and equipment. Refrigerants are very powerful GHGs and can leak from refrigeration and heat pump equipment during installation, maintenance, and operation. Annual refrigerant leakage varies significantly and is most often estimated to be between 1% and 10% of the total system refrigerant charge, but can be much higher if there is a catastrophic failure in the system.[4]

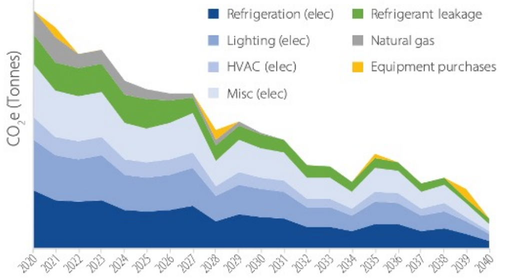


Figure 1. Example operational activities that impact emissions, representing an 87% reduction in GHG emissions. Data are for demonstration purposes only for a supermarket. Equipment purchases can refer to furniture purchases such as desks, chairs, and partitions for commercial building use.

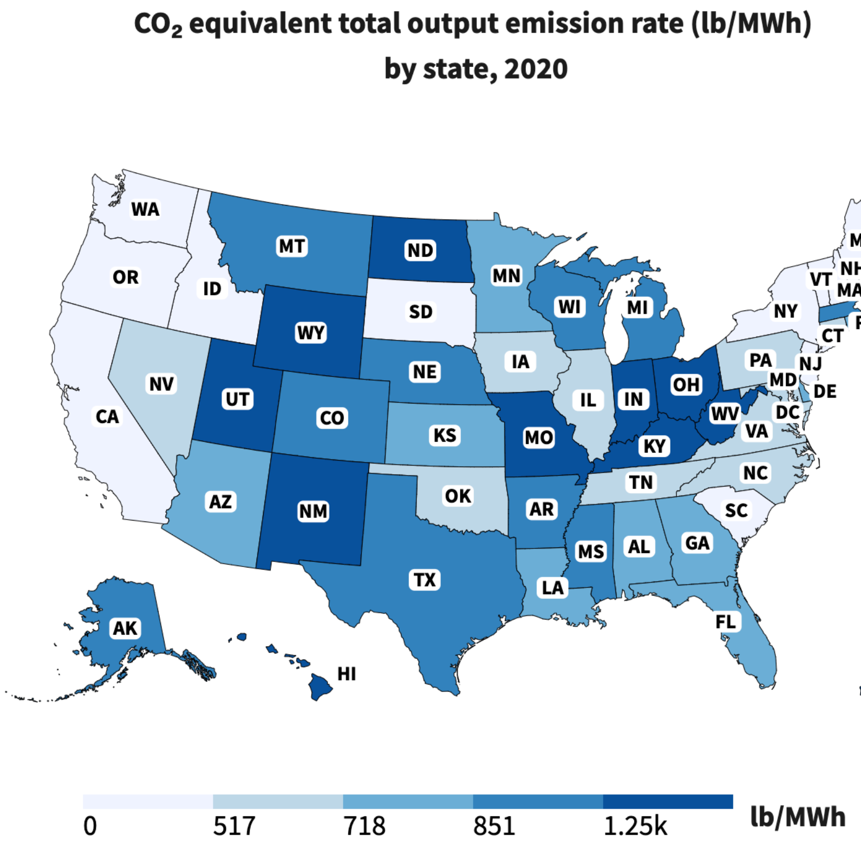
1 EIA 2021. Monthly Energy Review, preliminary data for 2020. https://www.eia.gov/totalenergy/data/monthly. US Energy Information Administration: Washington DC.
2 US EPA 2021. Sources of Greenhouse Gas Emissions. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions. Washington DC.
3 UNEP, IEA 2021. Global ABC 2021 Global status report.
4 Integral Group 2020. *"Refrigerants + Environmental Impacts: A Best Practice Guide"* https://www.integralgroup.com/news/refrigerants-environmental-impacts/. See Appendix A.4 for more data on leakage rates for HVAC systems.

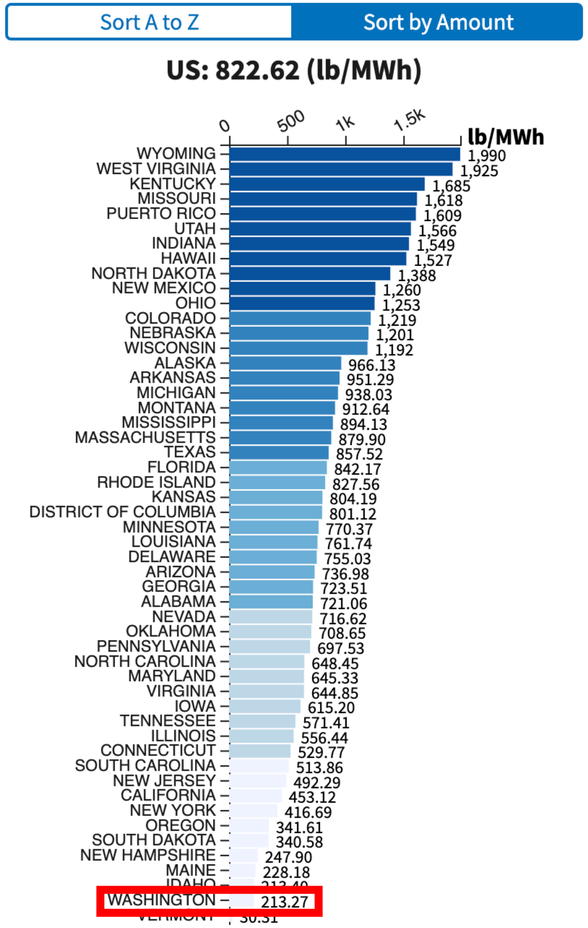
"National vs. Regional vs. Utility:
Emission factors can be calculated for different locations: national, regional, or utility.

The most common regional values are based on the 26 eGRID subregions defined by the EPA. ***State-level emission factors may not be good representations of local emissions and are not recommended."***

https://www.nrel.gov/docs/fy22osti/81671.pdf

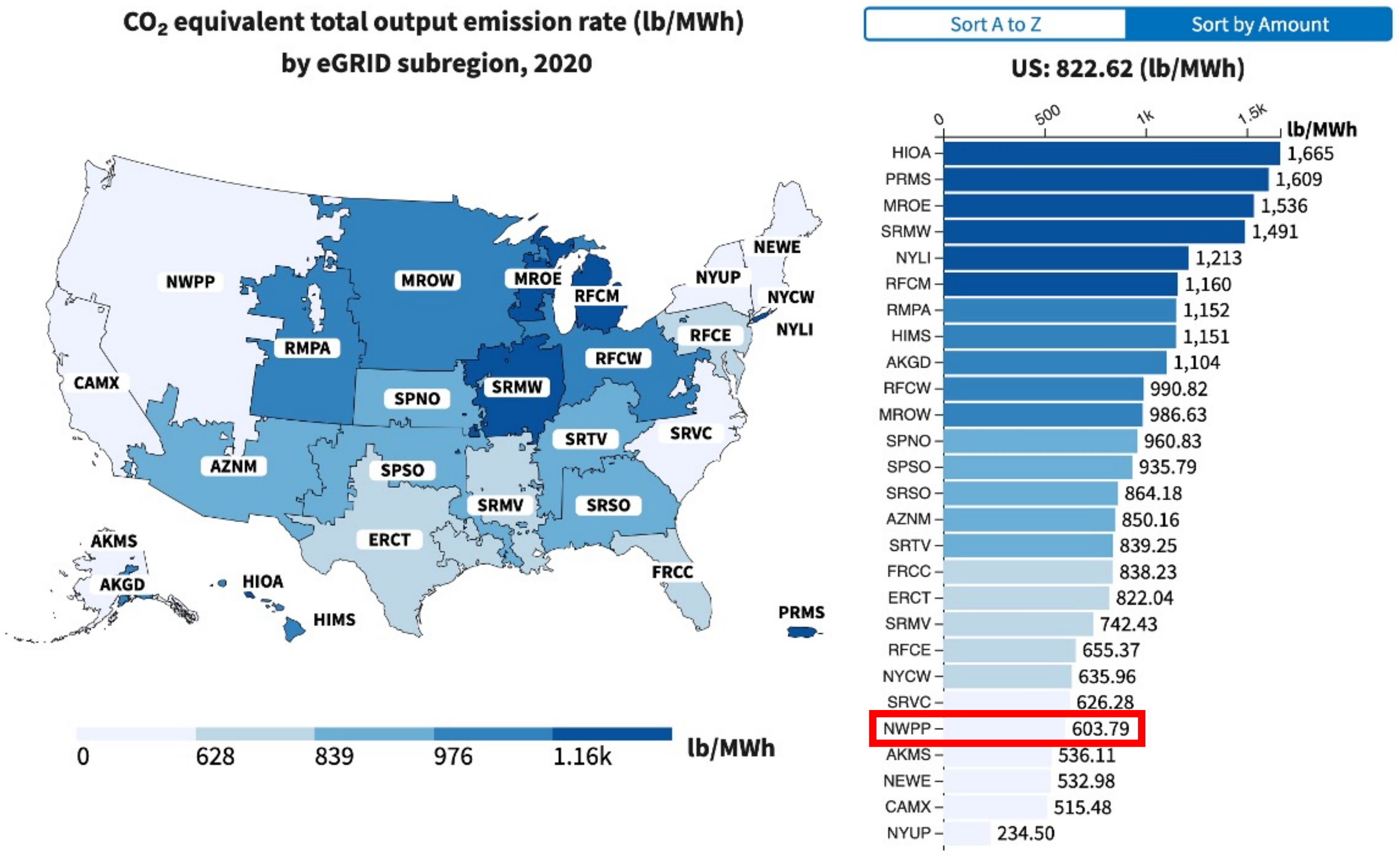
Operational Carbon Boundaries





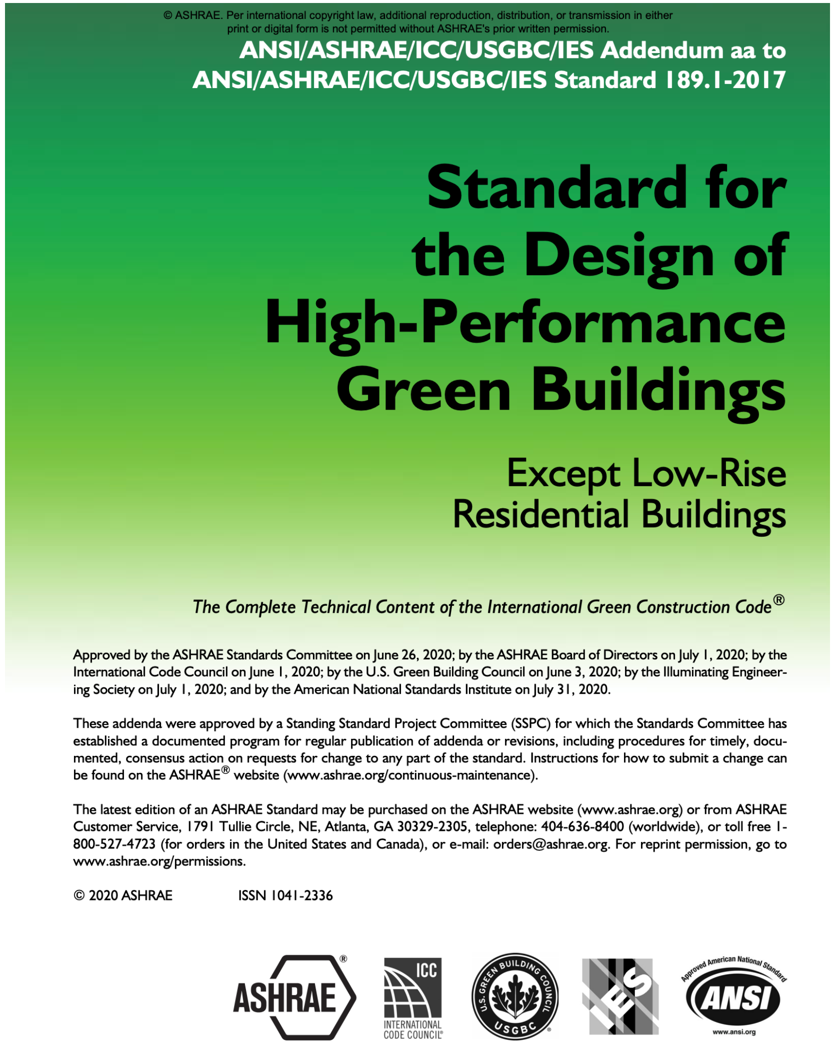
https://www.epa.gov/egrid/data-explorer

Operational Carbon Boundaries



https://www.epa.gov/egrid/data-explorer

Operational Carbon
ASHRAE 189.1-2017 Addendum aa
Upstream & Transmission Adjustment



ANSI/ASHRAE/ICC/USGBC/IES Addendum aa to ANSI/ASHRAE/ICC/USGBC/IES Standard 189.1-2017

Standard for the Design of High-Performance Green Buildings

Except Low-Rise Residential Buildings

The Complete Technical Content of the International Green Construction Code®

Approved by the ASHRAE Standards Committee on June 26, 2020; by the ASHRAE Board of Directors on July 1, 2020; by the International Code Council on June 1, 2020; by the U.S. Green Building Council on June 3, 2020; by the Illuminating Engineering Society on July 1, 2020; and by the American National Standards Institute on July 31, 2020.

These addenda were approved by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the standard. Instructions for how to submit a change can be found on the ASHRAE® website (www.ashrae.org/continuous-maintenance).

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 ISSN 1041-2336

ANSI/ASHRAE/ICC/USGBC/IEC (2020) Addendum aa for Standard 189.1-2017.
https://www.ashrae.org/file%20library/technical%20resources/standards%20and%20guidelines/standards%20addenda/189_1_2017_aa_20200731.pdf.
https://codes.iccsafe.org/content/IGCC2021P1/

Operational Carbon
IgCC 2021

TABLE 701.5.2 (TABLE 7.5.2)
SOURCE ENERGY CONVERSION FACTORS AND CO_2e EMISSIONS FACTORS

ENERGY FORM	SOURCE ENERGY CONVERSION FACTOR	CO_2e EMISSIONS FACTOR	
		lb/MWh	kg/MWh
Fuels Used Directly in Building			
Natural gas	1.09	681	309
LPG or propane	1.15	651	295
Fuel oil (residual)	1.19	738	335
Fuel oil (distillate)	1.19	715	324
Coal	1.05	892	405
Gasoline	1.19	744	337
Other fuels not specified in this table	1.05	892	405
Imported Electricity and Exported Renewable Electricity			
AKGD—ASCC Alaska Grid	2.52	1580	717
AKMS—ASCC Miscellaneous	1.21	738	335
AZNM—WECC Southwest	2.75	1496	679
CAMX—WECC California	1.94	957	434
ERCT—ERCOT All	2.58	1529	694
FRCC—FRCC All	2.97	1601	726
HIMS—HICC Miscellaneous	2.86	1717	779
HIOA—HICC Oahu	3.83	2460	1116
MROE—MRO East	3.08	2337	1060
MROW—MRO West	2.50	1686	765
NEWE—NPCC New England	2.87	1024	464
NWPP—WECC Northwest	1.39	936	425
NYCW—NPCC NYC/Westchester	2.92	1034	469
NYLI—NPCC Long Island	2.90	1600	726
NYUP—NPCC Upstate NY	1.97	540	245
RFCE—RFC East	3.05	1156	524
RFCM—RFC Michigan	3.06	1806	819
RFCW—RFC West	3.14	1757	797
RMPA—WECC Rockies	2.33	1829	830
SPNO—SPP North	2.67	1851	840
SPSO—SPP South	2.46	1737	788
SRMV—SERC Mississippi Valley	2.95	1421	645
SRMW—SERC Midwest	3.20	2234	1014
SRSO—SERC South	3.04	1651	749
SRTV—SERC Tennessee Valley	3.02	1677	761
SRVC—SERC Virginia/Carolina	3.11	1255	569
All other electricity	2.64	1418	643
District Thermal Energy			
Chilled water	0.63	339	154
Steam	1.83	1145	519
Hot water	1.73	1081	491

Informative Note: Values in this table represent averages for the United States and include both direct and indirect emissions. The source energy conversion factors are based on noncombustible renewable energy having a zero heat rate. The *carbon dioxide equivalent* emissions of methane (CH_4) and nitrous oxide (N_2O) are based on their GWP for a 20 year time horizon. Other assumptions are documented in Informative Appendix J.

https://codes.iccsafe.org/content/IGCC2021P1/

TABLE J102.1 (TABLE J2-1)
DIRECT AND INDIRECT EMISSIONS FROM FOSSIL FUELS USE [a]

(Source: Michael Deru and Paul Torcellini, Source Energy and Emission Factors for Energy Use in Buildings, National Renewable Energy Laboratory, Technical Report NREL/TP-550-38617, Revised June 2007, except as noted below.)

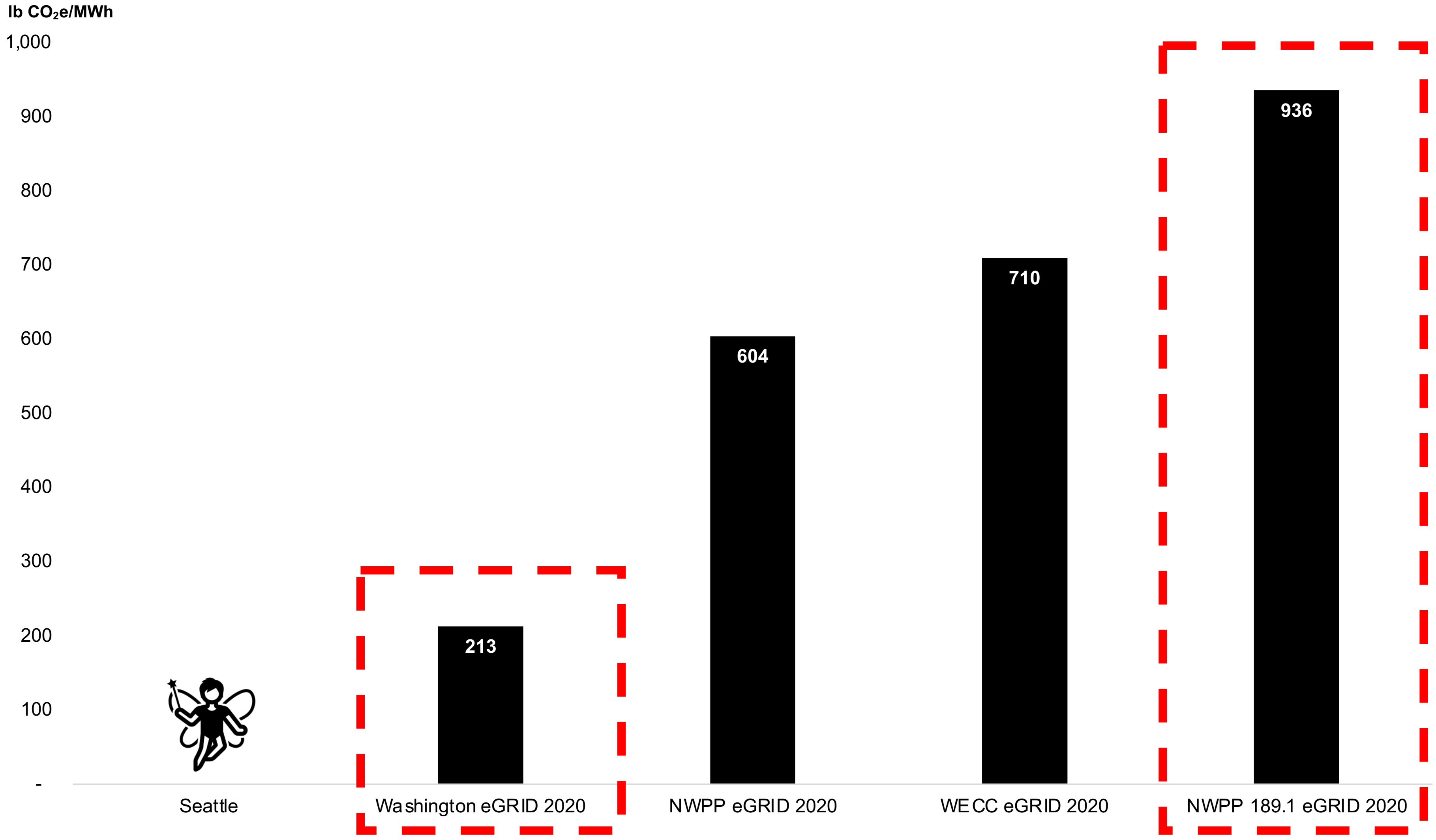
FUEL	CARBON DIOXIDE (CO_2)	METHANE (CH_4)	NITROUS OXIDE (N_2O)	CO_2e
Direct Emissions (lb/MWh of input)				
Natural gas (at the building)	412.14	0.0084	0.0084	415
Natural gas (at the power plant)	412.14	0.0084	0.0084	415
LPG (propane)	494.93	0.0081	0.0366	505
Residual fuel oil	581.98	0.0053	0.0027	583
Distillate fuel oil	560.88	0.0057	0.0029	562
Coal [b]	738.26	0.0323	0.1033	768
Gasoline	560.88	0.0057	0.0029	562
Biomass [c]	355.04	0.0243	0.0414	368
Indirect Emissions (lb/MWh of input)				
Natural gas (at the building) [d]	39.19	2.7000	0.0008	266
Natural gas (at the power plant) [d]	39.19	2.1000	0.0008	216
LPG or propane	76.86	0.8174	0.0014	146
Residual fuel oil	81.48	0.8695	0.0015	155
Distillate fuel oil	80.69	0.8585	0.0015	153
Coal [b]	26.16	1.1649	0.0005	124
Gasoline	95.54	1.0168	0.0018	181
Biomass [c]	16.60	0.0199	0.00008	18
Total Emissions (lb/MWh of input)				
Natural gas (at the building)	451.33	2.7084	0.0092	681
Natural gas (at the power plant)	451.33	2.1084	0.0092	631
LPG or propane	571.79	0.8255	0.0380	651
Residual fuel oil	663.46	0.8748	0.0042	738
Distillate fuel oil	641.56	0.8642	0.0044	715
Coal [b]	764.42	1.1972	0.1038	892
Gasoline	656.41	1.0225	0.0047	744
Biomass [c]	371.64	0.0442	0.0414	386

a. The NREL data in this report were derived from the United States Life Cycle Inventory (LCI) Database maintained by NREL.
b. The NREL report gives values for various types of coal, but bituminous is used for this analysis because it is most common form in the United States
c. Values for biomass were not reported in the NREL document. Figures in this table were derived separately from EIA data and information from the California Air Resources Board (CARB). The cumulative net emissions for the 20 year period are calculated by subtracting the estimated counterfactual emissions.
d. Indirect methane emissions for natural gas are based on total losses of 1.4% for gas delivered to power plants and 1.8% for gas delivered to buildings, per Table ES-1 of Life Cycle Analysis of Natural Gas Extraction and Power Generation, August 30, 2016, DOE/NETL-2015/1714.

TABLE J201.2 (TABLE J2-2)
GLOBAL WARMING POTENTIAL (UNITLESS MULTIPLIERS)
(SOURCE: IPCC 2013, AR4 WITHOUT CLIMATE CARBON FEEDBACKS)

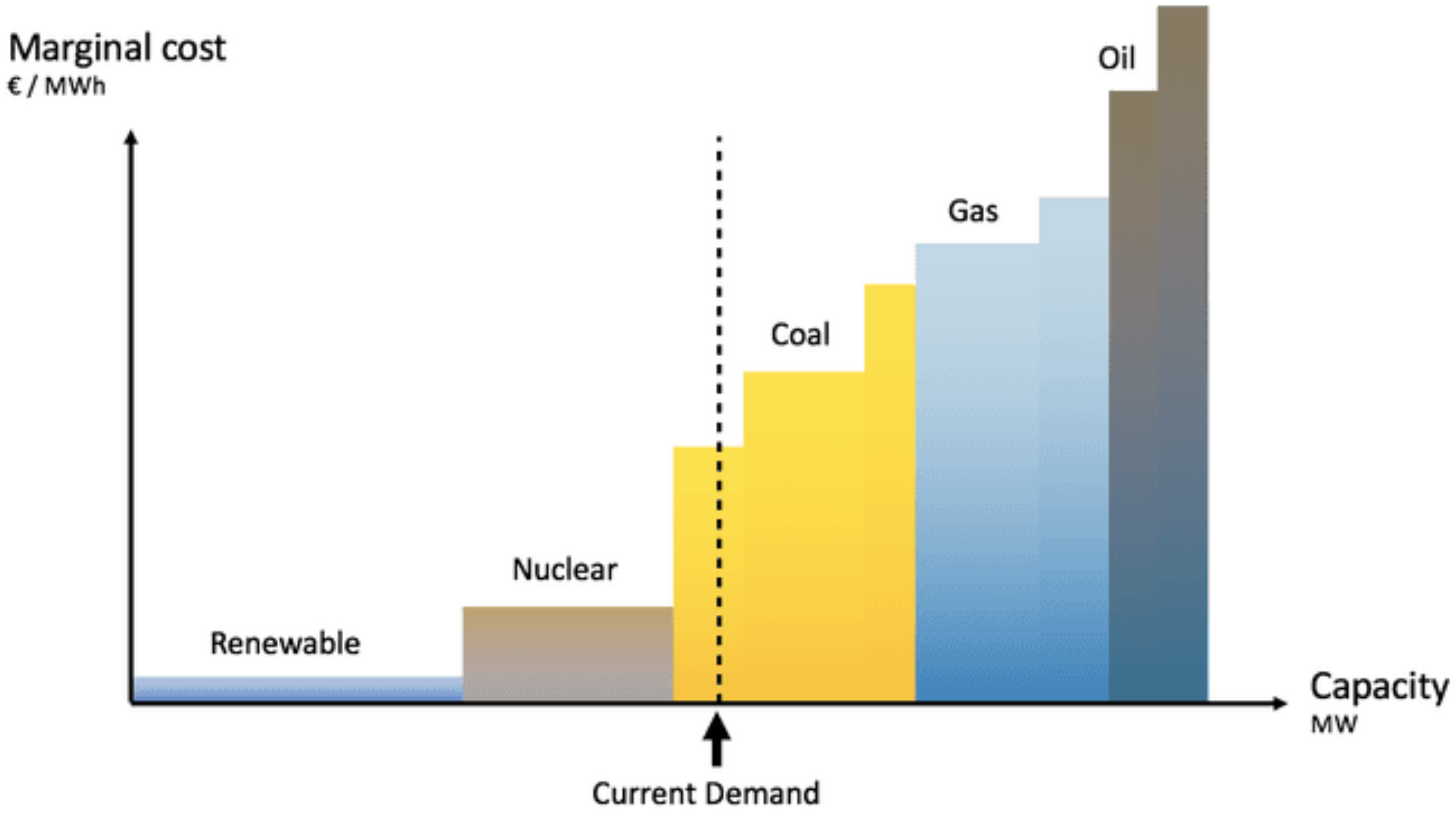
	CARBON DIOXIDE (CO_2)	METHANE (CH_4)	NITROUS OXIDE (N_2O)
20 year cumulative forcing	1	84	264
100 year cumulative forcing	1	28	265

Operational Carbon
Upstream & Transmission Adjustment



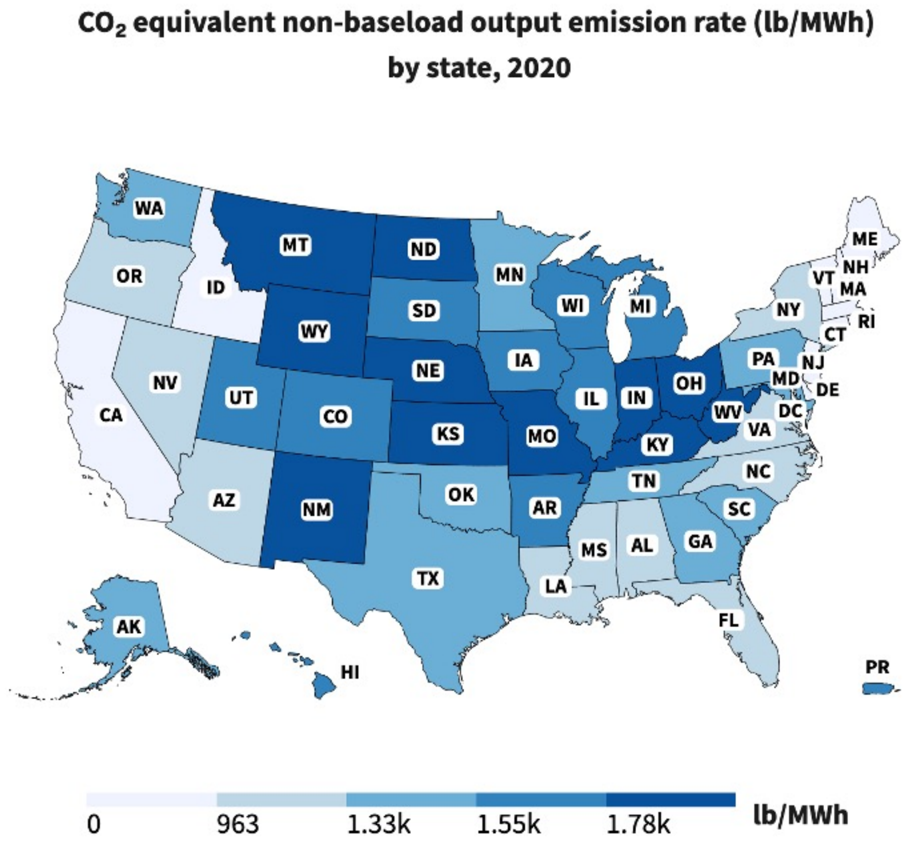
https://www.epa.gov/egrid/data-explorer

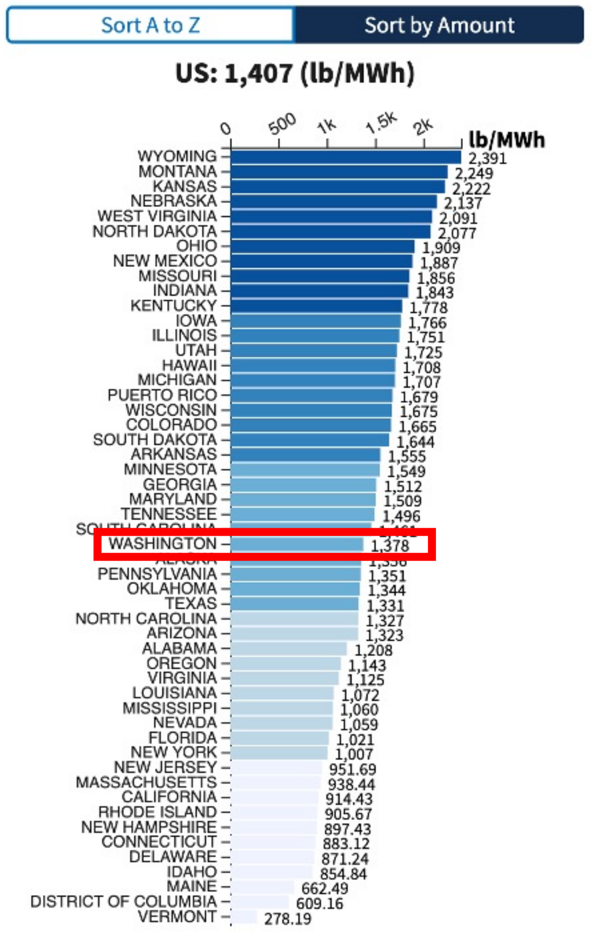
Emission Factors
Marginal Emissions Concept



https://www.electricitymaps.com/blog/marginal-emissions-what-they-are-and-when-to-use-them

Emission Factors
Marginal Emissions

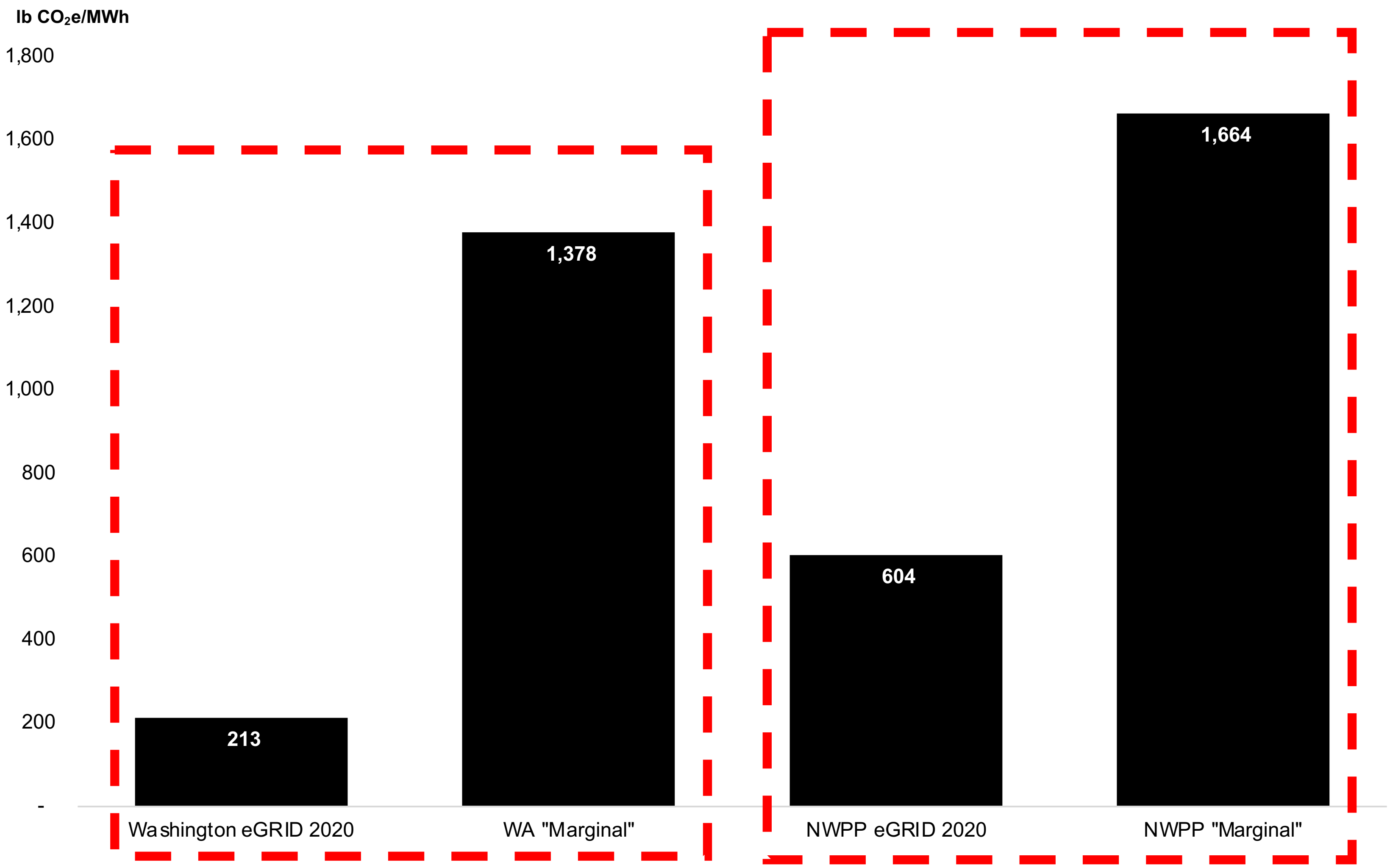




https://www.epa.gov/egrid/data-explorer

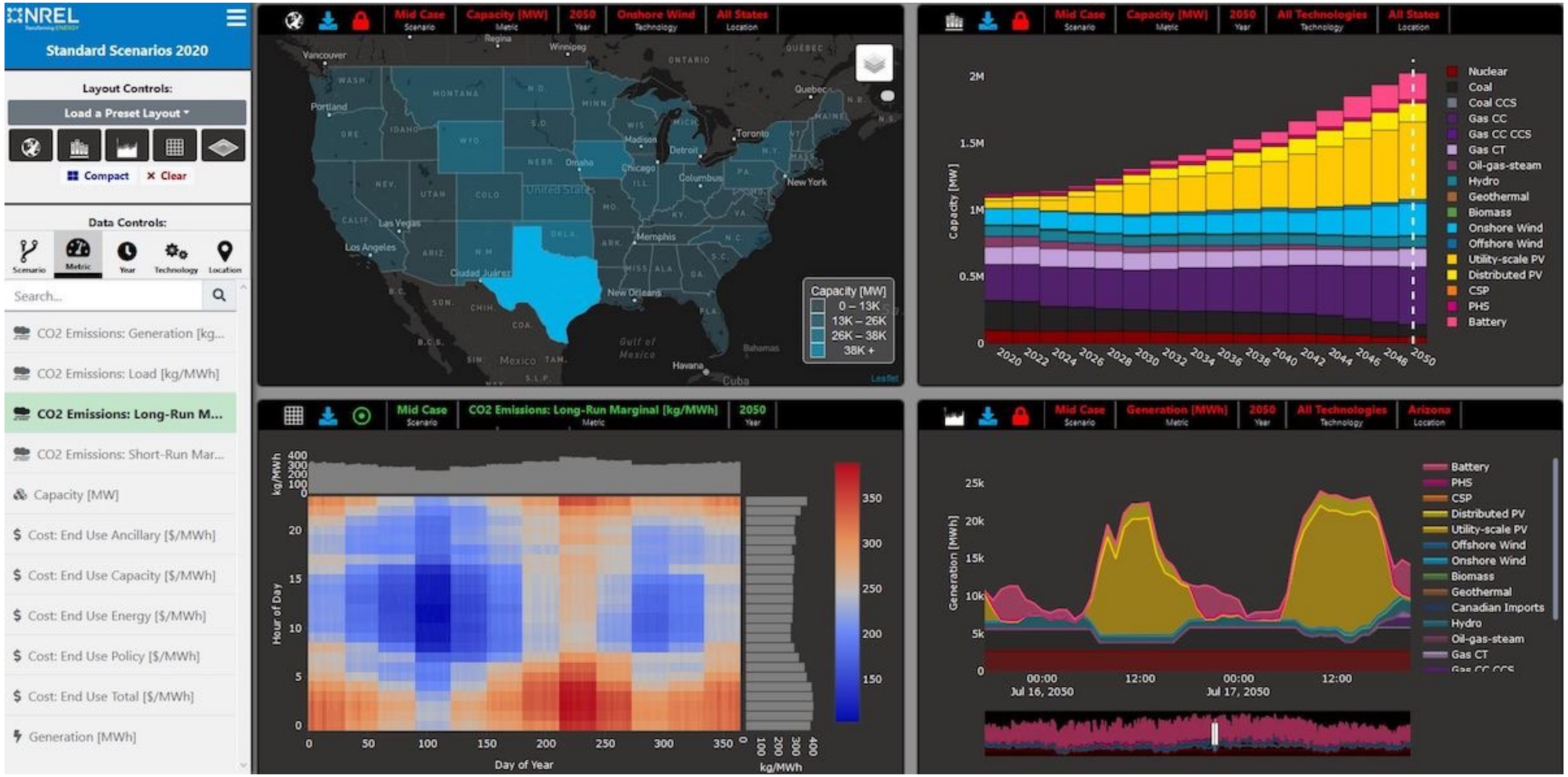
Emission Factors
Average vs Marginal or Non-Baseload

Use Short Term Marginal With Caution!



https://www.epa.gov/egrid/data-explorer

Emission Factors
Forward Looking or Long Run Emissions Rates

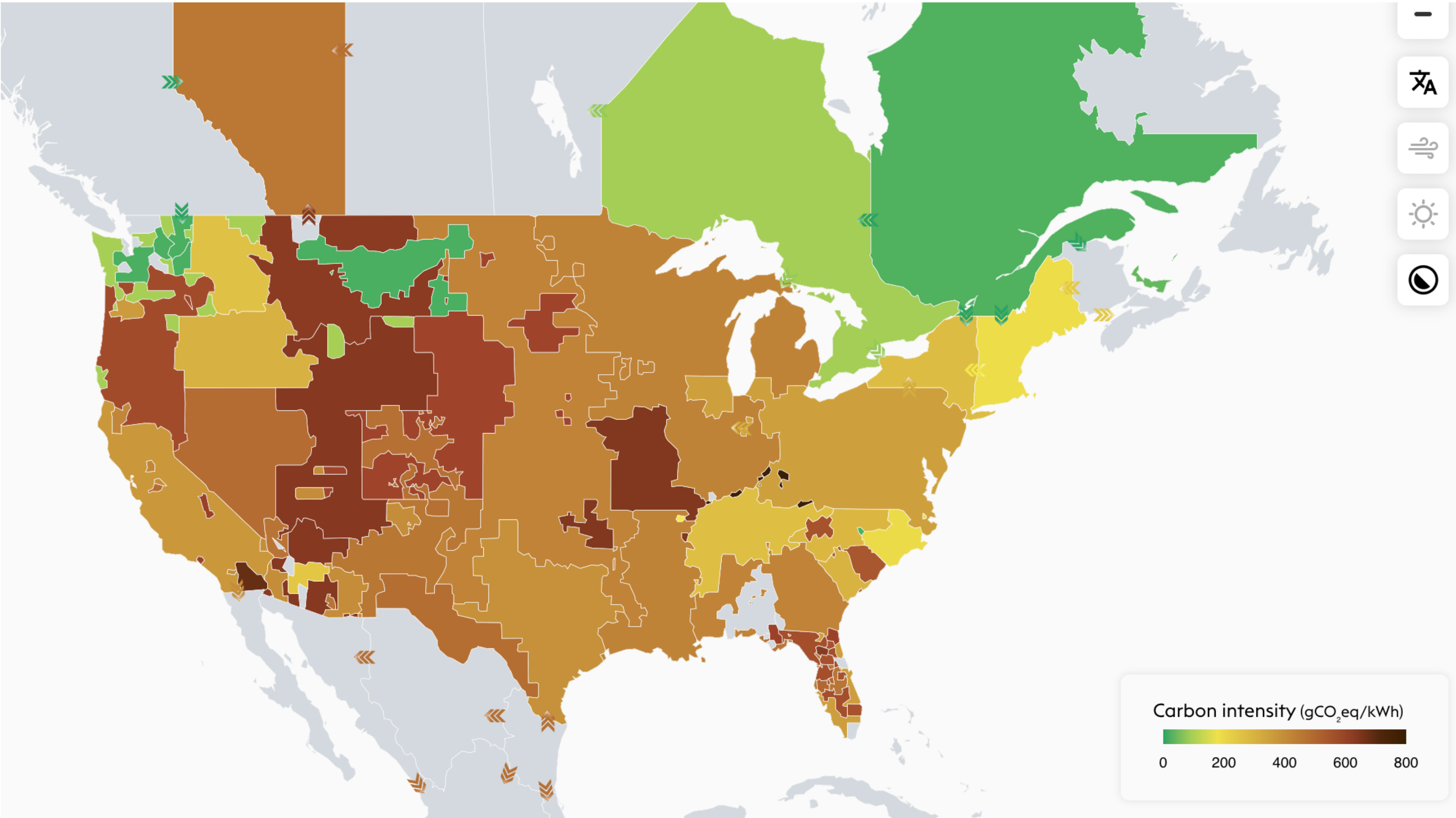


*A **long-run marginal emission rate** is the rate of emissions that would be either induced or avoided by a long-term (i.e., more than several years) change in electrical demand, incorporating both the operational and structural consequences of the change. It is therefore distinct from the more commonly known short-run marginal, which treats grid assets as fixed.*

https://www.nrel.gov/analysis/cambium.html

Boundary Conditions
Imports/Exports & Emissions Leakage

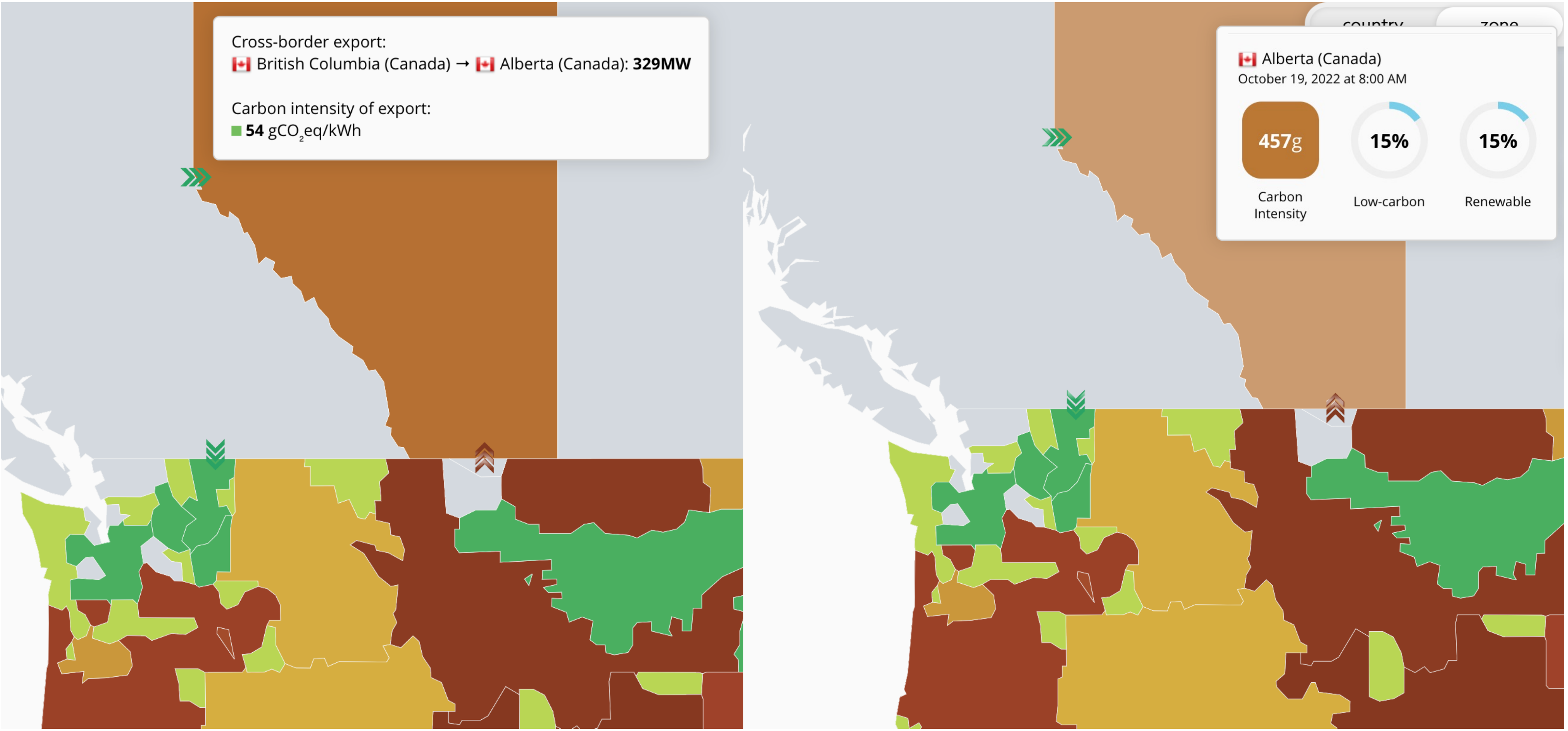
ELECTRICITY MAPS



https://app.electricitymaps.com/

Boundary Conditions
Imports/Exports & Emissions Leakage

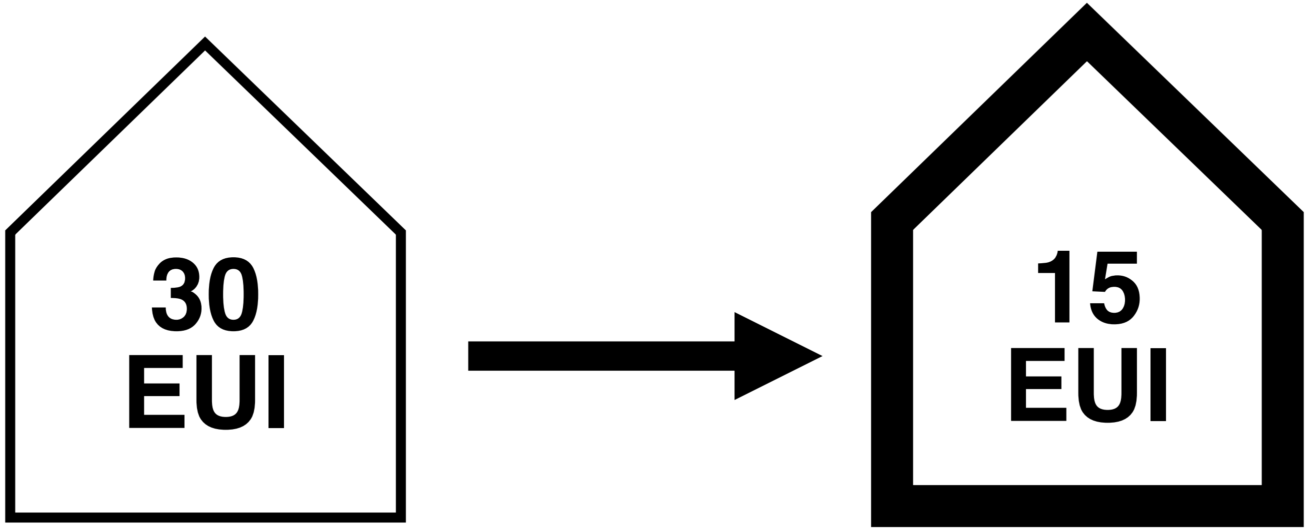
ELECTRICITY MAPS



https://app.electricitymaps.com/

Energy Use Intensity
& Operational Carbon

2,000 ft² NWPP Region



Typical Home

17,585 kWh/yr
16,460 lb/CO_2e

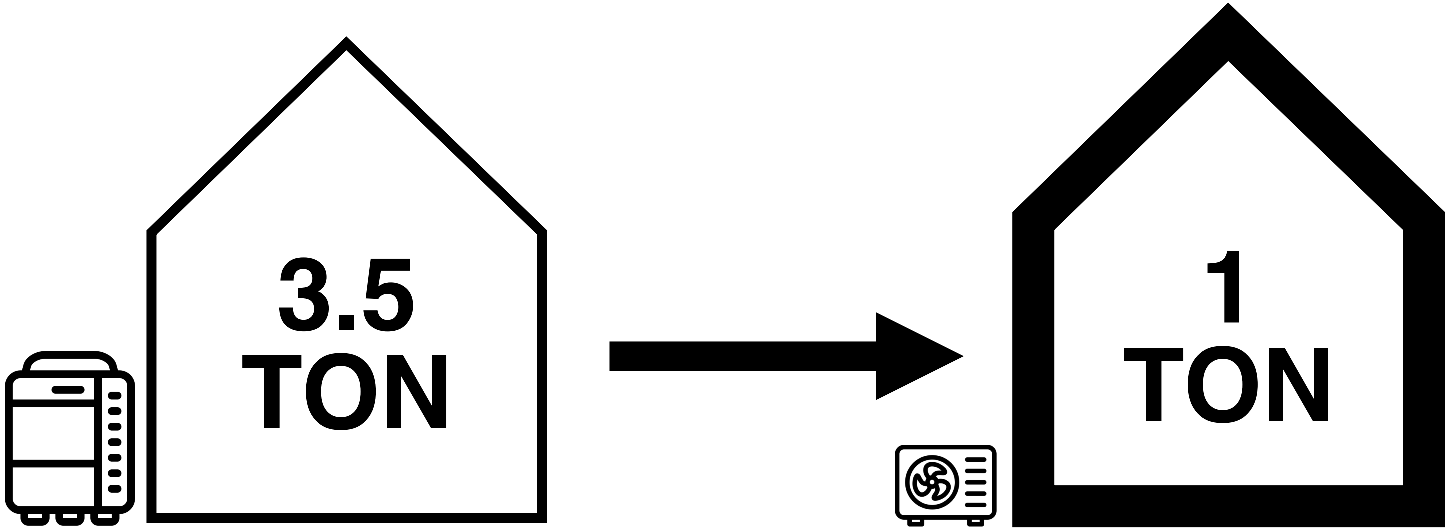
Passive House

8,793 kWh/yr
8,203 lb/CO_2e

eGRID Subregion **NWPP 0.936 lb CO_2e/kWh** (425 kg/MWh)

Energy Use Intensity & Load Reduction

2,000 ft² NWPP Region



Typical Home	**Passive House**
570 ft²/ton	**2,000 ft²/ton**
21 BTU/hr/ft²	6 BTU/hr/ft²

Heat Pump Embodied Carbon
Load Reduction Benefits
Equipment

3.5 ton
Indoor Unit **172 lb**
Outdoor Unit **283 lb**
≈1,800 lb/CO_2e

1 ton
Indoor Unit **93 lb**
Outdoor Unit **129 lb**
≈600 lb/CO_2e

Average MEP equipment is 9kgCO2e/kg (excluding refrigerant).

https://mylinkdrive.com/USA

Heat Pump Embodied Carbon
Load Reduction Benefits
Refrigerant

3.5 ton

R-410A **13.25 lb**

27,659 lb/CO2e GWP100

57,505 lb/CO2e GWP20

1 ton

R-410A **3.56 lb**

7,432 lb/CO2e GWP100

15,450 lb/CO2e GWP20

R410A 2,088 GWP100 & 4,340 GWP20

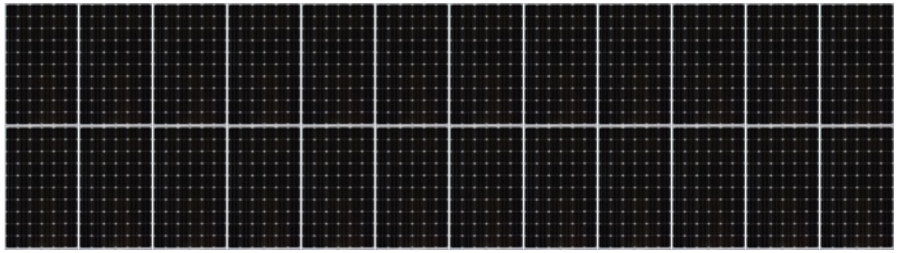
https://mylinkdrive.com/USA

PV Embodied Carbon
Load Reduction Benefits

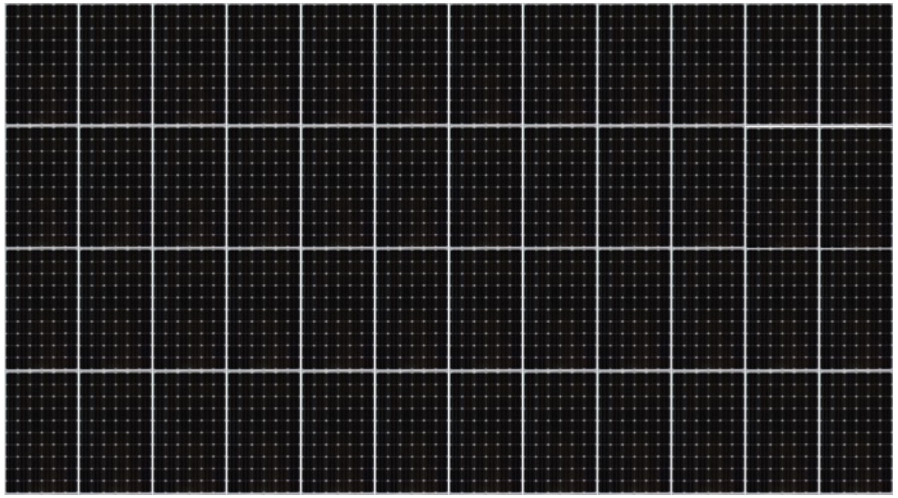
2,000 ft² NWPP Region

Typical Home		Passive House
30 EUI	→	**15 EUI**
17,585 kWh/yr		8,793 kWh/yr
÷		÷
1,000 kWh/yr per kW		1,000 kWh/yr per kW
17.6 kW		**8.8 kW**

Embodied Carbon
Net Zero PV System



8.8kW
11,932 lb CO_2e
(5,412 kg)



17.6 kW
23,863 lb CO_2e
(10,824 kg)

615 kgCO2/kWp

Embodied Carbon Context

1 kW = 615 kg CO_2e Upfront Emissions

1,000 kWh/yr x 20 years = 20,000 kWh

615 kg CO2e÷ 20,000 kWh = 31 gCO_2e/kWh

NWPP = 425 gCO_2e/kWh

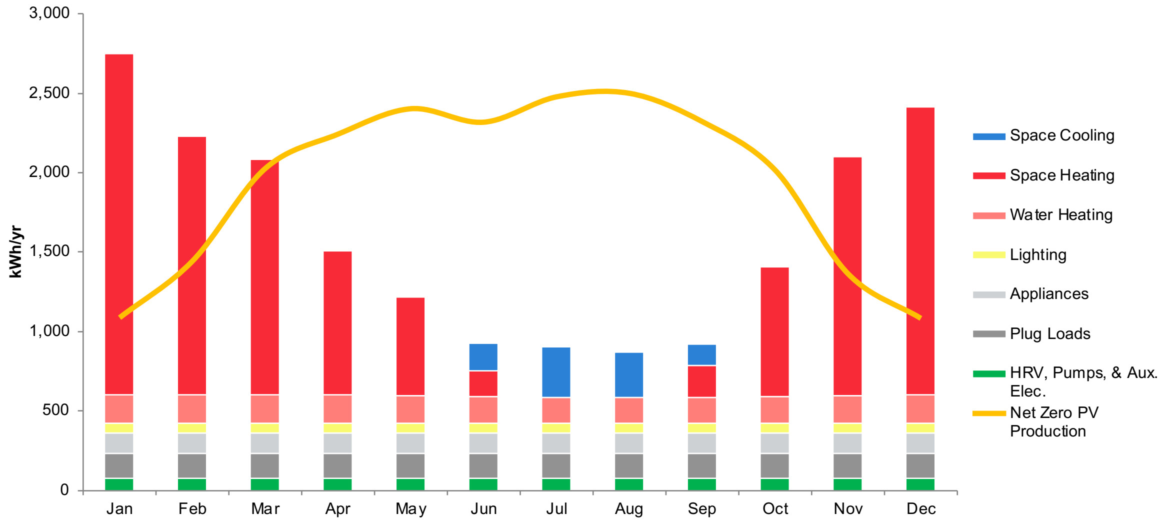
Arranged by decreasing median (gCO_2eq/kWh) values.

Technology	Min.	Median	Max.
Currently commercially available technologies			
Coal – PC	740	820	910
Gas – combined cycle	410	490	650
Biomass – Dedicated	130	230	420
Solar PV – Utility scale	18	48	180
Solar PV – rooftop	26	41	60
Geothermal	6.0	38	79
Concentrated solar power	8.8	27	63
Hydropower	1.0	24	2200[1]
Wind Offshore	8.0	12	35
Nuclear	3.7	12	110
Wind Onshore	7.0	11	56

https://en.wikipedia.org/wiki/Life-cycle_greenhouse_gas_emissions_of_energy_sources

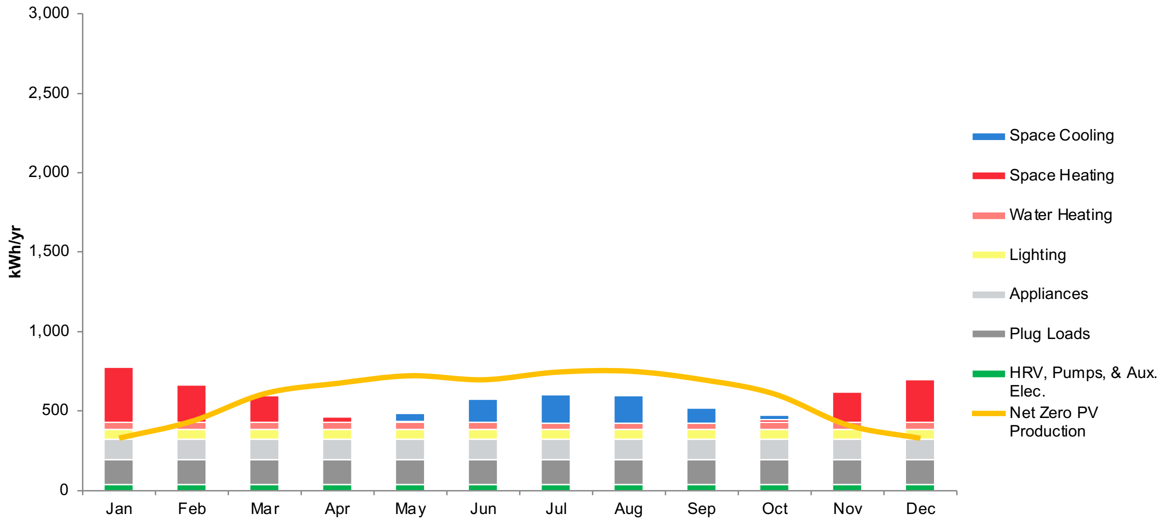
Seasonal Storage Context
Heating Demand Reduction

Code



Jan + Dec Heating
4,000 kWh

Passive House

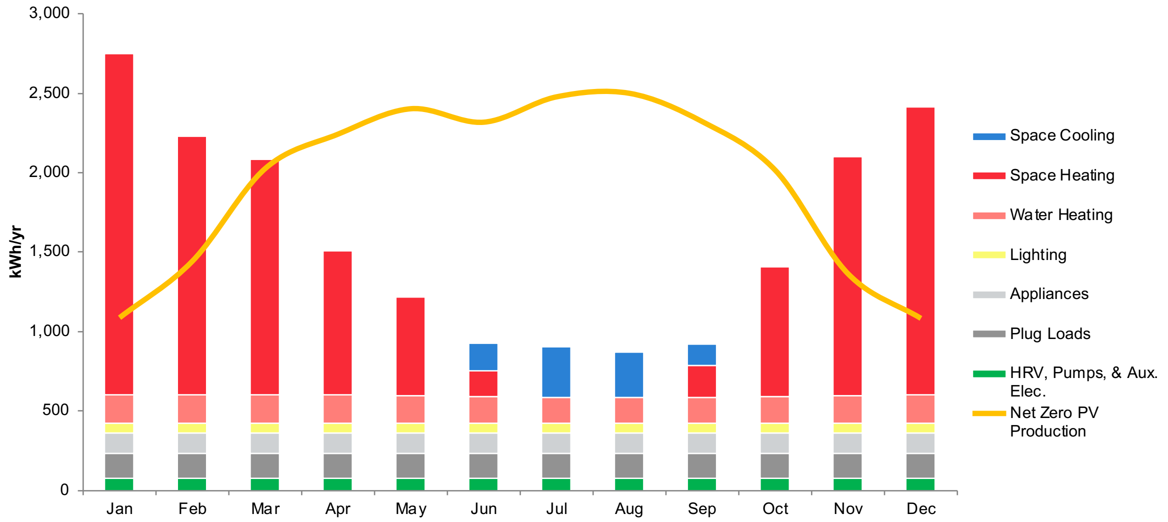


Jan + Dec Heating
600 kWh

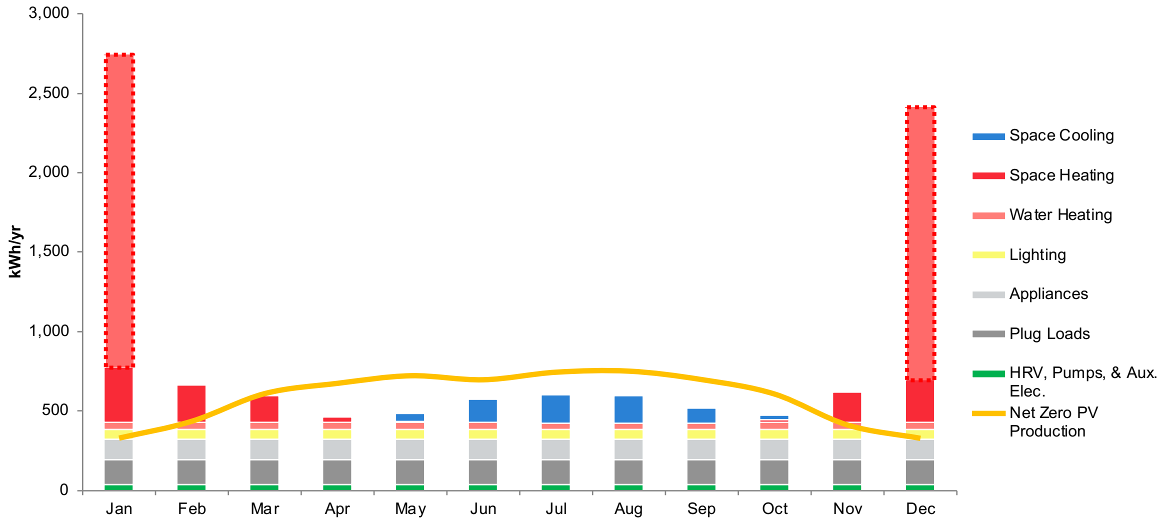
2,000 ft^2 Boise, ID

Seasonal Storage Context
Heating Demand Reduction

Code



Passive House



Jan + Dec Heating Deficit Code vs PH

3,400 kWh

Tesla Powerwall 13.5 kWh Storage

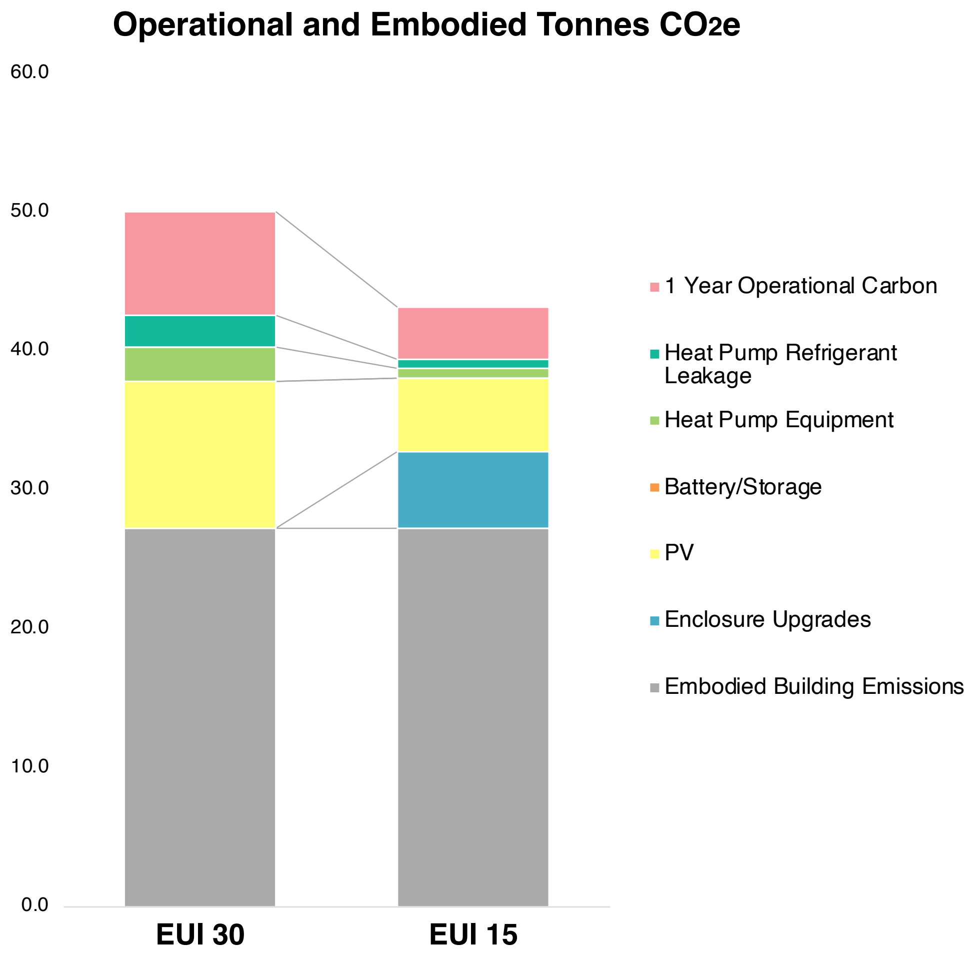
3,400/13.5= **252 Powerwalls**

≈600,000 lb CO_2e

2,000 ft² Boise, ID

Energy Use Intensity & Operational Carbon

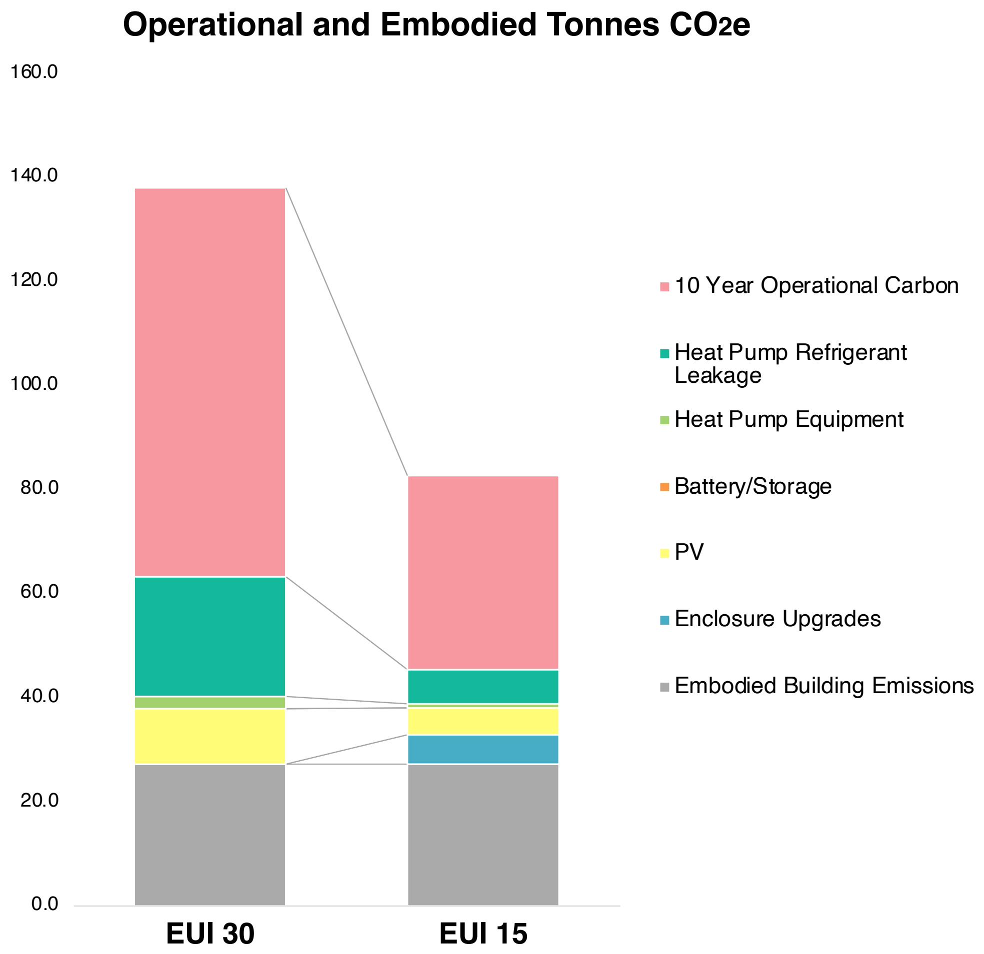
1 Year Net-Zero 2,000 ft^2 NWPP Subregion



eGRID Subregion **NWPP 0.936 lb CO_2e/kWh** (425 kg/MWh)

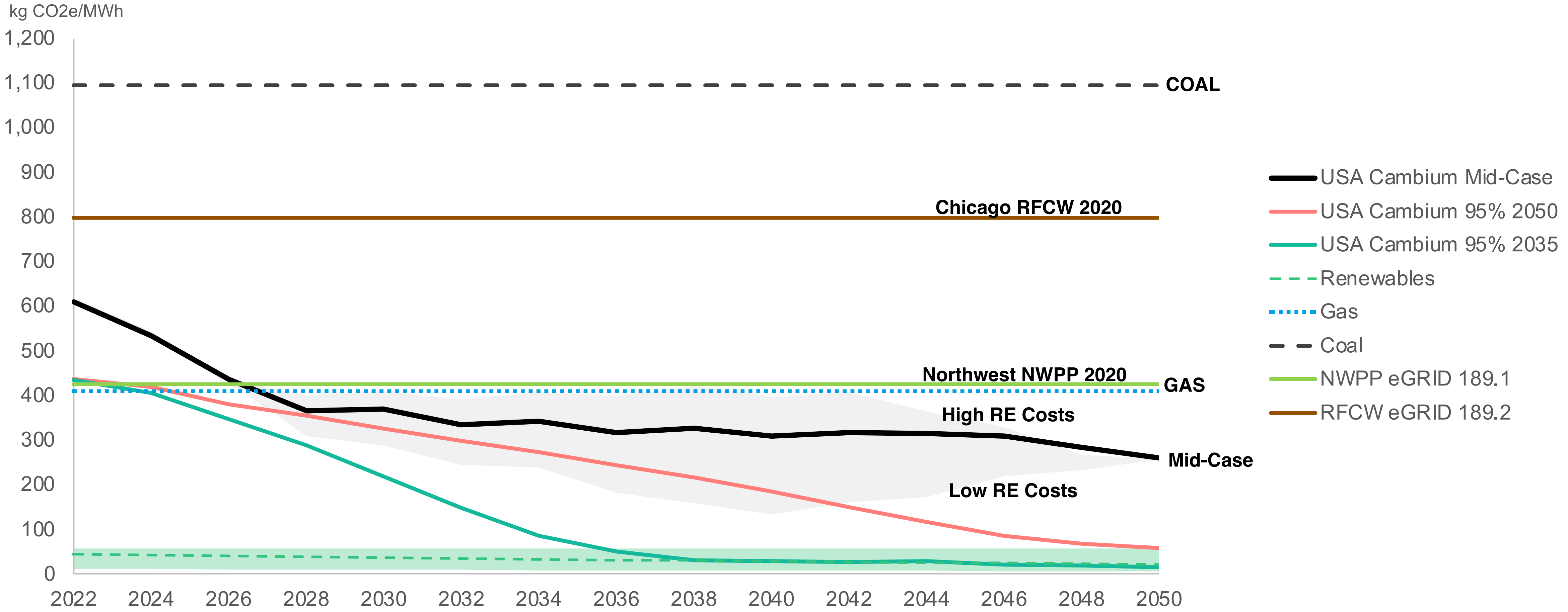
Energy Use Intensity
& Operational Carbon

10 Year Net-Zero 2,000 ft^2 NWPP Subregion



eGRID Subregion **NWPP 0.936 lb CO_2e/kWh** (425 kg/MWh)

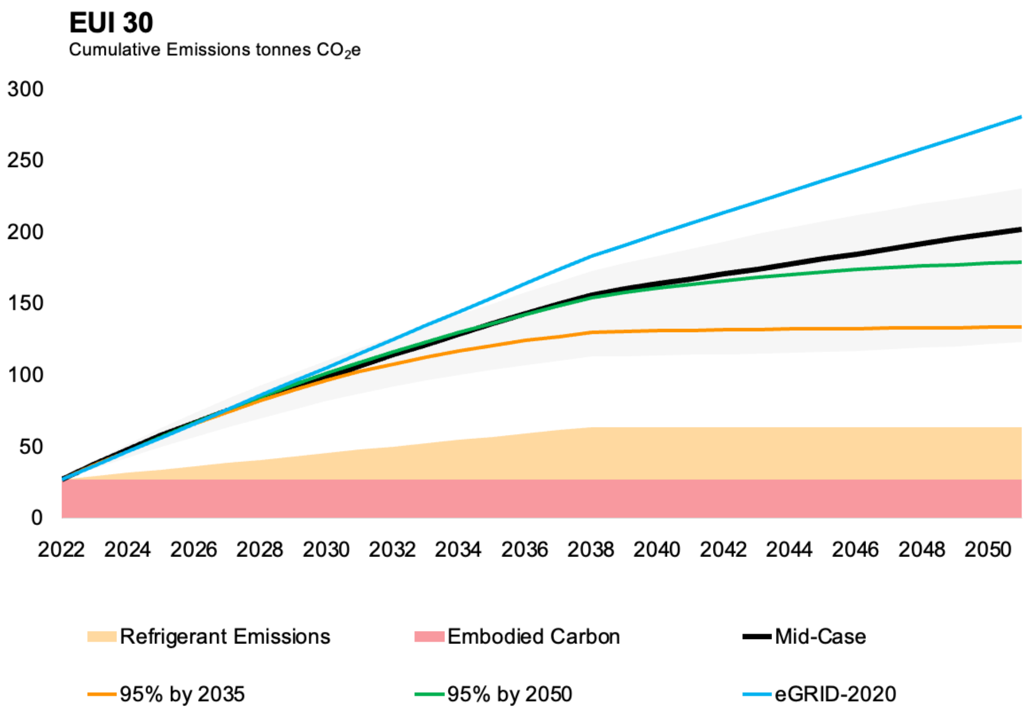
Operational Carbon
Future Emissions Scenarios

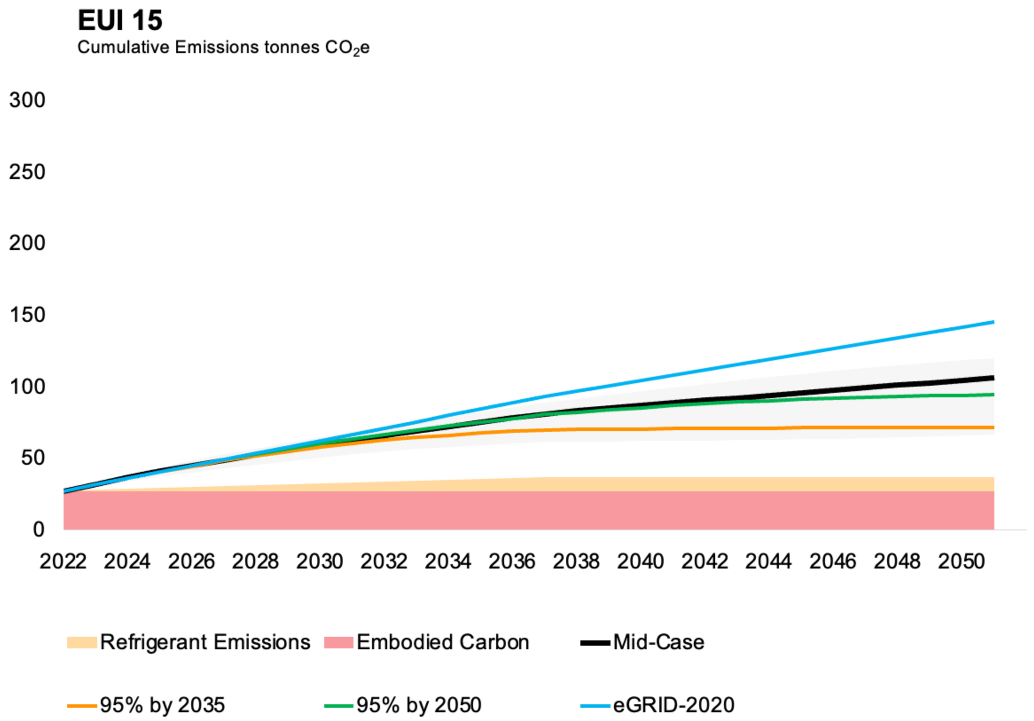


Standard Scenarios 2021 https://scenarioviewer.nrel.gov/

Energy Use Intensity
& Operational Carbon

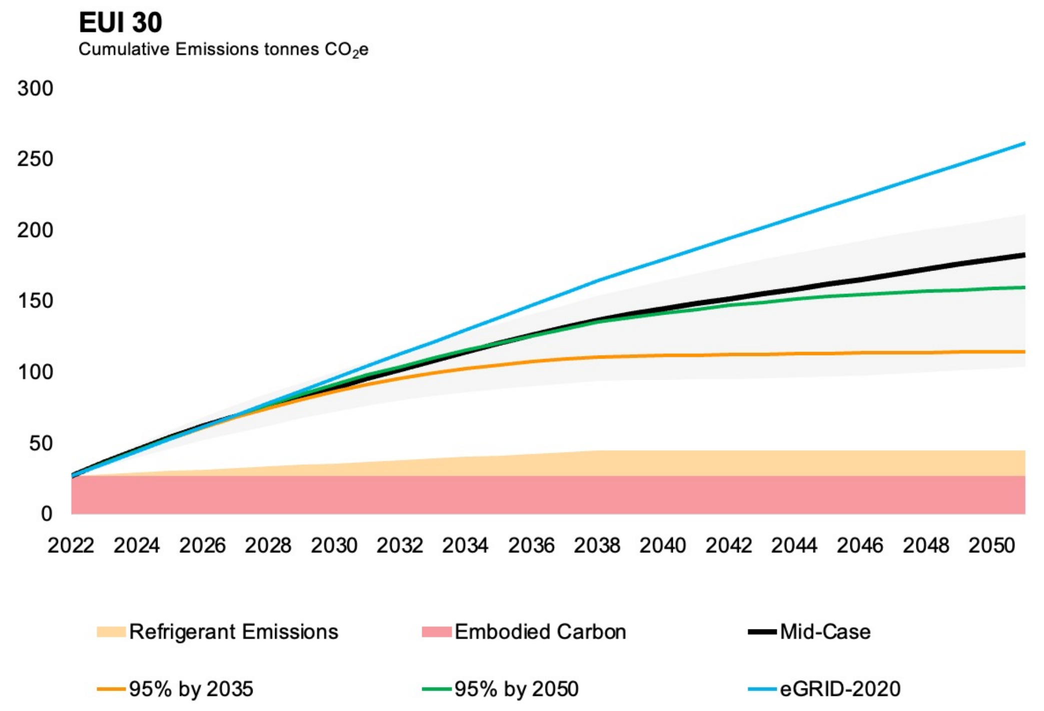
2050 Forecasts 2,000 ft² NWPP Subregion GWP20

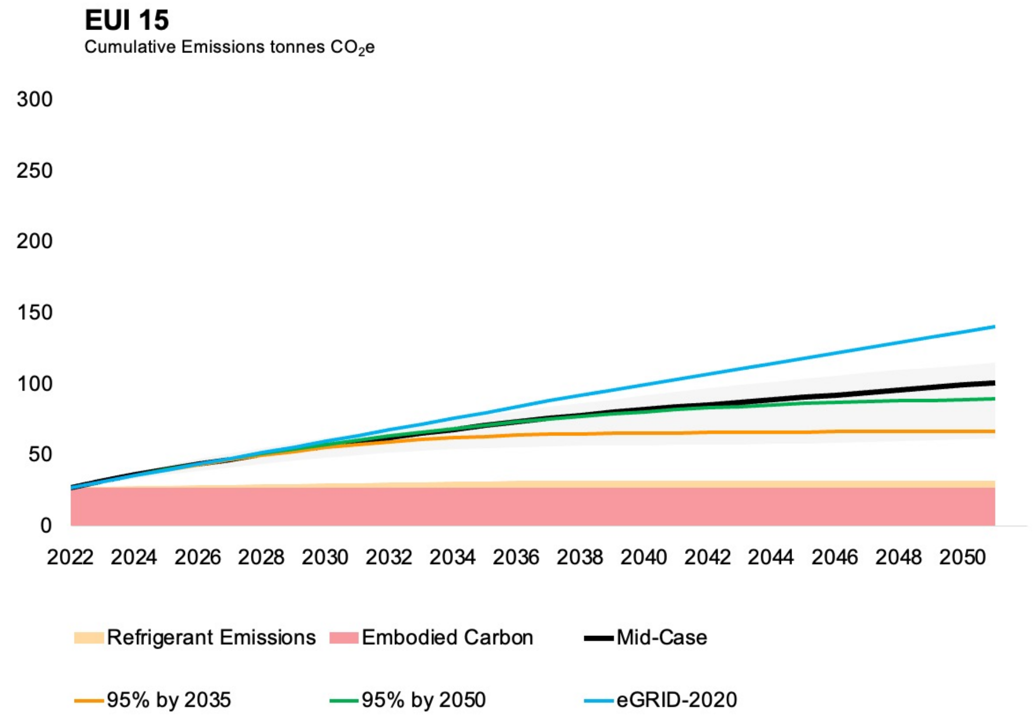




Energy Use Intensity & Operational Carbon

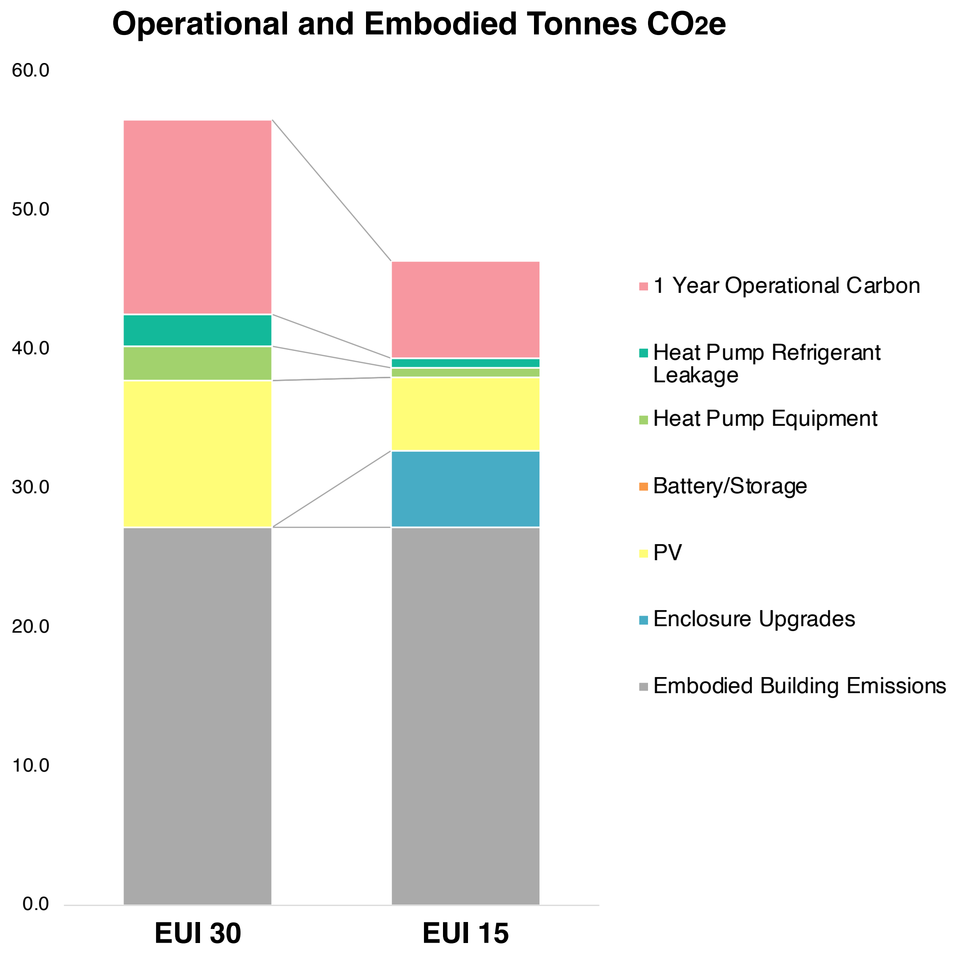
2050 Forecasts 2,000 ft² NWPP Subregion GWP100





Energy Use Intensity & Operational Carbon

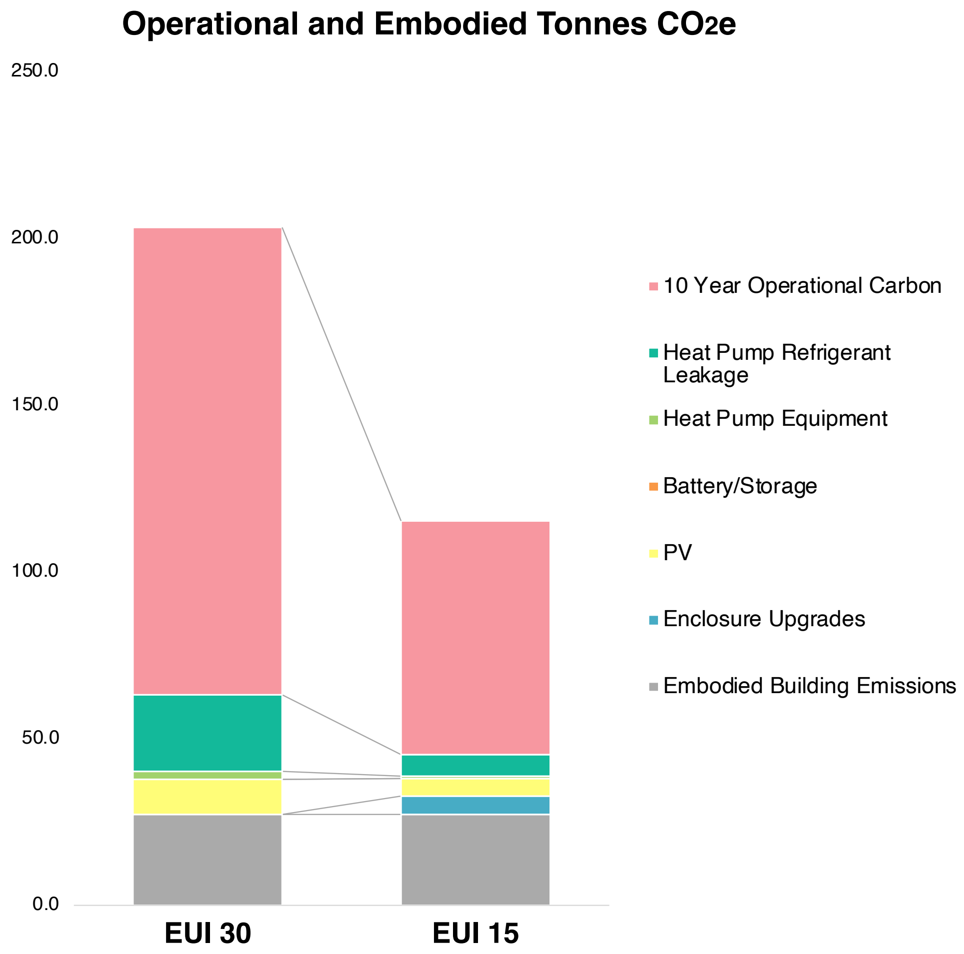
1 Year Net-Zero 2,000 ft² RFCW Subregion



eGRID Subregion **NWPP 1.757 lb CO_2e/kWh** (425 kg/MWh)

Energy Use Intensity & Operational Carbon

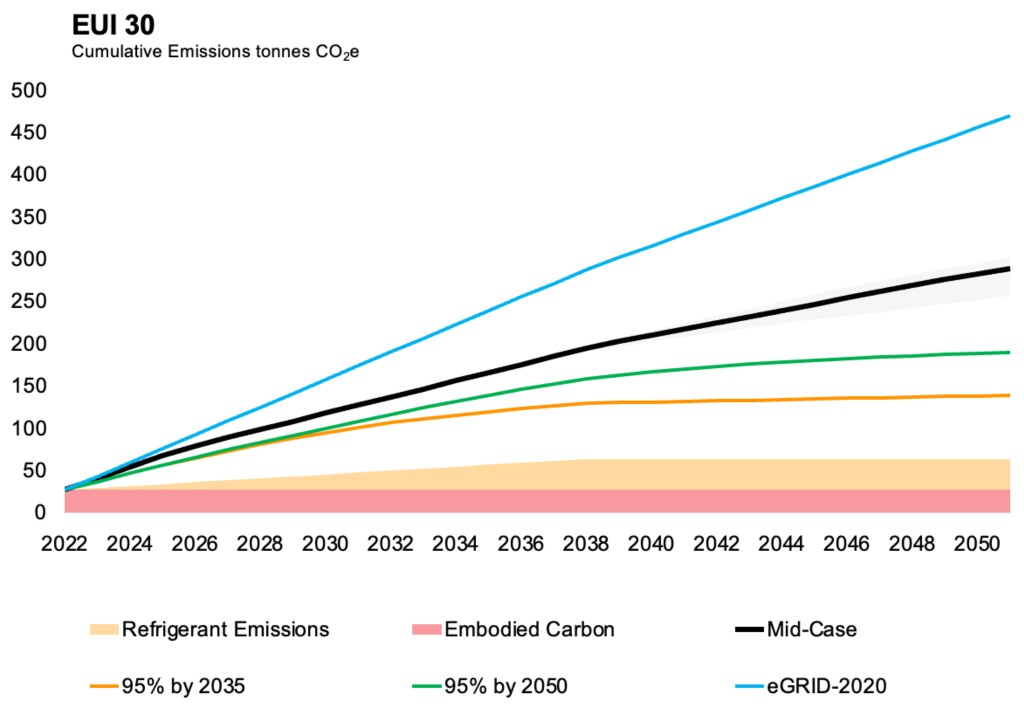
10 Year Net-Zero 2,000 ft^2 RFCW Subregion

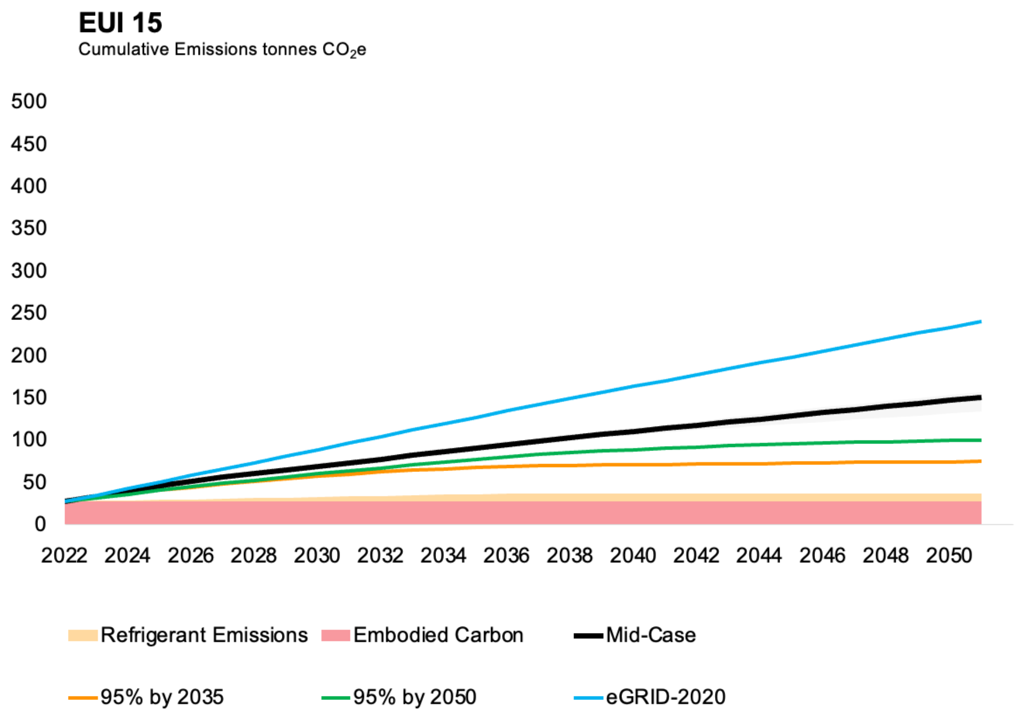


eGRID Subregion **NWPP 1.757 lb CO_2e/kWh** (425 kg/MWh)

Energy Use Intensity
& Operational Carbon

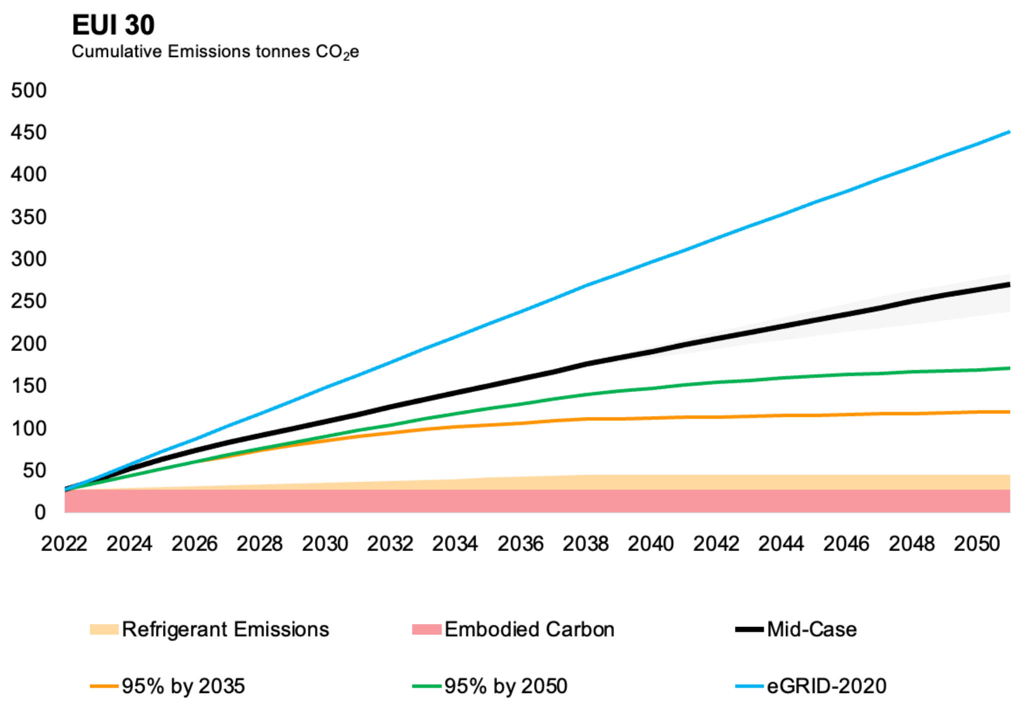
2050 Forecasts 2,000 ft² RFCW Subregion GWP20

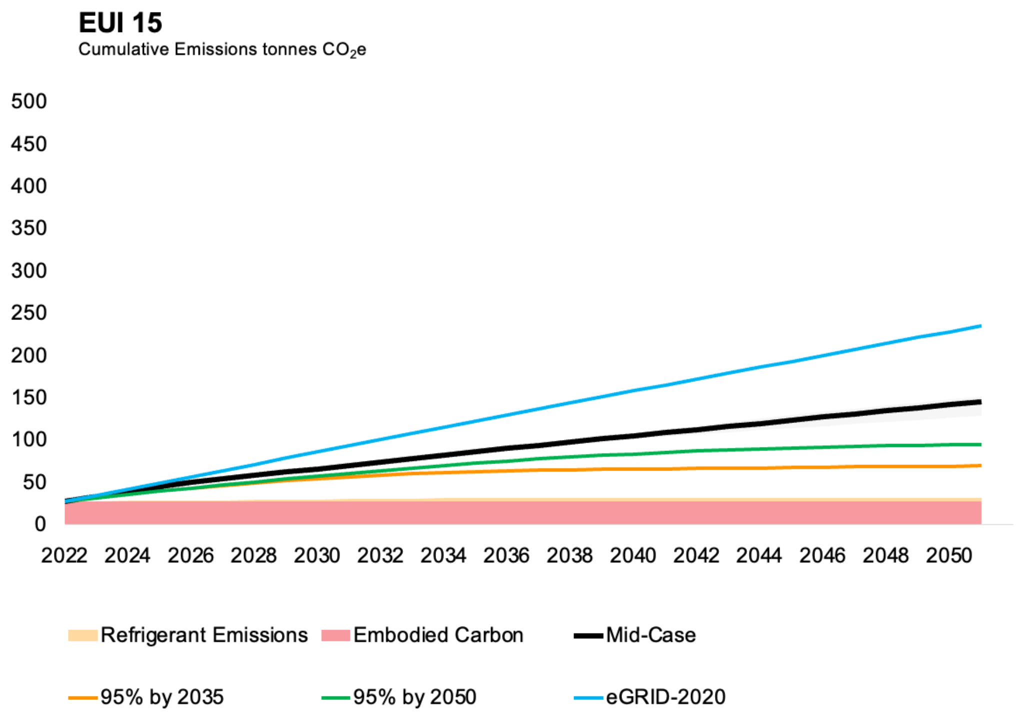




Energy Use Intensity & Operational Carbon

2050 Forecasts 2,000 ft² RFCW Subregion GWP100

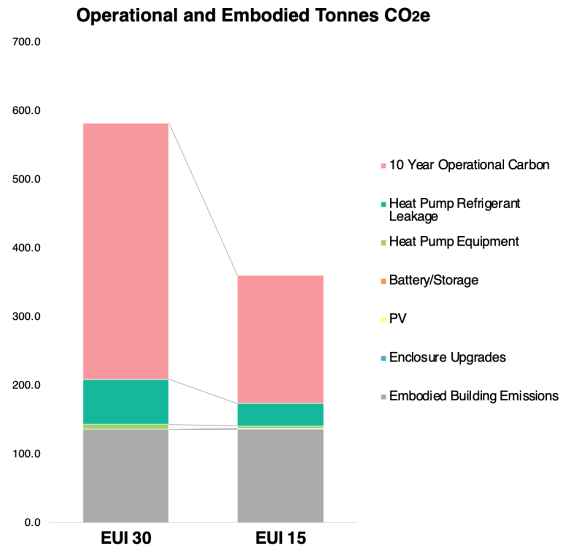


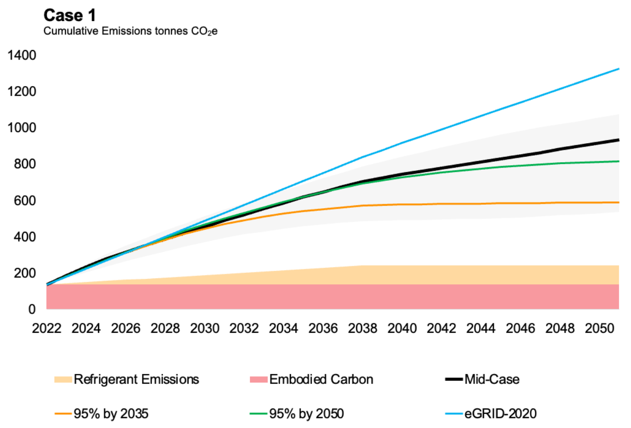


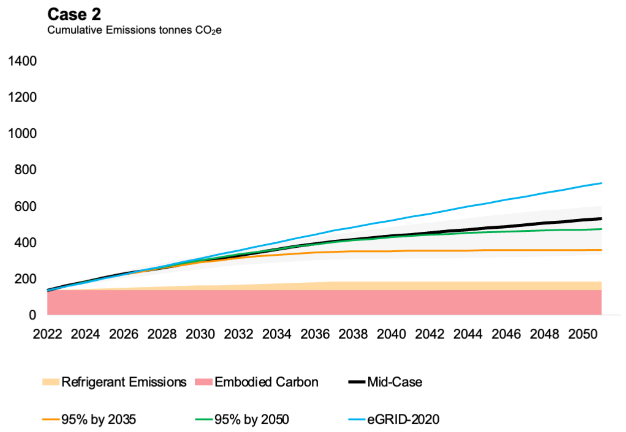
Thank you!

OC/EC estimator will be available for download presently at https://passivehouseaccelerator.com/

Slab Insulation Type	Select	avg [BEAM Avg | US & CA]	avg [BEAM Avg | US & CA]	
Slab Insulation Upgrade Emissions	lb CO_2e	0	0	0%
Wall Insulation Upgrade	R-Value	0	0	0%
Wall Insulation Type	Select	EPS foam board / R 4.0/inch avg [BEAM Avg | US & CA]	EPS foam board / R 4.0/inch avg [BEAM Avg | US & CA]	
Wall Insulation Upgrade Emissions	lb CO_2e	0	0	0%
Total Envelope Upgrade Emissions	lb CO_2e	0	2,773	100%
Whole Building Emissions	**Units**	**Case 1**	**Case 2**	
Output from BEAM or 3rd Party (no upgrades)	lb CO_2e/ft^2	30	30	0%
Total Building Emission Before Upgrades	lb CO_2e	300,000	300,000	0%
Simple Graph Inputs		**Case 1**	**Case 2**	
Years		10.0	10.0	0%
Name		EUI 30	EUI 15	
Embodied Building Emissions		136.1	136.1	0%
Enclosure Upgrades		0.0	1.3	100%
PV		0.0	0.0	0%
Battery/Storage		0.0	0.0	0%
Heat Pump Equipment		7.0	3.5	-50%
Heat Pump Refrigerant Leakage		65.7	32.9	-50%
10 Year Operational Carbon		373.4	186.7	-50%
Total Embodied and Operational Carbon		582.3	360.4	-38%
Operational %		64.1%	51.8%	-19%
Cumulative Emissions Forecast Graph Inputs		**Case 1**	**Case 2**	
Region		NWPP	NWPP	
Cambium Emission Factor		lrmer_co2e	lrmer_co2e	
Refrigerant GWP		GWP20	GWP20	
Avg Annual Leaked Refrigerant Emissions	kg CO_2e	6,570	3,285	-50%

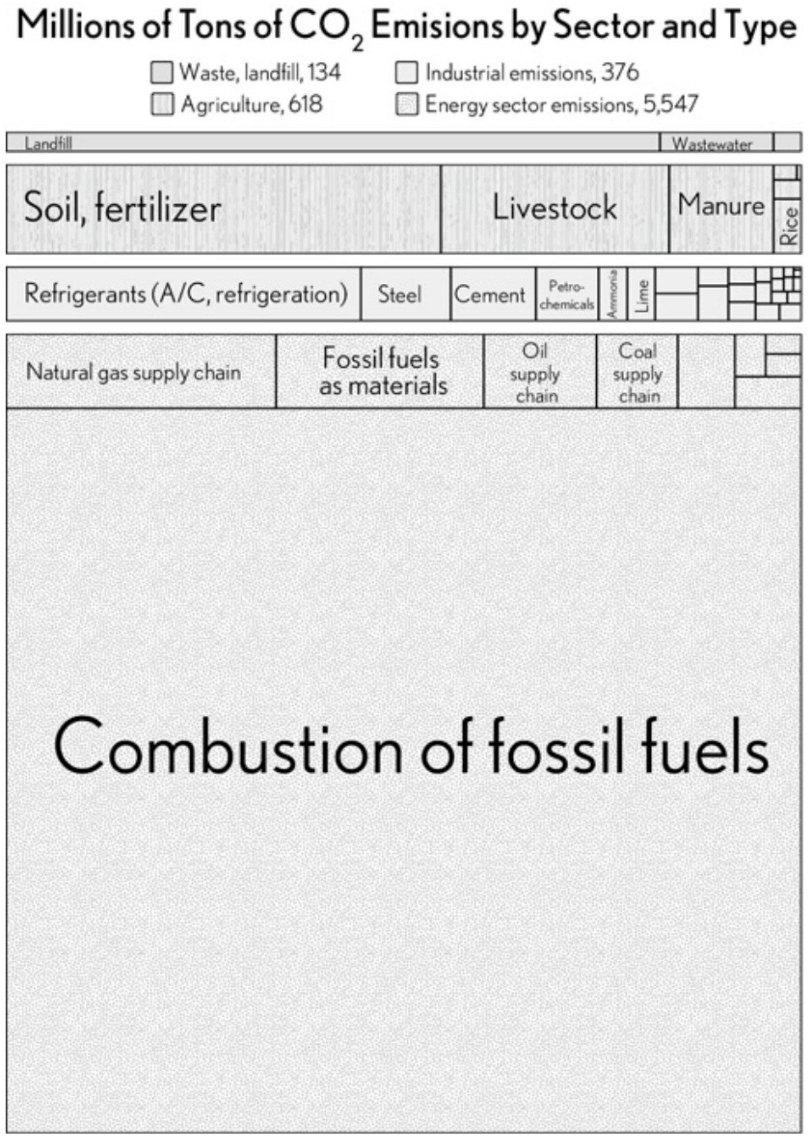






Supplemental Slides For OC/EC Estimator Reference

Inventory of US Greenhouse Gas Emissions and Sinks



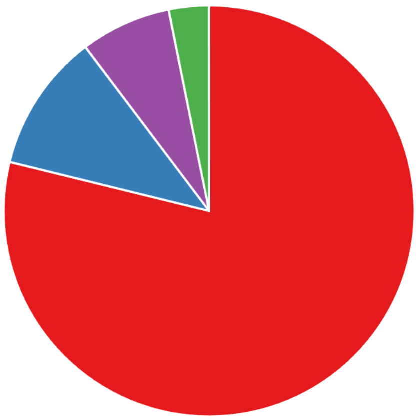
***"This book is principally concerned with the emergency of the nearly 75% of greenhouse-gas emissions related to the US energy system, which accounts for the overwhelming majority of our emissions** (the US is representative of the global problem, so throughout this book, while we focus on the US, our analysis is usually a reasonable proxy for the entire globe).1 Other emissions come from the agricultural sector (around 12%), land use and forestry (7%), and industrial non–energy use emissions (7%). Mobilizing to address climate change as suggested in this book would also address much of the industrial non-energy emissions, and a little of the other two, as well. Decarbonizing America's energy supply is about 85% of what we need to do. I have to believe that if we commit to solving 85% of the problem, the smart and passionate people working on the other 15% will do their part, too. For this reason, emissions unrelated to energy will receive only periodic mention throughout the rest of the book.*

Griffith, S. (2022). Electrify: An optimist's playbook for our Clean Energy Future. The MIT Press.
Environmental Protection Agency. (2021). Greenhouse Gas Inventory Data explorer. EPA. Retrieved September 2, 2022, from https://cfpub.epa.gov/ghgdata/inventoryexplorer/#allsectors/allsectors/allgas/econsect/current

Inventory of US Greenhouse Gas Emissions and Sinks

U.S. Greenhouse Gas Emissions by Gas, 2020

Emissions in million metric tons of carbon dioxide equivalent

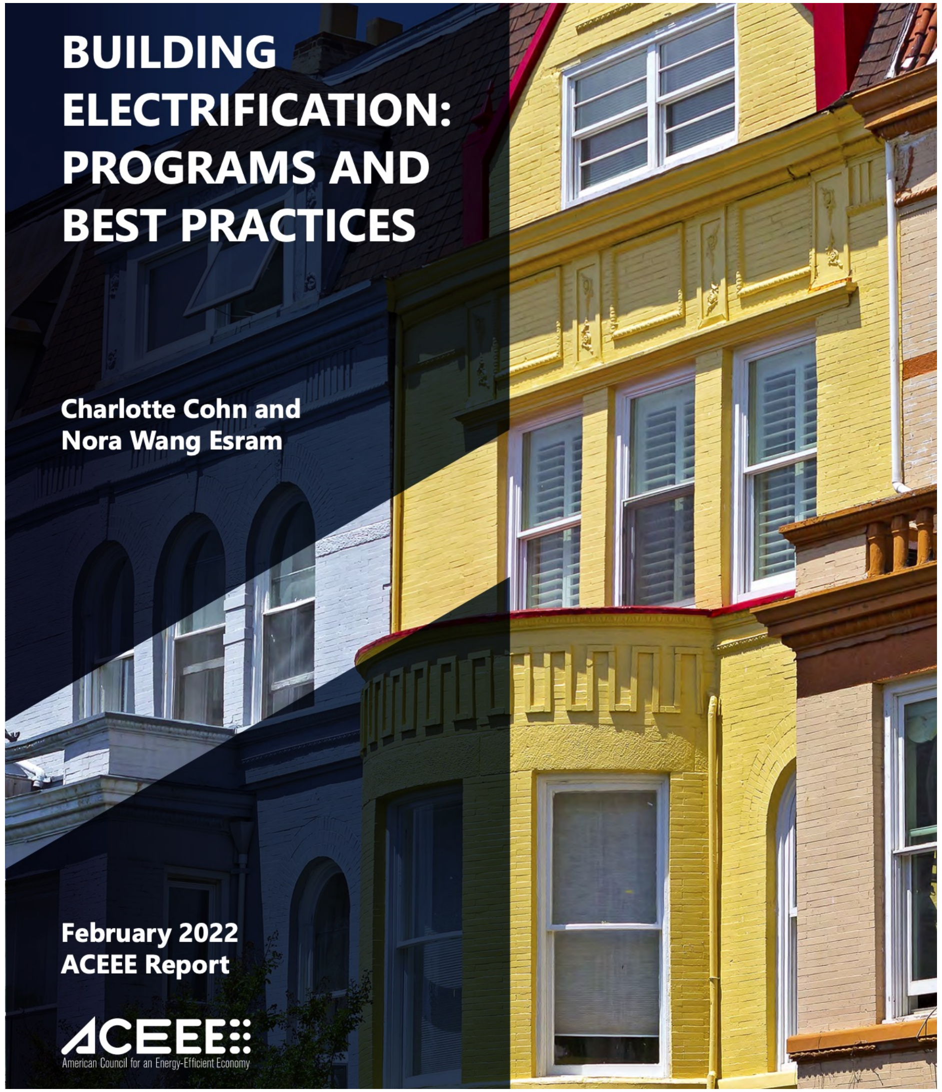


Carbon dioxide (78.8%) | Methane (10.9%) | Nitrous oxide (7.1%) | Fluorinated gases (3.2%)

Source: U.S. EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020.
https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

Environmental Protection Agency. (2021). Greenhouse Gas Inventory Data explorer. EPA. Retrieved September 2, 2022, from https://cfpub.epa.gov/ghgdata/inventoryexplorer/#allsectors/allsectors/allgas/econsect/current

Context



"Whole-building energy efficiency provides a strong foundation for electrification because it reduces a building's thermal load and peak demand.

A smaller overall heating load makes electrification more cost effective by reducing HVAC size, and a building's demand flexibility and resilience improve when a constant indoor temperature can be maintained for a longer period of time.

As electrification increases electric load during peak times, it may raise carbon emissions for some periods when carbon-intensive units, such as coal, are used for marginal generation.

A lower peak demand reduces these marginal emissions."

Cohn, C., and N. W. Esram. 2022. Building Electrification: Programs and Best Practices. Washington, DC: American Council for an Energy-Efficient Economy. aceee.org/research-report/b2201.

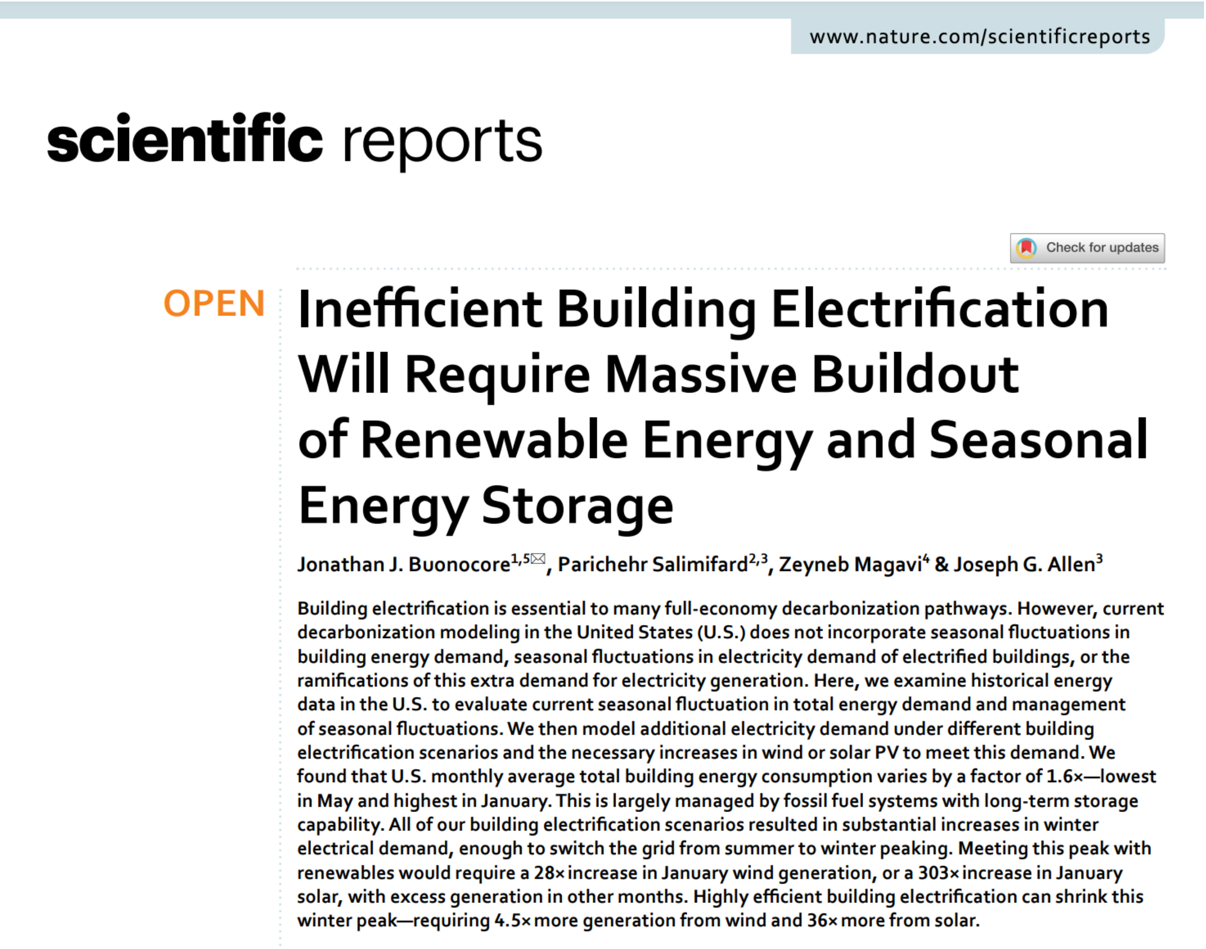
Context

"If you think about how energy is consumed around the world, people think it's consumed in the form of electricity, but in fact it's mostly consumed in the form of heat…If you want to decarbonize the world, you need to decarbonize buildings and industry. That means you need to decarbonize heat…"

Noel Bakhtian, executive director of Berkeley Lab's Energy Storage Center.

Cohn, C., and N. W. Esram. 2022. Building Electrification: Programs and Best Practices. Washington, DC: American Council for an Energy-Efficient Economy. aceee.org/research-report/b2201.

Seasonal Load
Summer to Winter Peak



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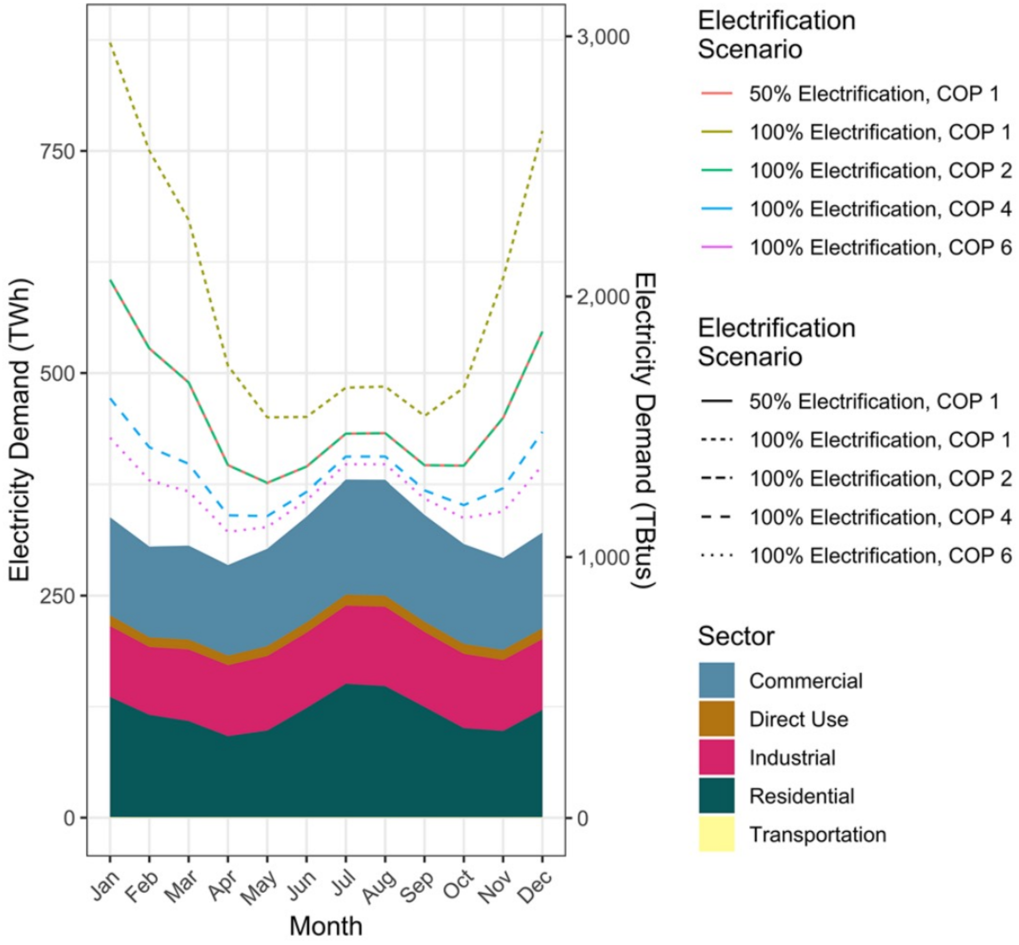
Inefficient Building Electrification Will Require Massive Buildout of Renewable Energy and Seasonal Energy Storage

Jonathan J. Buonocore[1,5]✉, Parichehr Salimifard[2,3], Zeyneb Magavi[4] & Joseph G. Allen[3]

Building electrification is essential to many full-economy decarbonization pathways. However, current decarbonization modeling in the United States (U.S.) does not incorporate seasonal fluctuations in building energy demand, seasonal fluctuations in electricity demand of electrified buildings, or the ramifications of this extra demand for electricity generation. Here, we examine historical energy data in the U.S. to evaluate current seasonal fluctuation in total energy demand and management of seasonal fluctuations. We then model additional electricity demand under different building electrification scenarios and the necessary increases in wind or solar PV to meet this demand. We found that U.S. monthly average total building energy consumption varies by a factor of 1.6×—lowest in May and highest in January. This is largely managed by fossil fuel systems with long-term storage capability. All of our building electrification scenarios resulted in substantial increases in winter electrical demand, enough to switch the grid from summer to winter peaking. Meeting this peak with renewables would require a 28× increase in January wind generation, or a 303× increase in January solar, with excess generation in other months. Highly efficient building electrification can shrink this winter peak—requiring 4.5× more generation from wind and 36× more from solar.



Buonocore, J. J., Salimifard, P., Magavi, Z., & Allen, J. G. (2022). Inefficient Building Electrification Will Require Massive Buildout of Renewable Energy and Seasonal Energy Storage. Scientific Reports, 12(1), 11931. https://doi.org/10.1038/s41598-022-15628-2

Emission Factors
Boundary Conditions

NREL
Transforming ENERGY

Photo by Dennis Schroeder, NREL 23201

Greenhouse Gas Emissions Accounting in Buildings

Building operations in the United States account for about 70% of electricity use, about 40% of the total U.S. primary energy consumption,[1] and about 30% of greenhouse gas (GHG) emissions.[2] Carbon dioxide (CO_2) emissions from building energy use and embodied emissions accounted for about 37% of global CO_2 emissions in 2020.[3] Thus, accurate GHG emissions accounting is critical to inform decisions for emissions reduction. This fact sheet provides an introduction to GHG emissions accounting for operation of buildings including equipment replacements and operational material purchases. It does not include embodied GHG emissions in existing buildings or from major retrofit construction activities.

What are operational activities that result in emissions and where are the opportunities to reduce emissions from commercial buildings?

The majority of GHG emissions from building activities come from combustion of fossil fuels for energy, either remotely for generation of electricity or on-site for heat and power generation. Carbon dioxide, methane, and nitrous oxide are all GHGs associated with combustion. Methane can also be released to the atmosphere from leakage in pipes, valves, and equipment. Refrigerants are very powerful GHGs and can leak from refrigeration and heat pump equipment during installation, maintenance, and operation. Annual refrigerant leakage varies significantly and is most often estimated to be between 1% and 10% of the total system refrigerant charge, but can be much higher if there is a catastrophic failure in the system.[4]

Figure 1. Example operational activities that impact emissions, representing an 87% reduction in GHG emissions. Data are for demonstration purposes only for a supermarket. Equipment purchases can refer to furniture purchases such as desks, chairs, and partitions for commercial building use.

1 EIA 2021. Monthly Energy Review, preliminary data for 2020. *https://www.eia.gov/totalenergy/data/monthly*. US Energy Information Administration: Washington DC.
2 US EPA 2021. Sources of Greenhouse Gas Emissions. *https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions*. Washington DC.
3 UNEP, IEA 2021. Global ABC 2021 Global status report.
4 Integral Group 2020. *"Refrigerants + Environmental Impacts: A Best Practice Guide"* *https://www.integralgroup.com/news/refrigerants-environmental-impacts/*. See Appendix A.4 for more data on leakage rates for HVAC systems.

Where can I find emission factors?

Source	Energy /Fuel	Scope	Time Scale	Region	Background Data Source	GWP-Year
EPA eGRID[6]	Electricity	Combustion to end use	Annual average and non-baseload	U.S., NERC regions, eGRID subregions, state, balancing areas	CAMD, EIA-860, EIA-923 (2019)	AR4, 100-yr
Green-e[7]	Electricity	Combustion to end use for residuals	Annual average	U.S., eGRID subregions	eGRID, Green-e certified sales	AR4 100-yr
Edison Electric Institute GHG database[8]	Electricity	Combustion to end use for total and residuals	Annual average	Utility (43% of country)	Utility data, (2018 and 2019)	AR4 100-yr
ASHRAE Standard 105-2021	Electricity & fuels	Full life cycle	Annual average and non-baseload	U.S., eGRID subregions	eGRID plus (2014, 2019)	20-yr & 100-yr
ASHARE Standard 189.1-2020	Electricity & fuels	Full life cycle	Annual average	U.S., eGRID subregions	EIA 2017	20-yr & 100-yr
Wattime	Electricity	Combustion to end use	15 minute marginal	Balancing areas	Real time	AR4, 100-yr
Cambium, NREL[9]	Electricity	Future projections	15 minute, hourly, average and marginal	U.S., regional assessment zones, balancing area	Simulated future energy scenarios with 2012 weather	AR4, 100-yr
EPA[10]	Fuels, refrigerants and others	Combustion or direct atmospheric release	Event-based	U.S.	Multiple (see resource documentation)	AR4, 100-yr

https://www.nrel.gov/docs/fy22osti/81671.pdf

Emission Factors
Boundary Conditions

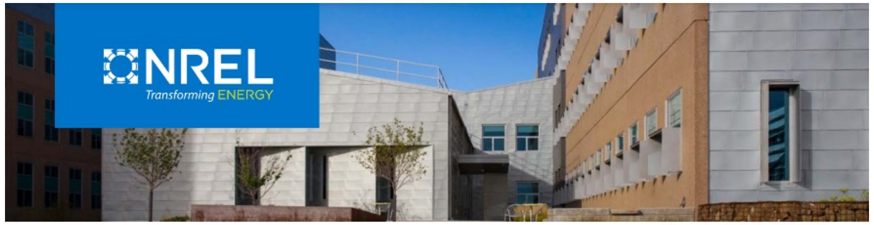


Photo by Dennis Schroeder, NREL 23201

Greenhouse Gas Emissions Accounting in Buildings

Building operations in the United States account for about 70% of electricity use, about 40% of the total U.S. primary energy consumption,[1] and about 30% of greenhouse gas (GHG) emissions.[2] Carbon dioxide (CO_2) emissions from building energy use and embodied emissions accounted for about 37% of global CO_2 emissions in 2020.[3] Thus, accurate GHG emissions accounting is critical to inform decisions for emissions reduction. This fact sheet provides an introduction to GHG emissions accounting for operation of buildings including equipment replacements and operational material purchases. It does not include embodied GHG emissions in existing buildings or from major retrofit construction activities.

What are operational activities that result in emissions and where are the opportunities to reduce emissions from commercial buildings?

The majority of GHG emissions from building activities come from combustion of fossil fuels for energy, either remotely for generation of electricity or on-site for heat and power generation. Carbon dioxide, methane, and nitrous oxide are all GHGs associated with combustion. Methane can also be released to the atmosphere from leakage in pipes, valves, and equipment. Refrigerants are very powerful GHGs and can leak from refrigeration and heat pump equipment during installation, maintenance, and operation. Annual refrigerant leakage varies significantly and is most often estimated to be between 1% and 10% of the total system refrigerant charge, but can be much higher if there is a catastrophic failure in the system.[4]

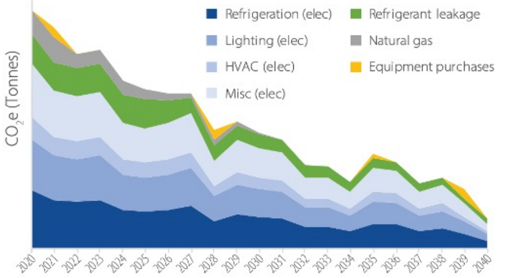


Figure 1. Example operational activities that impact emissions, representing an 87% reduction in GHG emissions. Data are for demonstration purposes only for a supermarket. Equipment purchases can refer to furniture purchases such as desks, chairs, and partitions for commercial building use.

1 EIA 2021. Monthly Energy Review, preliminary data for 2020. https://www.eia.gov/totalenergy/data/monthly. US Energy Information Administration: Washington DC.
2 US EPA 2021. Sources of Greenhouse Gas Emissions. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions. Washington DC.
3 UNEP, IEA 2021. Global ABC 2021 Global status report.
4 Integral Group 2020. *"Refrigerants + Environmental Impacts: A Best Practice Guide"* https://www.integralgroup.com/news/refrigerants-environmental-impacts/. See Appendix A.4 for more data on leakage rates for HVAC systems.

"National vs. Regional vs. Utility:
Emission factors can be calculated for different locations: national, regional, or utility.

The most common regional values are based on the 26 eGRID subregions defined by the EPA. State-level emission factors may not be good representations of local emissions and are not recommended."

https://www.nrel.gov/docs/fy22osti/81671.pdf

Emission Factors
Boundary Conditions


EPA
United States
Environmental Protection
Agency

THE EMISSIONS & GENERATION
RESOURCE INTEGRATED DATABASE
eGRID Technical Guide with Year 2020 Data

eGRID 2020

Office of Atmospheric Programs
Clean Air Markets Division

3.4.2 eGRID Subregion

eGRID subregions are identified and defined by EPA and were developed as a compromise between NERC regions (which EPA felt were too big) and balancing authorities (which EPA felt were generally too small). Using NERC regions and balancing authorities as a guide, the subregions were defined to limit the import and export of electricity in order to establish an aggregated area where the determined emission rates most accurately matched the generation and emissions from the plants within that subregion.

EPA (2022). EGRID2020 Technical Guide. U.S. Environmental Protection Agency
https://www.epa.gov/system/files/documents/2022-01/egrid2020_technical_guide.pdf.

Emission Factors
Boundary Conditions

EPA United States Environmental Protection Agency

Environmental Topics | Laws & Regulations | About EPA | Search 1/19/17 snapshot

Energy and the Environment

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How to use eGRID for Carbon Footprinting Electricity Purchases in Greenhouse Gas Emission Inventories

This paper provides and reviews recommendations regarding which year(s) of eGRID subregion GHG emissions factors to use for estimating Scopes 2 and 3 GHG emissions from electricity use under various conditions.

You will need Adobe Reader to view some of the files on this page. See EPA's About PDF page to learn more.

- How to use eGRID for Carbon Footprinting Electricity Purchases in Greenhouse Gas Emission Inventories (PDF) (22 pp, 537 K)

https://www3.epa.gov/ttnchie1/conference/ei20/session3/adiem.pdf

Emission Factors
eGRID Aggregation Level

United States Environmental Protection Agency

"Choosing an aggregation level that is too large (for example, the entire U.S.) includes generation that is not relevant to the regional resource mix.

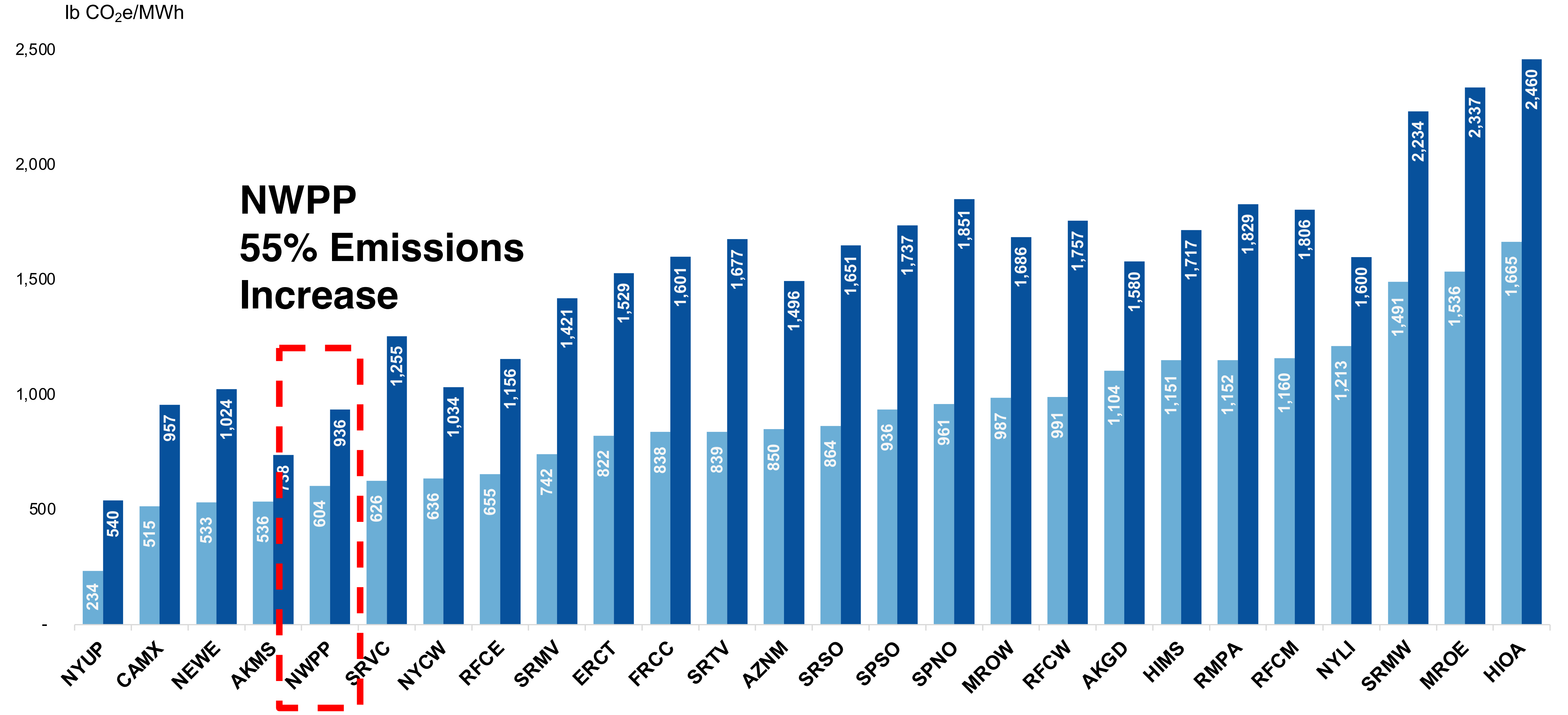
Conversely, an aggregation level that is too small (for example, EGC) may exclude generation that is relevant to the area.

Ideally, information about all of the interchanges of electricity between all of the utilities and all of the generators of electricity would be useful along with the generation data in creating output emission rates that account for the wholesale transactions between utilities and EGCs.

However, in the absence of public availability of such information, the ***eGRID subregion level data is generally considered the best generation based aggregation level that minimizes the import/export issues.*** *As discussed above, the eGRID subregion level does not eliminate the issue of imports of electricity from other areas to satisfy demand within the eGRID subregion. However, most or all of the system power in each eGRID subregion originates from within an eGRID subregion."*

https://www3.epa.gov/ttnchie1/conference/ei20/session3/adiem.pdf

Emission Factors
Upstream and Transmission Corrections



Emission Factors
Average vs Marginal

NREL
Transforming ENERGY

Photo by Dennis Schroeder, NREL 23201

Greenhouse Gas Emissions Accounting in Buildings

Building operations in the United States account for about 70% of electricity use, about 40% of the total U.S. primary energy consumption,[1] and about 30% of greenhouse gas (GHG) emissions.[2] Carbon dioxide (CO_2) emissions from building energy use and embodied emissions accounted for about 37% of global CO_2 emissions in 2020.[3] Thus, accurate GHG emissions accounting is critical to inform decisions for emissions reduction. This fact sheet provides an introduction to GHG emissions accounting for operation of buildings including equipment replacements and operational material purchases. It does not include embodied GHG emissions in existing buildings or from major retrofit construction activities.

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Figure 1. Example operational activities that impact emissions, representing an 87% reduction in GHG emissions. Data are for demonstration purposes only for a supermarket. Equipment purchases can refer to furniture purchases such as desks, chairs, and partitions for commercial building use.

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2 US EPA 2021. Sources of Greenhouse Gas Emissions. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions. Washington DC.
3 UNEP, IEA 2021. Global ABC 2021 Global status report.
4 Integral Group 2020. *"Refrigerants + Environmental Impacts: A Best Practice Guide"* https://www.integralgroup.com/news/refrigerants-environmental-impacts/. See Appendix A.4 for more data on leakage rates for HVAC systems.

Average emission factors *represent total emissions averaged over a set period, while* ***marginal emission factors*** *represent the emissions associated with the last generation source(s) used to meet an increase in demand.*

Average emission factors *are more accurate for carbon footprints while* ***marginal emission factors*** *may be appropriate for estimating carbon reductions from implementing energy efficiency measures.*

https://www.nrel.gov/docs/fy22osti/81671.pdf

Emission Factors
Average vs Marginal

Uncertainty in electricity emissions rates.
Emissions rates for electric utilities vary from year to year, depending on factors such as hydropower production. But perhaps more importantly, accounting for electricity emissions is the subject of considerable methodological debate.

On the one hand, SCL sources most of its electricity from low-carbon sources (hydropower dams and nuclear power plants), whereas Puget Sound Energy gets much of its energy from coal and natural gas plants—suggesting that electricity consumption in SCL's service territory produces much lower emissions than in PSE's.

Yet on the other hand, overall emissions across the generation portfolio of the entire Northwest Power Pool may be only minimally affected by the choice of putting new housing in SCL's service territory. (After all, building new housing in SCL's service territory doesn't cause the region's dams, nuclear plants, or wind farms to produce more electricity.)

The two very different methods of emissions accounting (averages for each utility vs. marginal emissions for the entire Northwest Power Pool) yield vastly different estimates for potential emissions reductions from housing location choices within King County. For this analysis, we develop high-end and low-end estimates of the potential emissions reductions due to different generation mixes with Seattle—but we recognize that emissions from electricity will remain uncertain and subject to debate.

Siteline (2011). Transfer of Development Rights. https://www.sightline.org/research_item/transfer-of-development-rights/.

Emission Factors
Average vs Marginal

THE EMISSIONS HIDDEN IN THE MARGINS

The difference between average and marginal emissions factors can be very large, and quite important. An average factor refers to the amount of emissions generated over a given time, divided by the amount of energy produced in that time. For example, the U.S. Pacific Northwest gets most of its electricity from hydropower, a low-emissions energy resource, and thus its average emissions factor is very low.

A marginal emissions factor refers to rate at which emissions would change with a small change to electricity load. Continuing the simplified Pacific Northwest example, imagine a time when hydropower is providing 75 percent of the region's power and gas-fired power plants are providing the remaining 25 percent. This means that the average emissions factor of power in the Pacific Northwest would be very clean, at 25 percent the emissions intensity of natural gas (approximately 210 lbs. CO2 per megawatt-hour (MWh)). So at first glance, a great way to reduce a company's or a person's carbon footprint would be to move to the Pacific Northwest, where the electricity is very clean.

Yet in many cases, natural gas is the marginal resource, meaning that if a new kilowatt-hour of electricity is needed at a certain time, it will be provided by natural gas. So a company or an individual moving to the Pacific Northwest would increase carbon emissions at a rate equal to 100 percent of natural gas (840 lbs. CO2 per MWh)—a very big difference! Thinking in marginal rather than average carbon emissions can dramatically affect a company's or a person's choice of optimal environmental impact.

https://rmi.org/combating-climate-change-measuring-carbon-emissions-correctly/#:~:text=A%20marginal%20emissions%20factor%20refers,providing%20the%20remaining%2025%20percent.

Emission Factors
Average vs Marginal

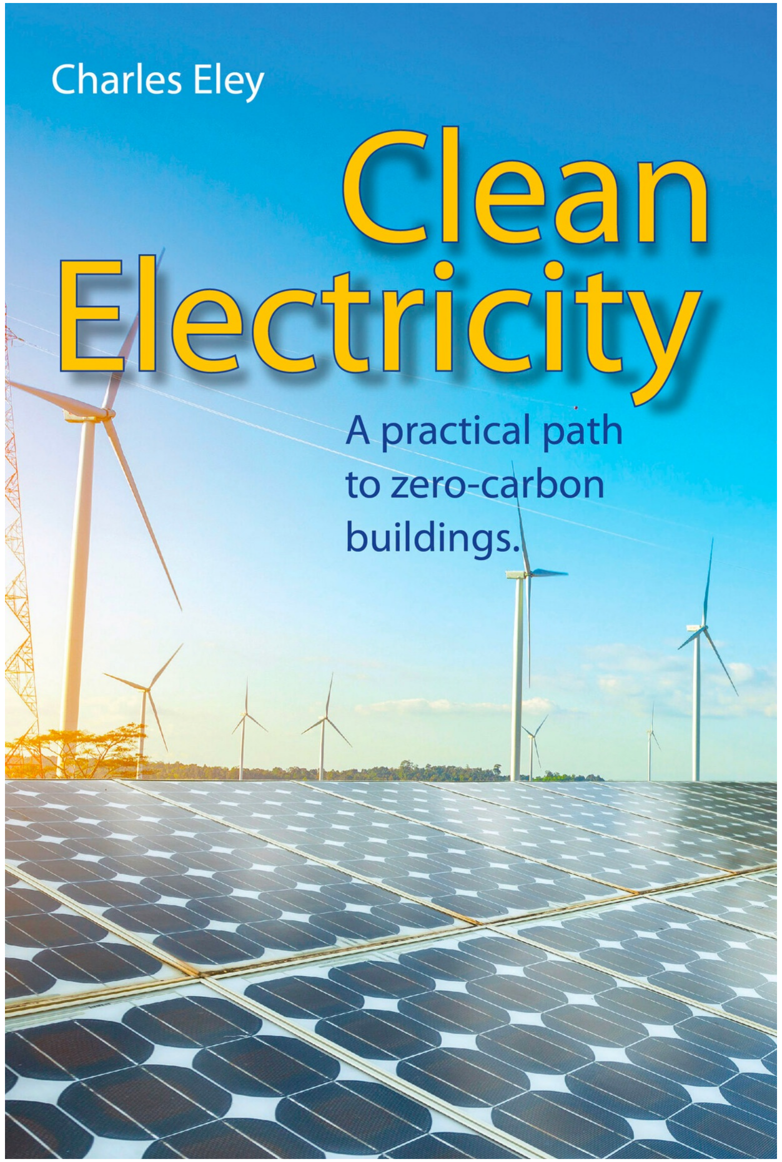
If hydropower is on the margin and an energy efficiency measure reduces demand, hydropower may be scaled back. If this is accomplished by diverting water to the spillway, then the efficiency measure achieves no emissions benefits.

However, this scenario is unlikely because diverting water to the spillway is essentially throwing away free electricity. It is more likely that an energy efficiency measure would shift the use of hydro, rather than displacing it.

Under normal circumstances, if hydropower scales back in response to an energy efficiency measure, the reservoir will fill with a little extra water, which will be used to generate power at some future time, thus displacing some other generator (e.g. a gas turbine). In other words, an energy efficiency measure in hour A may shift the use of hydropower and displace the marginal unit in hour B.

Siler-Evans, K. (2012). Evaluating Interventions in the U.S. Electricity System: Assessments of Energy Efficiency, Renewable Energy, and Small-Scale Cogeneration [PhD Thesis]. Carnegie Mellon University, Pennsylvania.

Emission Factors
Average vs Marginal

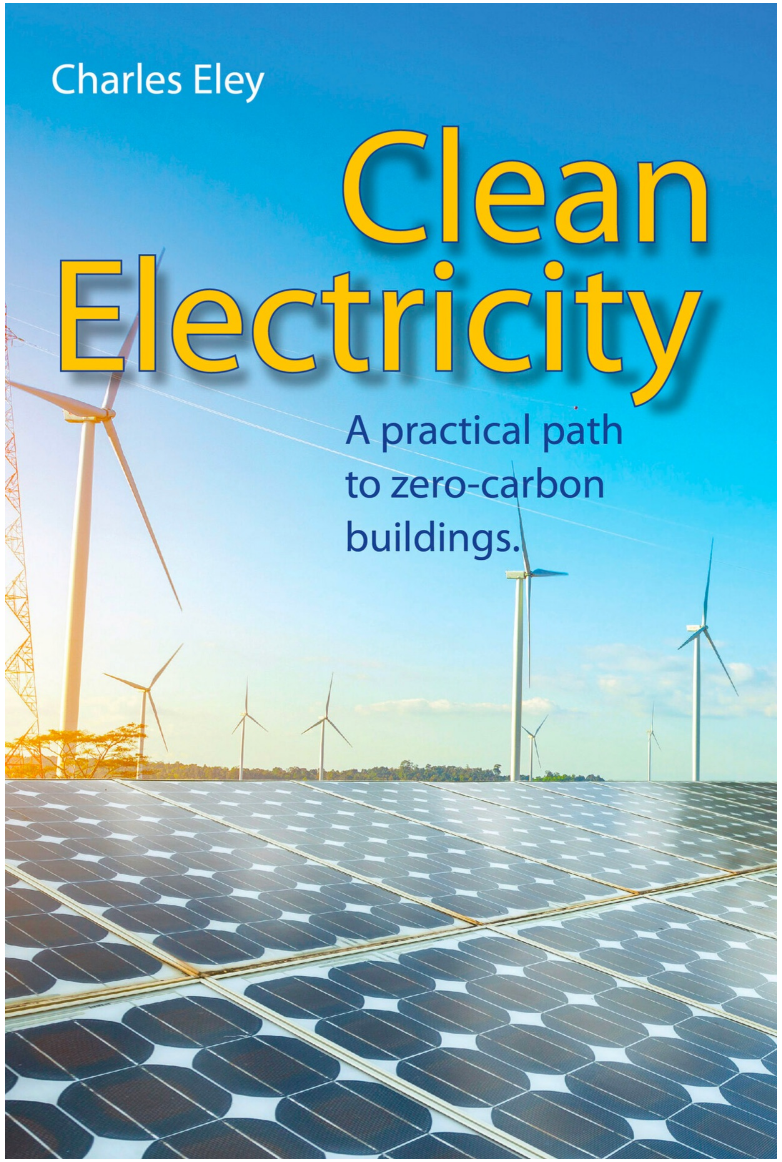


My friends in the Pacific Northwest may be feeling good, since, on average, 70 percent of electricity there is generated by clean hydropower and average carbon emissions are very low, but their elation is partly unwarranted.

If a new building is constructed, that adds load to the grid, or if they buy a new appliance, that increases electricity consumption, it is more likely that the additional (or marginal) electric load will be met by a coal plant in Idaho or Montana, as opposed to additional hydropower from the Grand Coulee Dam. Grand Coulee is already producing all it can, and extra (or marginal) demand must be met with generators elsewhere.

This illustrates the principal difference between average emissions and marginal emissions; when we add or subtract load from the grid, it's the marginal emissions that count.

Emission Factors
Average vs Marginal



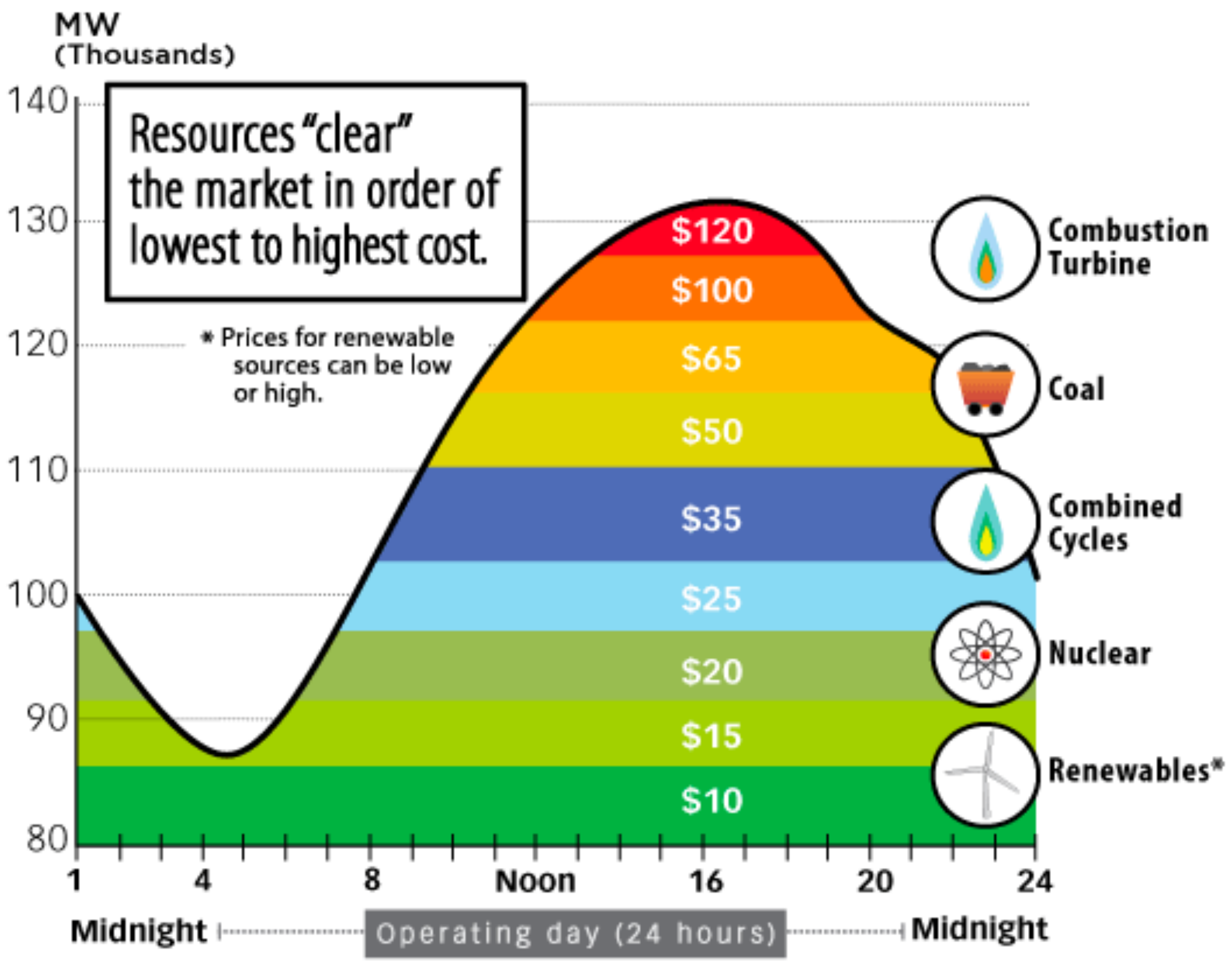
Marginal emissions, on the other hand, represent the change in emissions that occurs when the demand for electricity is increased by a relatively small increment, say, one megawatt. Recall that the balancing authority matches supply with demand by dispatching power plants in sequence, starting with the ones having the lowest marginal cost and dispatching those having the highest marginal cost last. If an inefficient and dirty peaking power plant is on the margin, it is the one that would be shut down first if there were a reduction in electric demand, and it would be the one that would be brought on line or ramped up if demand increased. The emissions of this dirty, peaking power plant represent the marginal emissions. It's those emissions that would be avoided if we reduced consumption, and it is those emissions that would be increased if we added load. ***While there are extensive hydro generating facilities in the Pacific Northwest, these plants would likely be running at capacity when electric demand is high. The marginal power plants would likely be fossil fuel plants, perhaps located in an adjacent state.***

Emission Factors
Long Run Emissions Rates

The AER's strength is its simplicity: It is derived by dividing the total emissions by the total electricity generation and adjusting for losses (Azevedo et al., 2020; eGrid, 2021). However, when used to estimate the consequences of an intervention it has a well-understood flaw in that changes to a system act on its margin, not its average. The generation mixture induced by new load often looks very different than the current average generation mixture.

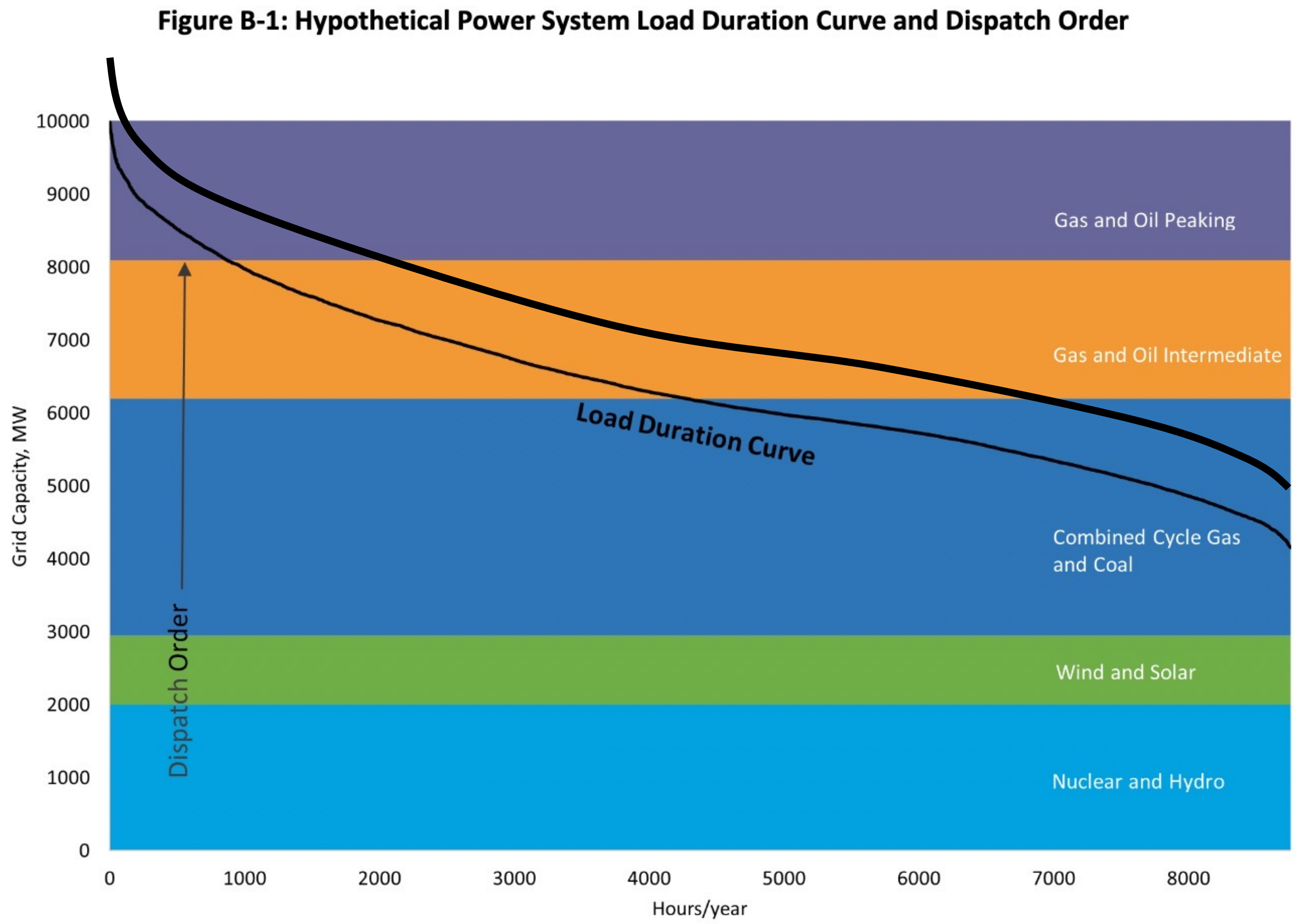
Gagnon P, Cole W. Planning for the evolution of the electric grid with a long-run marginal emission rate. iScience. 2022 Feb 11;25(3):103915. doi: 10.1016/j.isci.2022.103915. PMID: 35243264; PMCID: PMC8873608.

Emission Factors
Average vs Marginal



https://learn.pjm.com/three-priorities/keeping-the-lights-on/how-pjm-schedules-generation-to-meet-demand

Emission Factors
Average vs Marginal



https://www.epa.gov/avert/avoided-emission-rates-generated-avert

Operational Carbon Context CO_2e/kWh

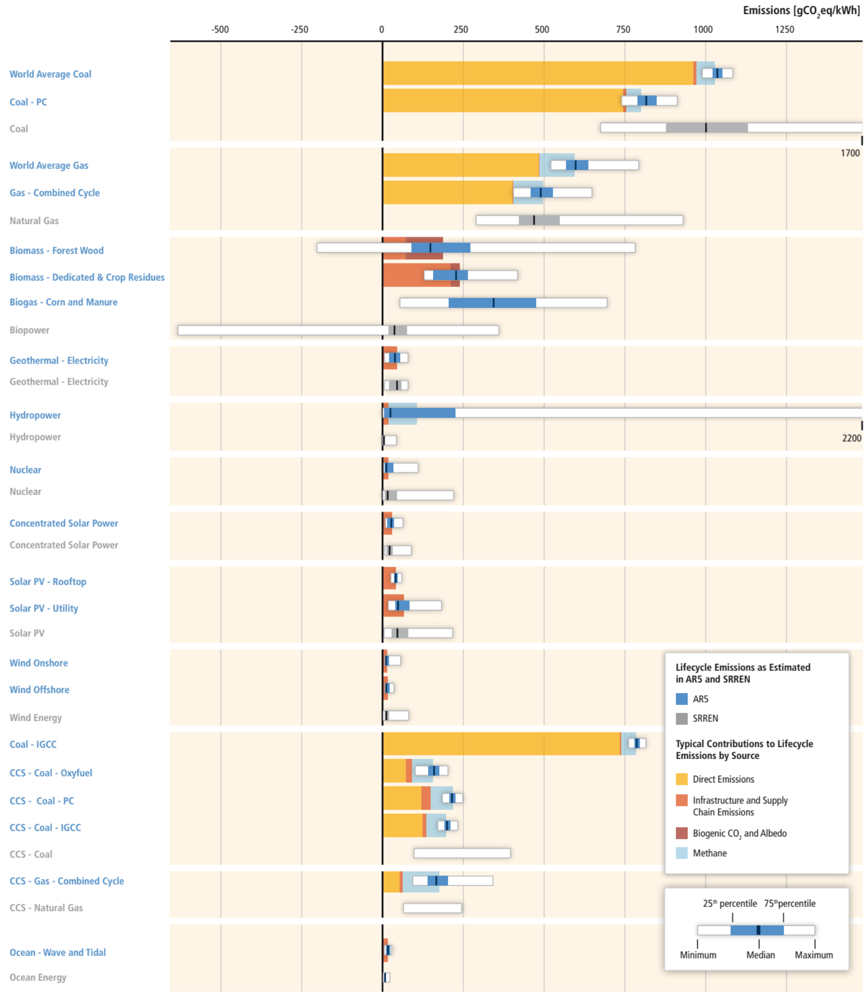
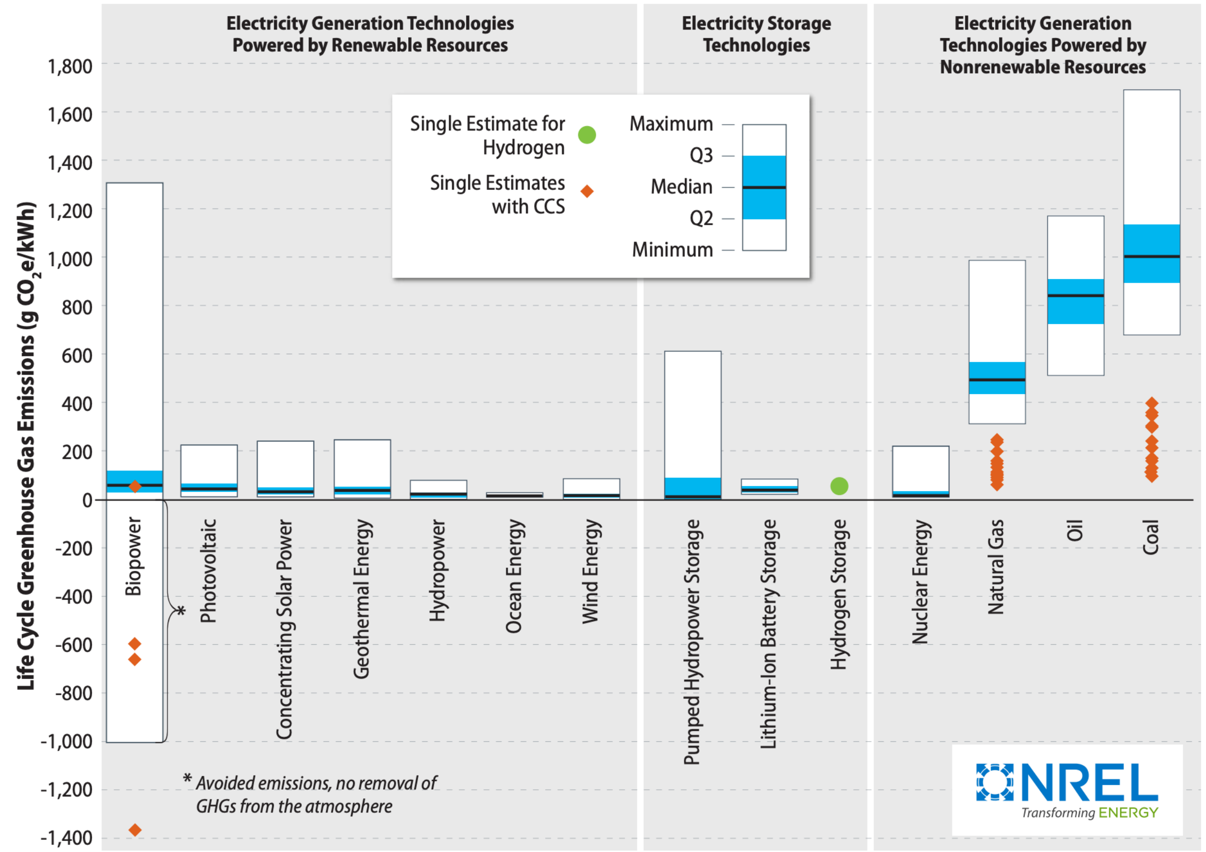


Figure 7.6 | Comparative lifecycle greenhouse gas emissions from electricity supplied by commercially available technologies (fossil fuels, renewable, and nuclear power) and projected emissions of future commercial plants of currently pre-commercial technologies (advanced fossil systems with CCS and ocean energy). The figure shows distributions of lifecycle emissions (harmonization of literature values for WGIII AR5 and the full range of published values for SRREN for comparison) and typical contributions to lifecycle emissions by source (cf. the notes below). Note that percentiles were displayed for RE and traditional coal and gas in the SRREN, but not for coal CCS and gas CCS. In the latter cases, the entire range is therefore shown. For fossil technologies, fugitive emissions of methane from the fuel chain are the largest indirect contribution and hence shown separately. For hydropower, the variation in biogenic methane emissions from project to project are the main cause of the large range. See also Annex II and Annex III.

Figure 2. Life cycle greenhouse gas emission estimates for selected electricity generation and storage technologies, and some technologies integrated with carbon capture and storage (CCS).



	Biopower	Photovoltaic	Concentrating Solar Power	Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Pumped Hydropower Storage	Lithium-Ion Battery Storage	Hydrogen Storage	Nuclear Energy	Natural Gas	Oil	Coal
Estimates	276 (+4)	46	36	35	149	10	186	16	29	1	99	80 (+13)	24	164 (+11)
References	57 (+2)	17	10	15	22	5	69	4	3	1	27	47 (+11)	10	53 (+9)

https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter7.pdf
https://www.nrel.gov/analysis/life-cycle-assessment.html

Emission Factors
So Many Flavors

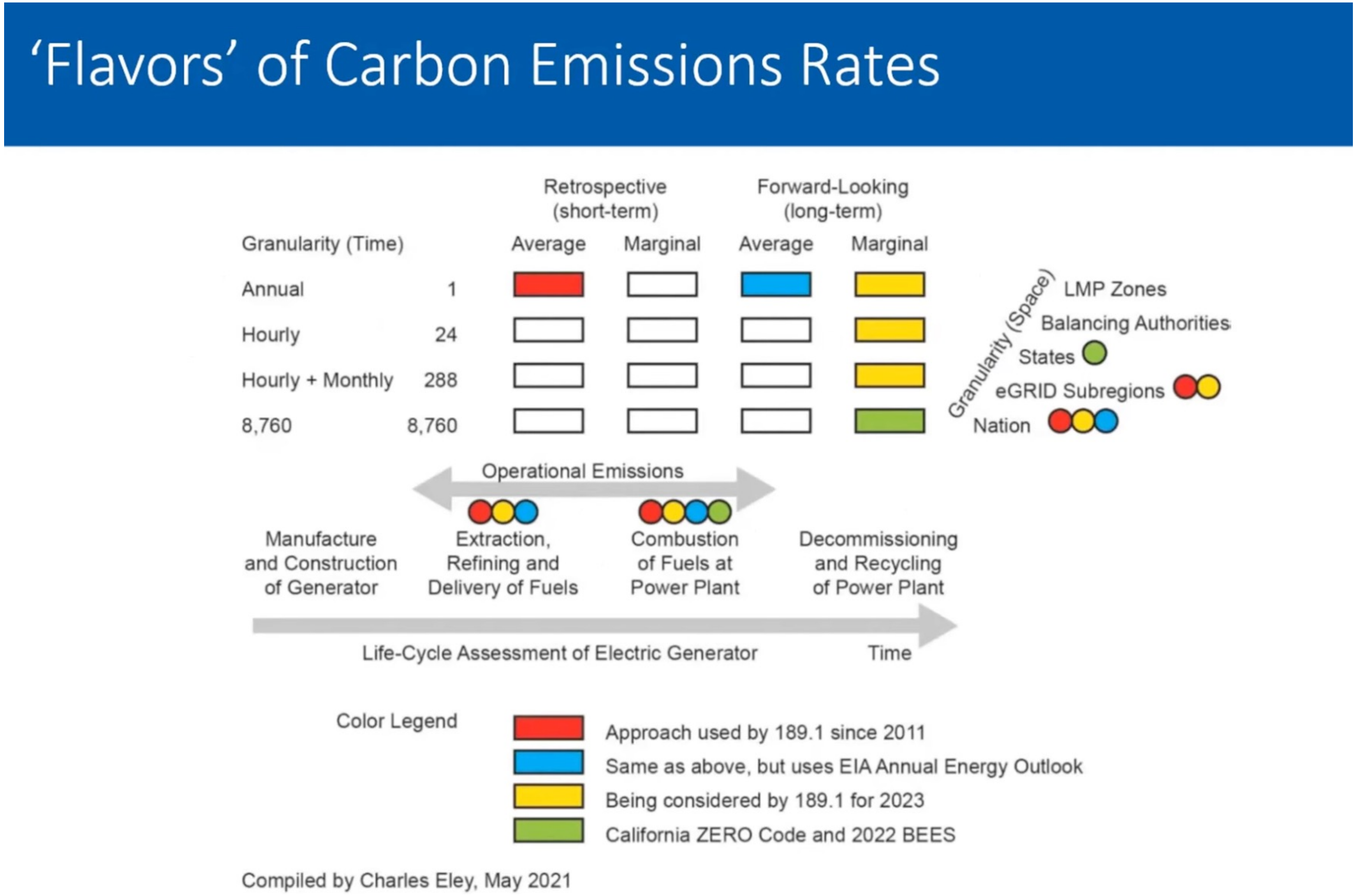
CarbonBrief
CLEAR ON CLIMATE

"Some plants, like nuclear, hydro, wind and solar are generally fully utilized and will not change their generation output if you buy an EV. What changes, at least in the short run, is primarily that coal and natural gas plants will increase generation in response to this new load. So, if your question is 'what will be the emissions consequences if I buy an EV versus a gasoline vehicle,' which I think is the right question for policy, then the answer should use the consequential grid mix (for small changes this is the marginal generation mix) rather than the average. The marginal grid mix typically has higher emissions intensity than the average."

However, the marginal emissions are something of a short-term estimate of EV impacts. As the demand from more EVs is added to the grid, gas and coal resources that are currently not being utilised may increase their output, but over the longer term additional generation sources will come online."

https://www.carbonbrief.org/factcheck-how-electric-vehicles-help-to-tackle-climate-change

Emission Factors
So Many Flavors



https://www.youtube.com/watch?v=VWLesd4THHU

Emission Factors
Long Run Emissions Rates

https://www.youtube.com/watch?v=VWLesd4THHU

Emission Factors
Long Run Emissions Rates

This analysis estimates the long-run marginal CO2e emission rate for electricity Washington. The longrun marginal emission rate is an estimate of the rate of emissions that would be either induced or avoided by a long-term (i.e., more than several years) change in electrical demand (Hawkes 2014).

The long-run marginal rate explicitly takes into account both the underlying evolution of the electric grid, as well as the potential for an incremental change in electrical demand to influence the structural evolution of the grid (i.e., the building and retiring of capital assets, such as generators and transmission lines). It is therefore distinct from the more-commonly-known short-run marginal, which also identifies the marginal generator but treats the grid assets as fixed (Azevedo et al. 2020).

The long-run marginal emission rate has been projected as typically lower then the short-run marginal emission rate, for the contiguous United States (Gagnon et al. 2020). This is because, when the potential for structural change is neglected (i.e., the short-run), the marginal generators are predominately natural gas and coal generators, ***whereas when structural changes are included (i.e., the long-run) the mixture often includes a greater contribution from wind and solar generators, resulting in a lower emission rate.***

https://www.youtube.com/watch?v=VWLesd4THHU

Emission Factors
Long Run Emissions Rates

"Crucially, this method captures the total effect of the change in load across the Western Interconnection – i.e., it captures the potential for policy leakage related to the Clean Energy Transformation Act (CETA).

As an example, if Washington is induced to consume more hydropower, and as a result exports less hydropower to neighboring states, it is possible that the neighboring states (not being subject to CETA) may choose to increase the utilization of their coal and natural gas generators, to make up for the reduction in hydropower. In this manner, an increase in load in Washington can result in an increase in emissions, even if the electricity being purchased by the utilities serving Washington is entirely clean. Almost all of the emitting generation sources shown in the results of this analysis are a result of this type of policy leakage.

This method produces a long-run marginal CO2e emission rate for electricity consumed in the state of Washington. The estimate is made for an electric load introduced in 2024 and evaluated over a 20-year horizon.

The CO2e rate reported in this analysis only includes emissions from direct combustion. It does not include upstream emissions from the fuel cycle, or the emissions associated with commissioning and decommissioning capital assets."

https://www.youtube.com/watch?v=VWLesd4THHU

Emission Factors
Long Run Emissions Rates

Why does long-run versus short-run matter?

Two reasons:

1) Long-run is less carbon-intensive than short-run

Short-run: mostly natural gas and coal

Long-run: Mostly wind, solar, natural gas, and some coal

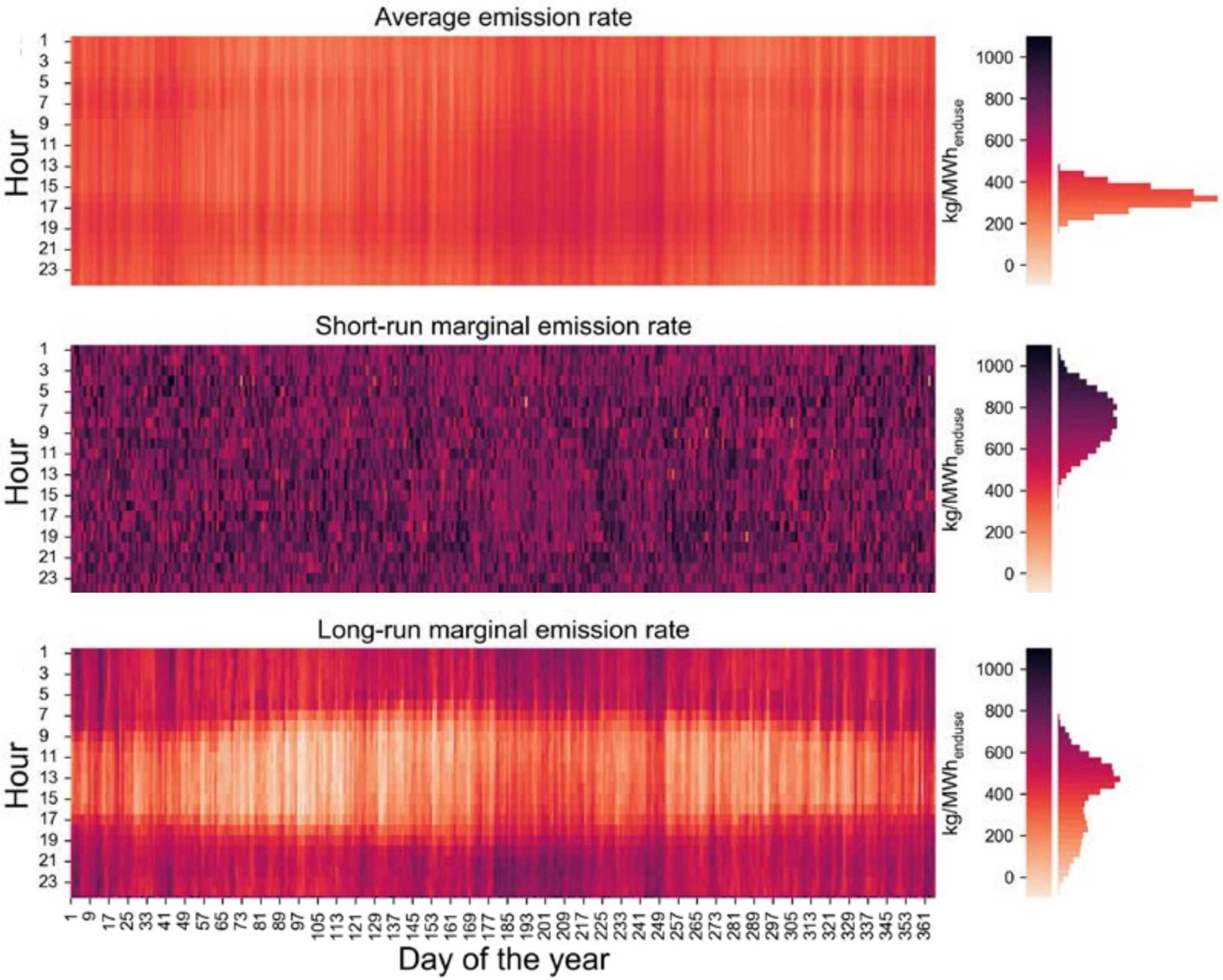
2) Seasonal and diurnal patterns are more clear in the long-run

E.g., adding load during daylight hours is easier to serve with solar energy

NREL |

https://www.youtube.com/watch?v=IXVE5MgWXIs

Emission Factors
Forward or Long Run Emissions Factors

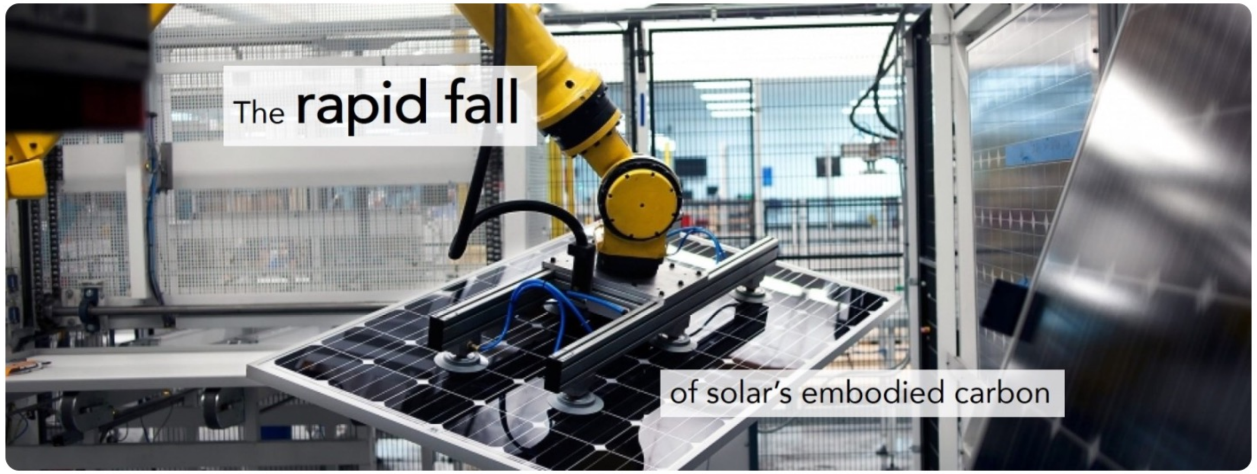


Planning for the evolution of the electric grid with a long-run marginal emission rate (2022) Pieter Gagnon
https://www.nrel.gov/docs/fy22osti/82503.pdf

Embodied Carbon
Solar PV

The rapid fall of solar's embodied carbon

Published on July 15, 2021



Chris Worboys
Energy & Passivhaus Consultant

+ Follow

Worboys, C. (2022, May 26). The rapid fall of solar's Embodied Carbon. LinkedIn. Retrieved June 13, 2022, from https://www.linkedin.com/pulse/rapid-fall-solars-embodied-carbon-chris-worboys/

Embodied Carbon
Solar PV

Author's calculations indicate that the embodied carbon of solar in 2020 was around **615 kgCO2/kWp**

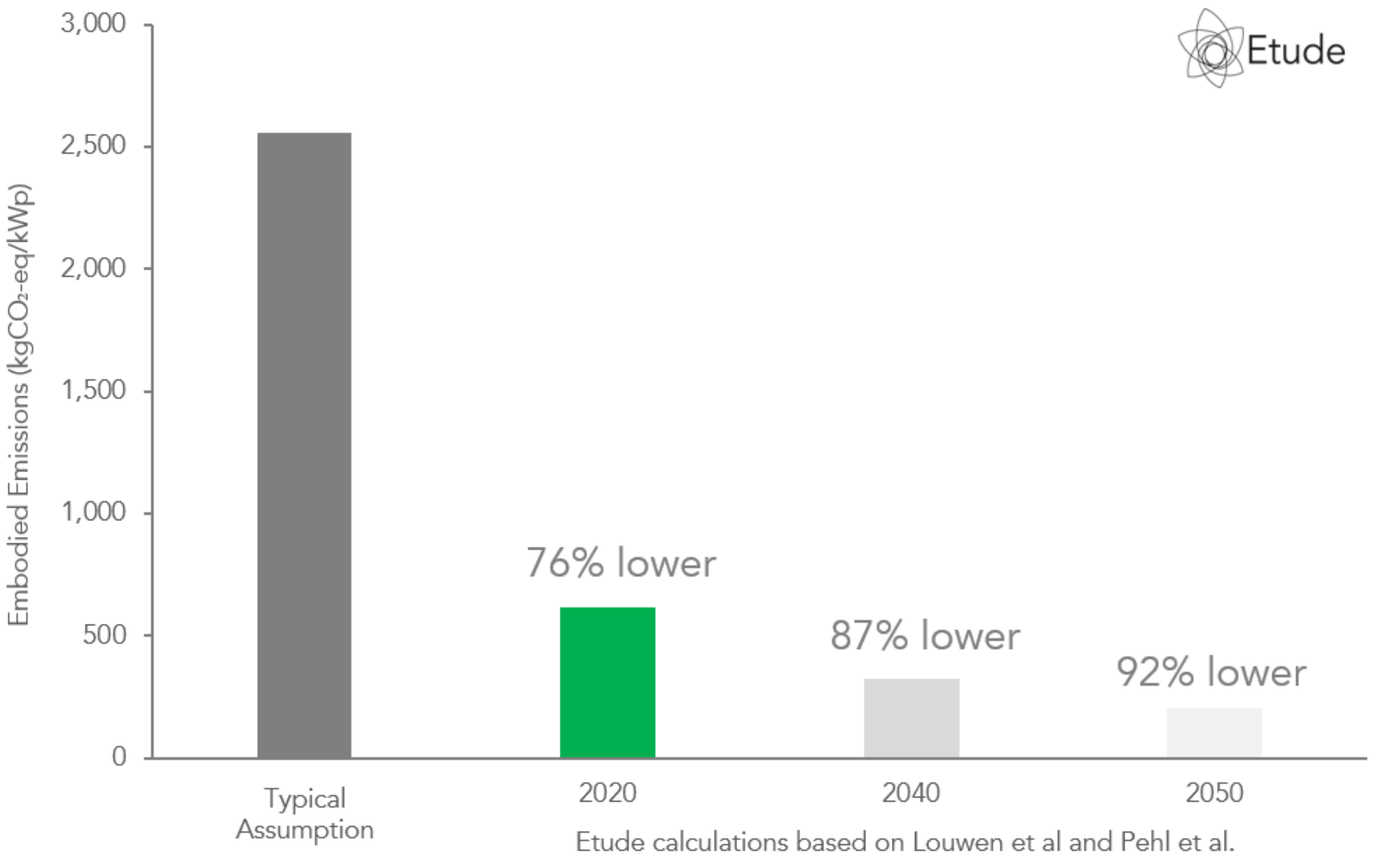
This is **76% lower** than the **2,560 kgCO2/kWp** that is commonly referenced.

First Solar's Global Sustainability Director also recently reported a typical value **of 500-600 kgCO2/kWp** for monocrystalline silicon.

Looking forward to 2040, Louwen et al project a drop to **325 kgCO2/kWp** and by 2050 Pehl et al project just **205 kgCO2/kWp**

Worboys, C. (2022, May 26). The rapid fall of solar's Embodied Carbon. LinkedIn. Retrieved June 13, 2022, from https://www.linkedin.com/pulse/rapid-fall-solars-embodied-carbon-chris-worboys/

Embodied Carbon
Solar PV



Worboys, C. (2022, May 26). The rapid fall of solar's Embodied Carbon. LinkedIn. Retrieved June 13, 2022, from https://www.linkedin.com/pulse/rapid-fall-solars-embodied-carbon-chris-worboys/

Embodied Carbon
Solar PV

What about the carbon payback?

Calculating a 'carbon payback' time by comparing solar's embodied carbon against operational emissions from the UK's electricity grid can suggest that long periods are required before solar achieves a carbon break-even point. There appear to be several issues with this approach that indicate it may not be a sensible way of establishing the environmental performance of solar:

1. **Technical accuracy:** It is not equitable to compare embodied emissions of solar to operational emissions for the electricity grid. This approach ignores the embodied emissions associated with fossil fuel extraction and construction of power plants, (including other sources of renewable energy). A full lifecycle emissions comparison would be fairer.

2. **Catch 22:** The carbon payback time of any renewable generator trends toward infinity as the grid decarbonises. This means if we base our decisions on carbon payback, we will never install enough renewable energy to decarbonise the electricity grid. Also note that the carbon intensity of grid electricity falls below zero in all of the National Grid's net zero compliant scenarios.

3. **Decarbonising other sectors:** Once the grid has fully decarbonised, we still need new renewable energy generation to decarbonise heating and transport, and to meet any increase in demand for electricity. If we base our decisions on carbon payback time, calculated within the power sector alone, deployment of this essential new renewable generation will never take place.

4. **Outdated figures:** Existing analyses appear to compare embodied (solar) and operational (grid) carbon emissions from two different points in time. This is producing misleading results. As the embodied carbon of solar has changed significantly over the past decade, it is important that up-to-date figures are used (though for the reasons outlined above, we might want to think about better ways to evaluate the performance of solar).

Worboys, C. (2022, May 26). The rapid fall of solar's Embodied Carbon. LinkedIn. Retrieved June 13, 2022, from https://www.linkedin.com/pulse/rapid-fall-solars-embodied-carbon-chris-worboys/

Embodied Carbon
Solar PV

Moving beyond carbon payback

If we accept that carbon payback is no longer a sensible measure of solar's environmental performance, then what next? For a start, we could acknowledge the Climate Change Committee's advice that a six fold increase in solar capacity is required; this is already reflected in the National Grid's Future Energy Scenarios.

The role of solar in achieving net zero should then become clear to architects, engineers, consultants, local authorities, and others. Hopefully this would translate into an increased sense of urgency, and the importance of good solar design would follow. This doesn't mean we should forget about embodied carbon, but focus could shift toward how to minimise it. Here are a few ideas to get started:

- Specify solar panels produced by Jinko, Longi, First Solar or Hanwha Q-Cells, who have all committed to 100% renewable electricity to supply their facilities.

- Specify high efficiency panels to reduce the amount of mounting structure required per unit of energy produced. Manufacturers are already phasing out less efficient polycrystalline technology and are increasingly competing on efficiency as a way to deliver array level cost reductions. Typical power ratings for a 1.75m x 1.05m panel are now 380W, with over 420W available, and even higher powers anticipated.

- Specify panels with a 30 year power output warranty to increase system lifetime, and select a linear power output warranty to increase lifetime system energy generation. Both reduce embodied carbon per unit of energy generated.

- Specify microinverters or DC Optimisers to increase lifetime energy yield per panel. Some microinverters have 25 year warranties, so can be expected to last two to three times as long as a central inverter on a standard warranty.

- Specify an extended warranty if using central inverters. Standard 5-12 year warranties can typically be increased to 10, 15, 20 or even 25 years for a modest additional cost.

Worboys, C. (2022, May 26). The rapid fall of solar's Embodied Carbon. LinkedIn. Retrieved June 13, 2022, from https://www.linkedin.com/pulse/rapid-fall-solars-embodied-carbon-chris-worboys/

Embodied Carbon
Solar PV

Moving beyond carbon payback

- Building mounted solar is often a great way to reduce embodied carbon. In many cases, existing structure can support panels with less material than would be required for a ground mount system. Facade and roof materials can be substituted for solar panels. Roof designs can be optimised to create unshaded monopitch solar arrays, increasing energy generation, which reduces embodied carbon per unit of energy produced.

- Timber can be used in mounting systems to reduce embodied carbon, as demonstrated at one of the UK's largest solar farms:

Worboys, C. (2022, May 26). The rapid fall of solar's Embodied Carbon. LinkedIn. Retrieved June 13, 2022, from https://www.linkedin.com/pulse/rapid-fall-solars-embodied-carbon-chris-worboys/

Embodied Carbon
Solar PV

Whole life carbon of photovoltaic installations
TECHNICAL REPORT - FEBRUARY 2022

ELEMENTA
WILLMOTT DIXON
SINCE 1852

Hamot, L., Drewinak, D., & Burgess, T. (2022, February 1). Whole life carbon of photovoltaic installations .
Retrieved June 13, 2022, from https://willmottdixon.co.uk/asset/17094

Embodied Carbon
Solar PV

Embodied carbon results by scenarios

The following graph shows the embodied carbon impact of a whole PV installation across 25 years (assumed to be a PV service life) for different scenarios.

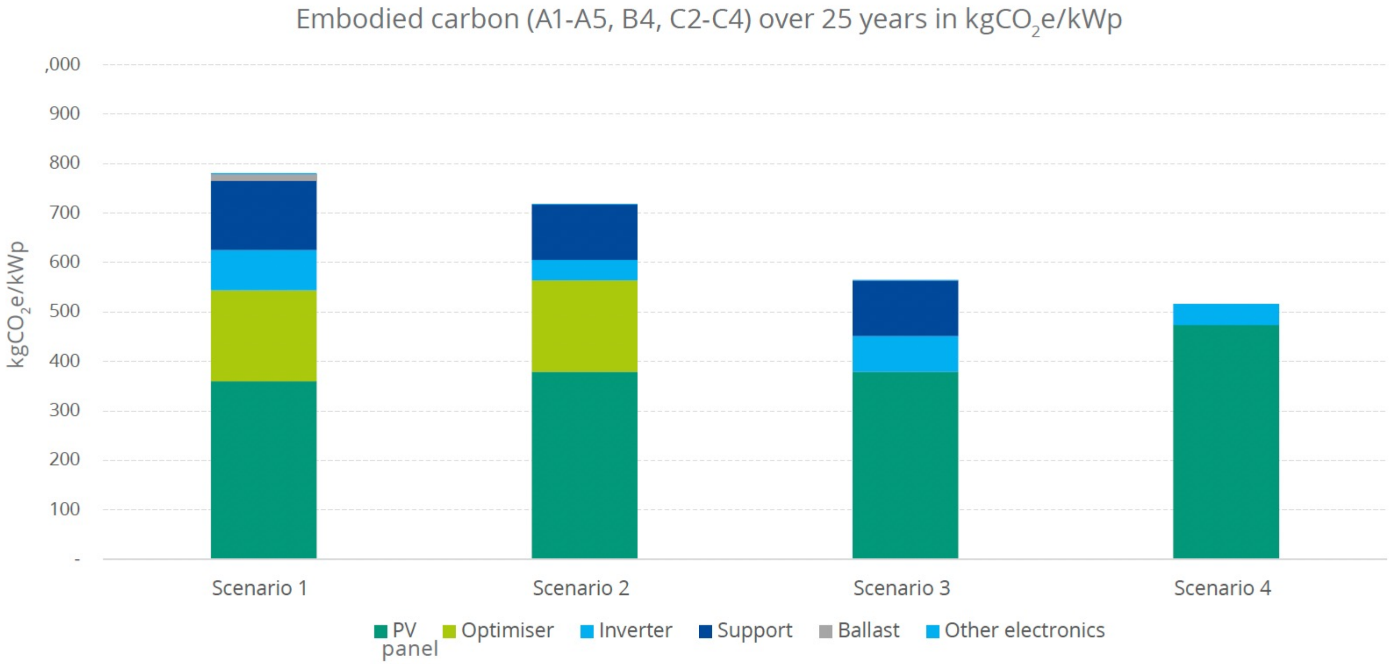


Figure 4 - Embodied carbon over 25 Years

Scenario 1: Project A, Flat roof, PV monocrystalline, Optimisers

Scenario 2: Project B, Pitched roof, PV monocrystalline, Optimisers

Scenario 3: Project B, Pitched roof, PV monocrystalline, No optimisers

Scenario 4: Project B, Pitched roof, PV thin-film, No optimisers

Hamot, L., Drewinak, D., & Burgess, T. (2022, February 1). Whole life carbon of photovoltaic installations .
Retrieved June 13, 2022, from https://willmottdixon.co.uk/asset/17094

Embodied Carbon
Solar PV

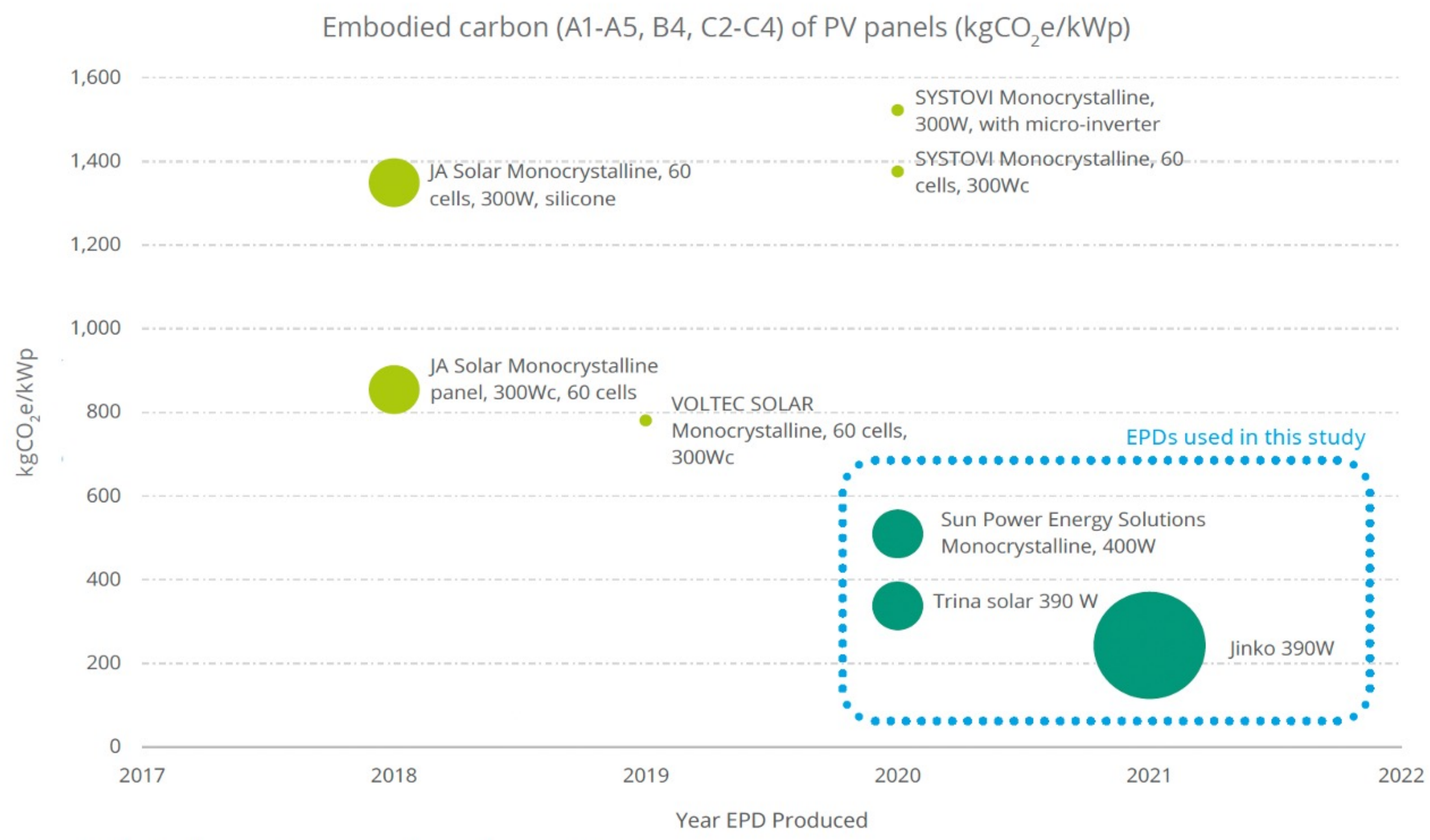


Figure 5: Embodied carbon of monocrystalline module over time. The size of the dot represent the market share, and the green dot represent the products used in the study.

Hamot, L., Drewinak, D., & Burgess, T. (2022, February 1). Whole life carbon of photovoltaic installations .
Retrieved June 13, 2022, from https://willmottdixon.co.uk/asset/17094

Embodied Carbon
Solar PV

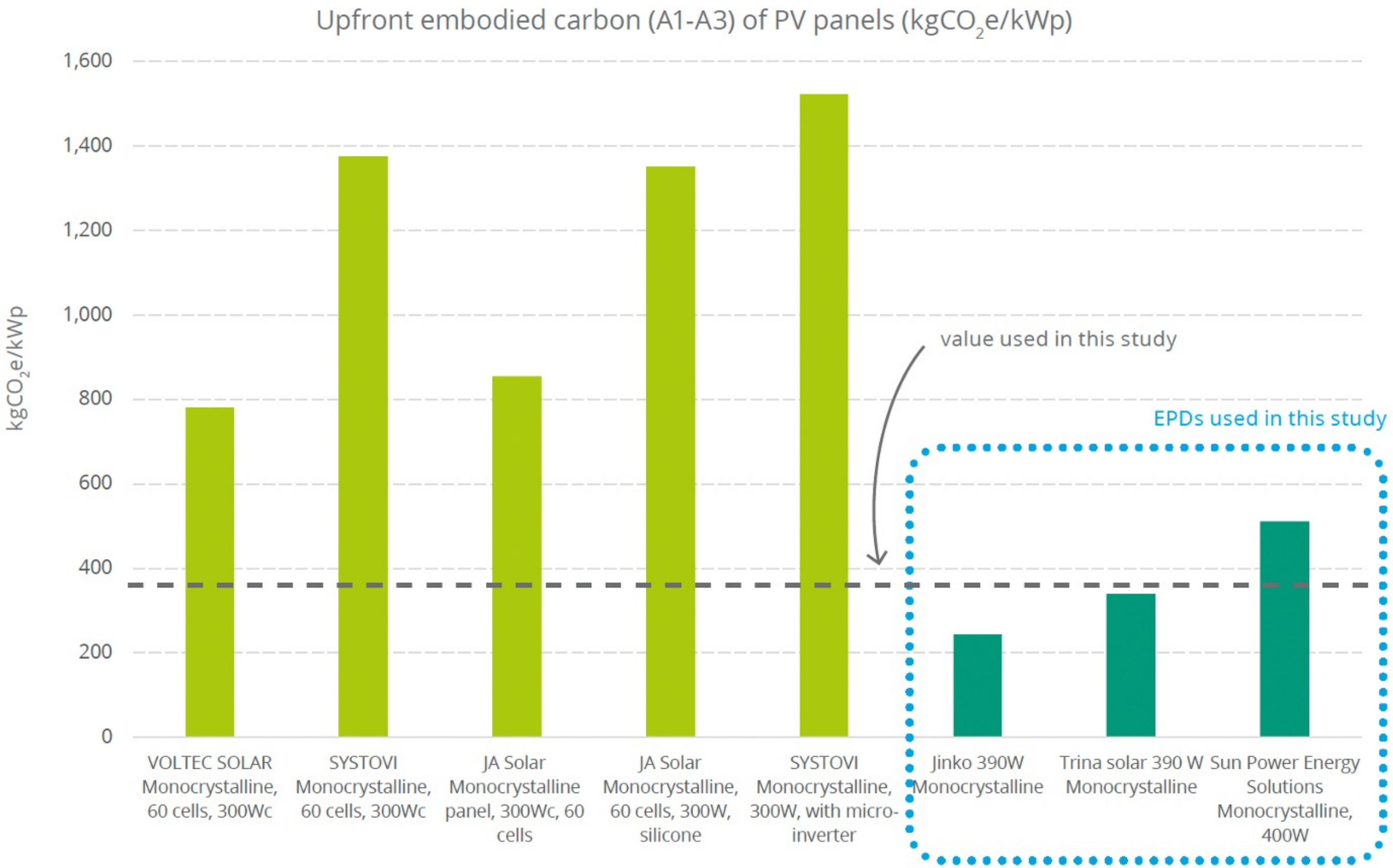


Figure 6 – Embodied carbon impact associated with lifecycle stages A1-A3 from various EPDs

Hamot, L., Drewinak, D., & Burgess, T. (2022, February 1). Whole life carbon of photovoltaic installations . Retrieved June 13, 2022, from https://willmottdixon.co.uk/asset/17094

Embodied Carbon
Solar PV

PV as an offset mechanism - 'why it is not about payback'

We are used to thinking about the payback of measures that reduce carbon emissions – for example a financial payback (a result of energy savings) when installing additional insulation.

Recently, the industry has started looking at both the embodied carbon impact and operational carbon savings to evaluate the net effect of carbon reduction measures. This can inform decision making based on whether the embodied carbon outlay is worth the operational carbon reductions. It is tempting to take this same approach when considering whether to install PVs or not, However, doing so might have unintended consequences and could ignore other important global factors. For example, when carrying out these calculations, the future decarbonisation of the grid is taken into account based on the assumption that significantly more renewable generation will be added to the grid in coming years. In order to meet our climate targets, we need to shift progressively to 100% renewables, so new installations of PV and other renewable energy systems are required to decarbonise the grid further

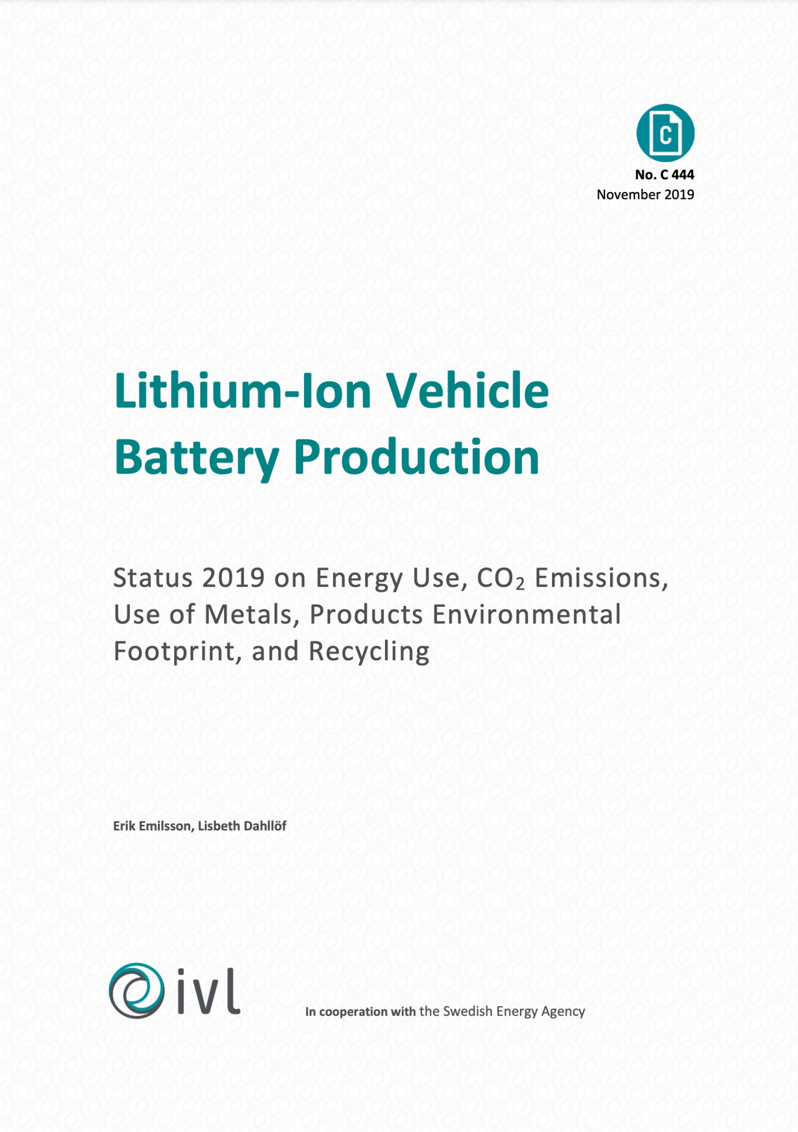
This means we need to 'invest' embodied carbon into installing renewable energy infrastructure. Without that initial 'embodied carbon' investment the grid will not decarbonise further. As the grid decarbonises, local supply chains also benefit from accessing renewable energy, reducing the upfront embodied carbon content of their products.

Intuitively we can understand that PV installations are required to decarbonise our electricity grids and to move away from fossil fuels such as coal and gas. The UK grid needs to substantially increase capacity to deal with the likely increased demand of the energy in the future (e.g. heat pumps and electric cars) and rooftop solar PV represents a significant opportunity to support this renewable energy generation push.

Even though our results suggest that PV as a pure carbon offset mechanism will be less useful going forward (as operational offsets diminish in line with decarbonisation), the additional renewable capacity to help balance supply and demand will be far more important in its contribution to the energy transition.

Hamot, L., Drewinak, D., & Burgess, T. (2022, February 1). Whole life carbon of photovoltaic installations .
Retrieved June 13, 2022, from https://willmottdixon.co.uk/asset/17094

Embodied Carbon
Battery Storage



No. C 444
November 2019

Lithium-Ion Vehicle Battery Production

Status 2019 on Energy Use, CO_2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling

Erik Emilsson, Lisbeth Dahllöf

ivl

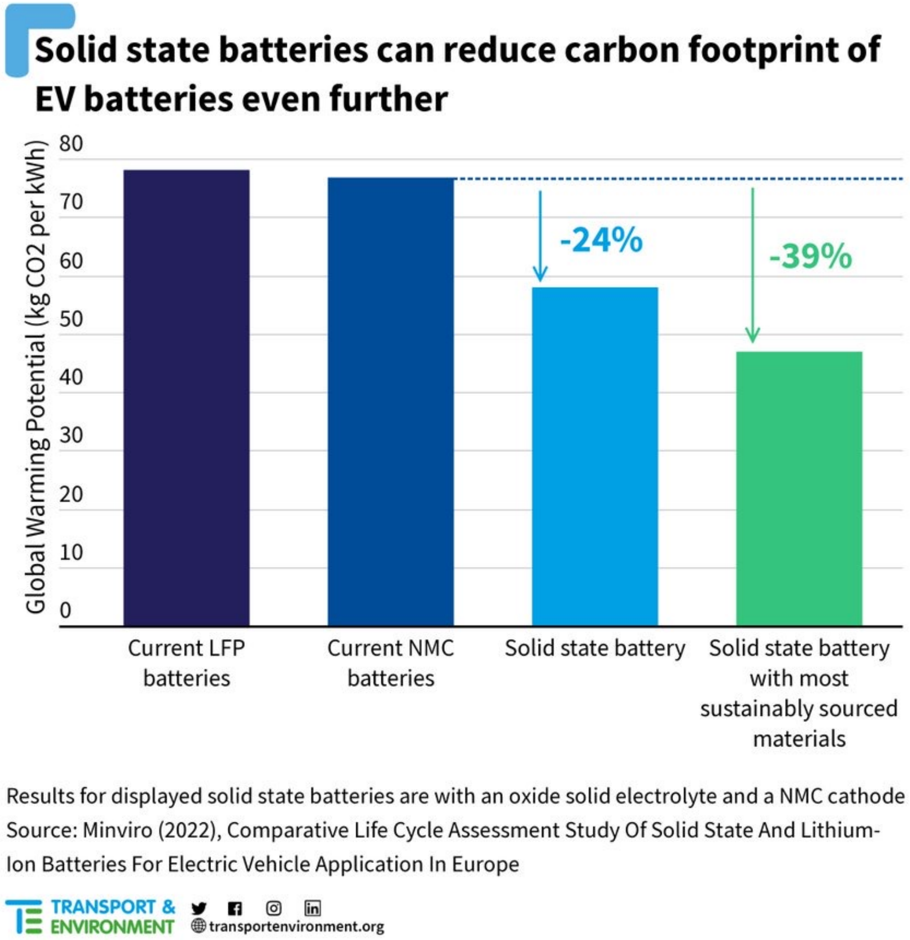
In cooperation with the Swedish Energy Agency

https://www.ivl.se/download/18.34244ba71728fcb3f3faf9/1591706083170/C444.pdf

According to new calculations, the production of lithium-ion batteries on average emits somewhere between 61-106 kilos of carbon dioxide equivalents per kilowatt-hour battery capacity produced. If less transparent data is included, the upper value will be higher; 146 kilos carbon dioxide equivalents per kilowatt hour produced. The large emissions range primarily depends on production methods and the type of electricity used in the battery manufacturing process. Current figures for climate emissions are lower than they were in the 2017 report where the average was 150-200 kilos of carbon dioxide equivalents per kWh of battery capacity.

"That emissions are lower now is mainly due to the fact that battery factories have been scaled up and are running at full capacity, which makes them more efficient per unit produced. We have also taken into account the possibility of using electricity that is virtually fossil-free in several of the production stages," says Erik Emilsson

Embodied Carbon
Battery Storage



https://transportenvironment.org/discover/solid-state-batteries-can-further-boost-climate-benefits-of-evs-study/

Embodied Carbon
Heat Pumps

CIBSE JOURNAL

Embodied energy: the whole picture

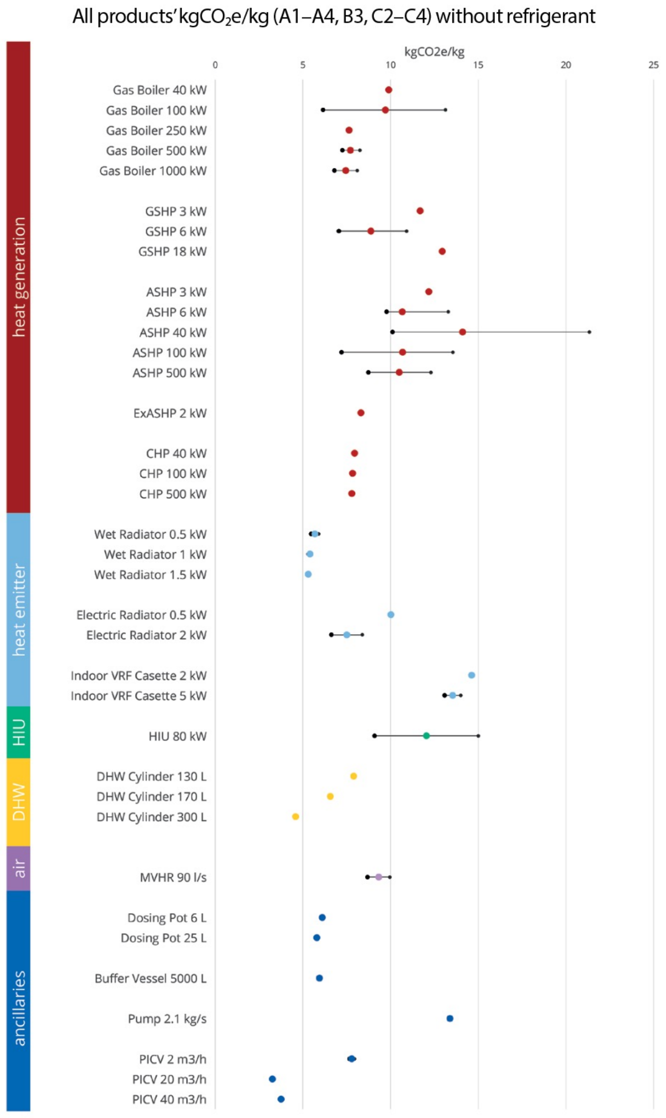
New CIBSE research shows that embodied energy in heating and hot-water systems accounts for up to 25% of a dwelling's whole-life embodied carbon. Elementa Consulting's Yara Machnouk reports on the study that will form the basis of CIBSE guidance TM65.1

Posted in October 2021

UK heat and hot-water systems examined contain an average of 9kgCO2e per kg of product weight

Machnouk, Y. (2021, October 1). Embodied energy: The whole picture. CIBSE Journal. Retrieved June 13, 2022, from https://www.cibsejournal.com/technical/embodied-energy-the-whole-picture/

Embodied Carbon
Heat Pumps



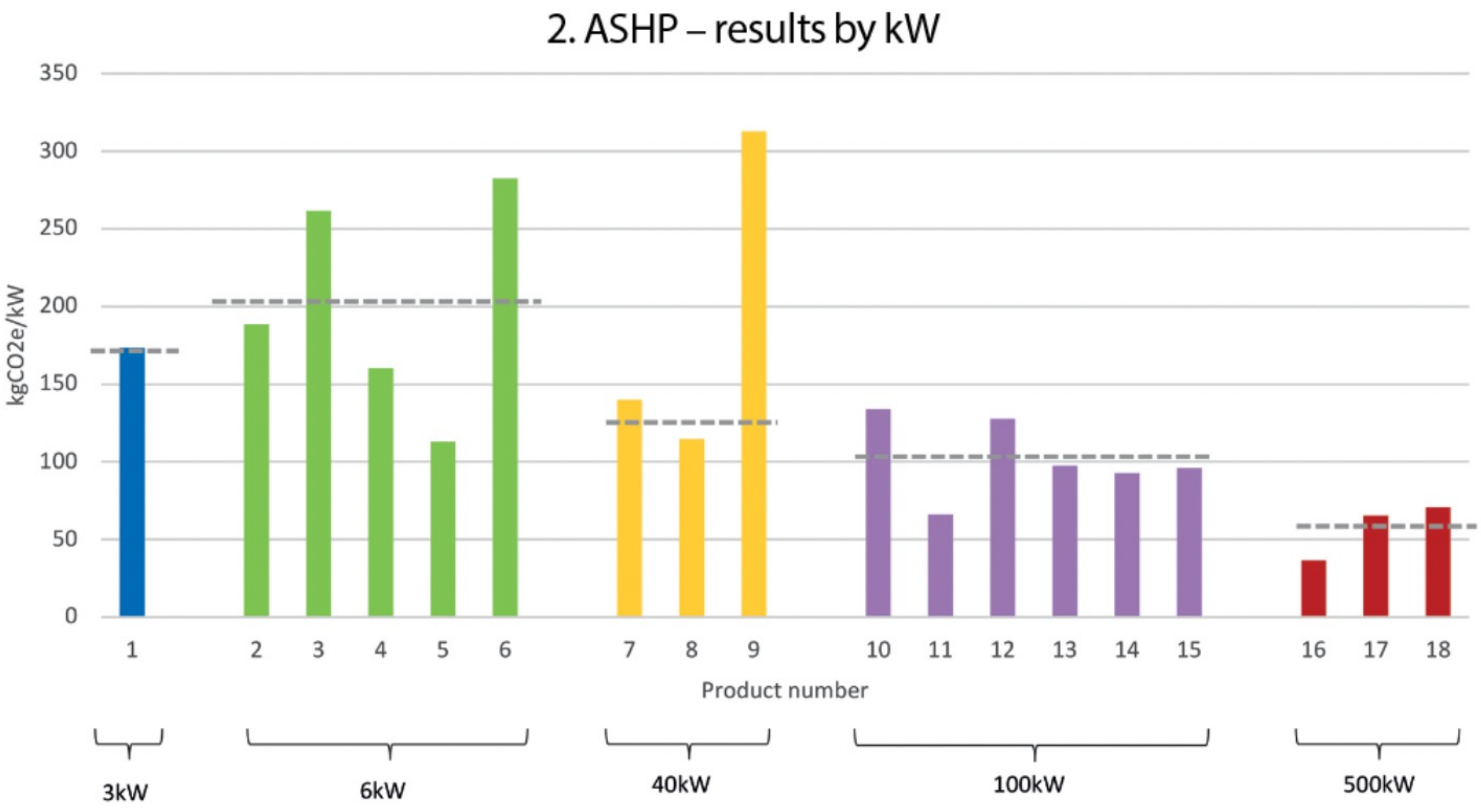
Machnouk, Y. (2021, October 1). Embodied energy: The whole picture. CIBSE Journal. Retrieved June 13, 2022, from https://www.cibsejournal.com/technical/embodied-energy-the-whole-picture/

Embodied Carbon
Heat Pumps

The range of embodied carbon impact (at product level) by weight of products investigated is estimated between **3kgCO2e/kg** and **21kgCO2e/kg**, and the average is **9kgCO2e/kg** (excluding refrigerant).

Machnouk, Y. (2021, October 1). Embodied energy: The whole picture. CIBSE Journal. Retrieved June 13, 2022, from https://www.cibsejournal.com/technical/embodied-energy-the-whole-picture/

Embodied Carbon
Heat Pumps



The dotted line indicates the average generic embodied carbon value.
Figure 2: Embodied carbon emissions for different sizes of ASHPs

Machnouk, Y. (2021, October 1). Embodied energy: The whole picture. CIBSE Journal. Retrieved June 13, 2022, from https://www.cibsejournal.com/technical/embodied-energy-the-whole-picture/

Embodied Carbon
E3 Calculator & MEP 2040

Refrigerant Impact Calculator
Powered by BHoM
MEP 2040
ABOUT

Input

EQUIPMENT LIFE EXPECTANCY	Dataset
REFRIGERANT	Dataset
REFRIGERANT CHARGE (KG)	100 Kg
LEAKAGE RATE	Dataset

Sources

Leakage rate datasets

Dataset	Installation	Annual	End of life recovery	Remaining at end of life	Additional notes
ASHRAE 228P Refrigerant Leakage Rates		✓			
BREEAM Refrigerant Leakage Rates		✓			
CIBSE TM65 2021 Refrigerant Leakage Scenarios		✓	✓		
EPA Refrigerant Leakage Rates	✓	✓	✓	✓	
GHG Protocol Leakage Rates	✓	✓	✓		High and Low Values provided for Installation, Annual and End of Life Recovery

Life Expectancy datasets

Dataset	Life expectancy	Additional notes
GHG Protocol Leakage Rates	✓	Median Value Extracted from Table
LEED Default Equipment Life	✓	

https://www.refrigerantimpact.org/

Embodied Carbon
E3 Refrigerant Avoided Cost Calculator

Energy+Environmental Economics

3. Refrigerant leakage for device *i*

This use case was developed primarily to calculate the increases in GHG impact due to refrigerant leakage when new heat pump devices are installed. This calculation can also determine changes in GHG impact when high GWP refrigerants are replaced with lower GWP refrigerants, or when a new device replaces an older one with a different refrigerant charge, leakage rate, or refrigerant.

The cost of refrigerant leakage will be determined by multiplying the refrigerant leakage by the natural gas GHG value. This allows us to estimate either increased or decreased GHG costs for any situation where refrigerant charge (M_i), leakage $\left(q_{ann,i}\, t_i + q_{EOL,i}\,(1 - q_{ann,i} t_{EOL,i})\right)$, or refrigerant GWP ($GWP_i$) has changed. Note that the natural gas GHG value is used instead of the electric model GHG adder because this use case applies primarily to building electrification measures.

The term $(q_{ann,i}\, t_i + q_{EOL,i}\,(1 - q_{ann,i} t_{EOL}))$ represents the fraction of refrigerant charge that is leaked into the atmosphere over the device's life. It includes both the operational leakage that occurs through normal use, and the end-of-life leakage that occurs at disposal. The operational leakage is equal to the annual leakage rate (q_{ann}) multiplied by the device's expected useful lifetime (t). The end-of-life leakage depends on both the end-of-life leakage rate for each device (q_{EOL}, which depends on the typical disposal practice for device type *i*) and on the extent to which refrigerant that is lost during the device's lifetime is replaced (i.e., "topped off").

For example, disposal practices for residential heat pump devices often do not follow regulations requiring refrigerant recycling, and instead the refrigerant is generally vented (i.e., completely leaked) before disposal. If this occurs in 85% of the units disposed, then, $q_{EOL,i}$ = 85% for these types of devices. If the device is never topped off (as is typical for some residential devices) then $t_{EOL} = t - 20$ years. If the annual leakage rate (q_{ann}) is 2%/year and the effective useful life (t) is 20 years, then the total leakage is

$$q_{ann,i}\, t_i + q_{EOL,i}\,(1 - q_{ann,i} t_{EOL,i})$$

= 2%/year * 20 years + 85% [1 – (2%/year * 20 years)]
= 40% + 85% (1 – 40%)
= 40% + 51%
= 91%

Value of refrigerant leakage =

$$-\ M_i * \left(q_{ann,i}\, t_i + q_{EOL,i}\,(1 - q_{ann,i} t_{EOL,i})\right) * GWP_i * P_{GHGg}$$

(tonnes) (dimensionless) $\left(\frac{tonnes\ CO2e}{tonne}\right)$ $\left(\frac{\$}{tonne\ CO2e}\right)$

The 2022 Refrigerant Calculator was updated such that refrigerant leakage is discounted at the mid-year rather than the end-of-year to be more consistent with continual leakage throughout a device's life. Note that in some cases, a measure may lead to an incurred cost due to refrigerant leakage rather than avoided cost. For instance, if a heat pump replaced a counterfactual natural gas appliance, the natural gas appliance

https://www.ethree.com/public_proceedings/energy-efficiency-calculator/

Embodied Carbon
Heat Pumps

OzonAction Kigali Fact Sheet 3

OzonAction

GWP, CO_2(e) and the Basket of HFCs

UN environment

Background: Progress towards the HFC phase-down targets under the Kigali Amendment will be measured in **tonnes CO_2 equivalent**. It is very important that policy makers and industry stakeholders understand how this parameter is calculated and the way that it enables a flexible approach to HFC phase-down to be adopted by each country. To calculate tonnes CO_2 equivalent it is necessary to know the **GWP**[1] (global warming potential) of each relevant gas.

What is GWP? Global warming potential (GWP) is a measure of the relative global warming effects of different gases. The GWP indicates the amount of heat trapped by 1 tonne of a gas relative to the amount of heat trapped by 1 tonne of CO_2 over a specific period. CO_2 was chosen by the Intergovernmental Panel on Climate Change (IPCC) as the reference gas and its GWP is defined as 1. Most HCFCs and HFCs have GWPs that are thousands of times higher than the GWP of CO_2. For example, HFC-134a has a GWP of 1 430. This means that the emission of 1 tonne of HFC-134a will create the same contribution to global warming as the emission of 1 430 tonnes of CO_2.

Why are there different GWP values for the same gas? Different publications do not always quote the same GWP values for a particular gas. There are two main reasons for this:

a) GWPs can be defined to measure impact over different timescales, e.g. 20 years, 100 years or 500 years. This results in different GWP values for each of these timescales.

b) There is some uncertainty about the best GWP value to assign to each gas. A key source of GWP data are the IPCC Assessment Reports. GWP values published by the IPCC have been updated several times over the last 20 years.

GWPs used under the Kigali Amendment: Under the Kigali Amendment a standard set of GWP values has been agreed for reporting consumption and production of HFCs. The GWPs of HCFCs and HFCs are listed in Annex C and Annex F of the Montreal Protocol and are based on the 100-year GWPs in the IPCC 4th Assessment Report.

Some HCFCs and HFCs are used as pure fluids e.g. HFC-134a in various RAC applications. However, many of the most commonly used HFCs are blends of two or more separate HFC molecules. The GWP of a blend is the weighted average of the GWPs of the blend components. See Box 1 for an example calculation of a blend GWP.

Box 1: Calculating the GWP of a Blend

A widely-used blend is R-404A. It consists of:

52% HFC-143a + 44% HFC-125 + 4% HFC-134a

GWPs: HFC-143a: 4470 HFC-125: 3500 HFC-134a: 1430

Blend GWP = 52% * 4470 + 44% * 3500 + 4% * 1430

= 3922

Group	Fluid	Montreal Protocol Standard GWP Value
HFCs	HFC-134a	1 430
	HFC-227ea	3 220
HFC blends	R-404A	3 922
	R-410A	2 088
HCFCs	HCFC-22	1 810
	HCFC-141b	725

The GWPs of HCFCs are of importance because they form part of a country's baseline consumption (see Kigali Fact Sheet 5 for details on baselines).

The table shows the GWP values that should be used for some of the most common HFCs and HCFCs. A table at the end of this Fact Sheet includes a comprehensive list of GWP values for all relevant molecules and blends.

[1] See Kigali Fact Sheet 14 for a glossary of all acronyms used

United Nations Environment Programme (2017). GWP, CO2(e) and the Basket of HFCs - OzonAction Kigali Fact Sheet 3. https://wedocs.unep.org/20.500.11822/26866.

What is GWP?

Global warming potential (GWP) is a measure of the relative global warming effects of different gases. The GWP indicates the amount of heat trapped by 1 ton of a gas relative to the amount of heat trapped by 1 ton of CO_2 over a specific period.

CO_2 was chosen by the Intergovernmental Panel on Climate Change (IPCC) as the reference gas and its GWP is defined as 1.

United Nations Environment Programme (2017). GWP, CO2(e) and the Basket of HFCs - OzonAction Kigali Fact Sheet 3. https://wedocs.unep.org/20.500.11822/26866.

GWP20 vs GWP100

Different publications do not always quote the same GWP values for a particular gas. There are two main reasons for this:

a) GWPs can be defined to measure impact over different timescales, e.g. 20 years, 100 years or 500 years. This results in different GWP values for each of these timescales.

b) There is some uncertainty about the best GWP value to assign to each gas. A key source of GWP data are the IPCC Assessment Reports. GWP values published by the IPCC have been updated several times over the last 20 years.

United Nations Environment Programme (2017). GWP, CO2(e) and the Basket of HFCs - OzonAction Kigali Fact Sheet 3. https://wedocs.unep.org/20.500.11822/26866.

Embodied Carbon
Heat Pumps

The large contribution of projected HFC emissions to future climate forcing

Guus J. M. Velders[a,1], David W. Fahey[b], John S. Daniel[b], Mack McFarland[c], and Stephen O. Andersen[d]

[a]Netherlands Environmental Assessment Agency, PO Box 303, 3720 AH Bilthoven, The Netherlands; [b]National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Boulder, CO 80305; [c]DuPont Fluoroproducts, Wilmington, DE 19805; and [d]U.S. Environmental Protection Agency, Code 6202J, 1200 Pennsylvania Avenue NW, Washington, DC 20460

Edited by Mark H. Thiemens, University of California at San Diego, La Jolla, CA, and approved May 14, 2009 (received for review March 13, 2009)

The consumption and emissions of hydrofluorocarbons (HFCs) are projected to increase substantially in the coming decades in response to regulation of ozone depleting gases under the Montreal Protocol. The projected increases result primarily from sustained growth in demand for refrigeration, air-conditioning (AC) and insulating foam products in developing countries assuming no new regulation of HFC consumption or emissions. New HFC scenarios are presented based on current hydrochlorofluorocarbon (HCFC) consumption in leading applications, patterns of replacements of HCFCs by HFCs in developed countries, and gross domestic product (GDP) growth. Global HFC emissions significantly exceed previous estimates after 2025 with developing country emissions as much as 800% greater than in developed countries in 2050. Global HFC emissions in 2050 are equivalent to 9–19% (CO_2-eq. basis) of projected global CO_2 emissions in business-as-usual scenarios and contribute a radiative forcing equivalent to that from 6–13 years of CO_2 emissions near 2050. This percentage increases to 28–45% compared with projected CO_2 emissions in a 450-ppm CO_2 stabilization scenario. In a hypothetical scenario based on a global cap followed by 4% annual reductions in consumption, HFC radiative forcing is shown to peak and begin to decline before 2050.

preferred refrigerant in consumer products requiring a large charge, where hydrocarbon flammability is problematic (6). The use of HFCs is expected to be minor in many other applications because other low-GWP compounds and not-in-kind (i.e., non-halocarbon based) technologies are available. Overall, not-in-kind technologies are not expected to initially satisfy as large a fraction of future demand as was the case during the CFC phaseout (7).

Multiple scenarios of global HFC emissions are available from SRES (8) and IPCC/TEAP (2). These scenarios are now of limited use because of limited range of years (IPCC/TEAP) or outdated assumptions concerning the transition from HCFCs to HFCs (SRES). The SRES GWP-weighted emissions for refrigeration and AC are ≈20% below what we infer here from observed atmospheric mixing ratios for 2007 (*SI Text*). The 2007 HFC emissions for these applications from IPCC/TEAP (2) are somewhat higher, but this scenario ends in 2015. Others (9–11) have reported HFC scenarios similar to the SRES assumptions and do not consider a more detailed market development as discussed here.

We report new baseline scenarios for the consumption and

Velders, G., Fahey, D., Daniel, J., McFarland, M., & Andersen, S. (2009). The large contribution of projected HFC emissions to future climate forcing. Proceedings Of The National Academy Of Sciences, 106(27), 10949-10954. https://doi.org/10.1073/pnas.0902817106

Embodied Carbon
Heat Pumps

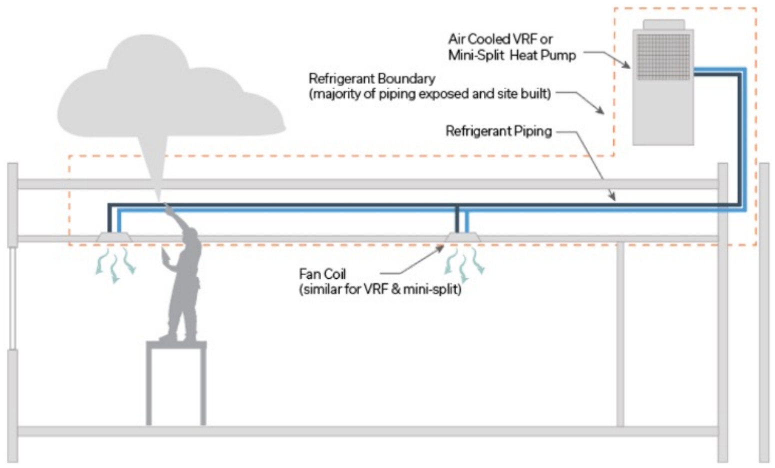
Table S2. Major applications, lifetimes, direct global warming potentials and radiative efficiencies of the major HCFCs and HFCs

Compound	Main applications	Lifetime, years	GWP, 20-year	GWP, 100-year	GWP, 500-year	Radiative efficiency ($W \cdot m^{-2} \cdot ppb^{-1}$)
HCFC-22	Refrigeration, AC	12	5,160	1,810	549	0.2
HCFC-141b	Insulating foams	9.3	2,250	725	220	0.14
HCFC-142b	Insulating foams	17.9	5,490	2,310	705	0.2
HFC-32	Refrigeration, AC	4.9	2,330	675	205	0.11
HFC-125	Refrigeration, AC	29	6,350	3,500	1,100	0.23
HFC-134a	Refrigeration, AC, Mobile AC, Insulating foams	14	3,830	1,430	435	0.16
HFC-143a	Refrigeration, AC	52	5,890	4,470	1,590	0.13
HFC-152a	Plastic foams, Aerosols	1.4	437	124	38	0.09
HFC-245fa	Insulating foams	7.6	3,380	1,030	314	0.28
HFC-365mfc	Insulating foams	8.6	2,520	794	241	0.21
R-404A*	Refrigeration, AC		6,010	3,922	1,328	
R-410A†	Refrigeration, AC		4,340	2,088	653	
Average values weighted by consumption in developing countries						
HCFCs		11.4	4,299	1,502	456	
HFCs		21.7‡	4,582‡	2,362‡	766‡	

Values taken from IPCC (26).
*R-404A is a blend of HFC-143a (52%), HFC-125 (44%), and HFC-134a (4%).
†R-410A is a blend of HFC-32 (50%) and HFC-125 (50%).
‡Values corresponding to the year 2040.

Velders, G., Fahey, D., Daniel, J., McFarland, M., & Andersen, S. (2009). The large contribution of projected HFC emissions to future climate forcing. Proceedings Of The National Academy Of Sciences, 106(27), 10949-10954. https://doi.org/10.1073/pnas.0902817106

Embodied Carbon
Heat Pumps



City of Seattle Refrigerant Emissions Analysis

GHG Emissions Calculation Methodologies

May 5, 2020

pae-engineers.com

REFRIGERANT METRIC: REFRIGERANT LBS / COOLING TON

The following emissions charts were sourced from previous PAE mechanical system designs based on the building and system type. The table below details an estimated refrigerant volume (lb) per ton of cooling. These metrics are organized by building type and mechanical system. Notice that distributed refrigerant systems such as VRF have high coefficients. High performance buildings should aim to have low refrigerant charges.

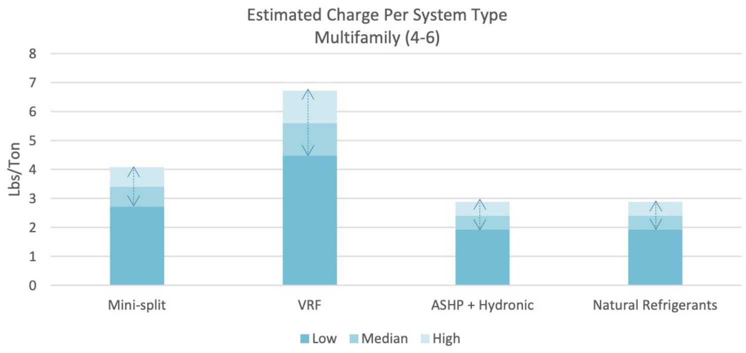


Figure 15: Refrigerant Pounds/Cooling Ton - Multifamily

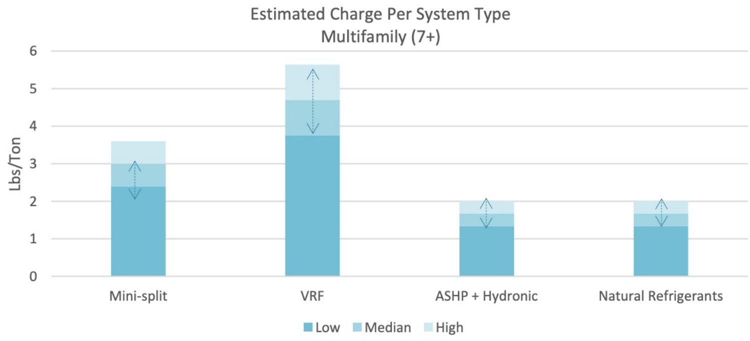
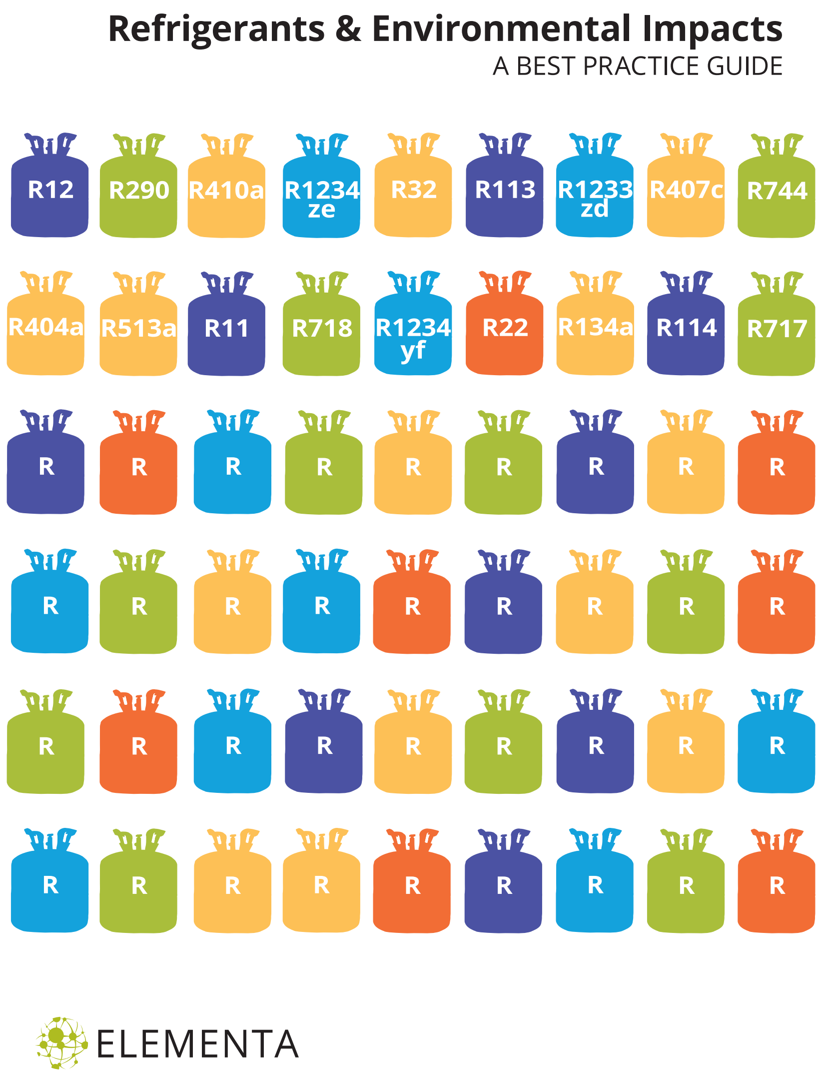


Figure 16: Refrigerant Pounds/Cooling Ton - Multifamily

https://www.seattle.gov/documents/Departments/OSE/Building%20Energy/SEA_Refrigerant_Analysis_May2020.pdf

Embodied Carbon
Heat Pumps



Hamot, L., Dugdale, H., & Boennec, O. (2020, September 1). Refrigerants & Environmental Impacts: A Best Practice Guide. Integral Group. https://www.integralgroup.com/news/refrigerants-environmental-impacts/

Embodied Carbon
Heat Pumps

Leakage Rates

Based on published data the following assumptions concerning annual refrigerant leakage could be assumed as follows:

Product	Annual leak rate – low	Annual leak rate – medium	Annual leak rate – high
Centralised and individual systems – where no refrigerant is initially charged on-site	1%	3.8%	6%
Distributed systems where a large amount of refrigerant pipework is installed and filled on-site	1%	6%	10%

Hamot, L., Dugdale, H., & Boennec, O. (2020, September 1). Refrigerants & Environmental Impacts: A Best Practice Guide. Integral Group.
https://www.integralgroup.com/news/refrigerants-environmental-impacts/

Embodied Carbon
Heat Pumps

Leakage Rates

The following table lists annual leakage rates reported from various studies:

Reference	Type of plant	Annual leak rate		date of paper
TM56 - Resource efficiency of building services	Air-cooled chiller	Lower	1%	2014
		Upper	5%	
	Water-cooled chiller	Lower	1%	
		Upper	5%	
	Rooftop	Lower	1%	
		Upper	5%	
	Split system	Lower	2%	
		Upper	8%	
	VRF system	Lower	1%	
		Upper	10%	
Methods of calculating Total Equivalent Warming Impact	Chillers	Lower	5%	2012
		Typical	7%	
		Upper	9%	
	Roof top packaged systems	Lower	4%	
		Typical	5%	
		Upper	9%	
	Split systems (single and multi)	Lower	3%	
		Typical	4%	
		Upper	9%	
BREEAM 2018	Unitary split	Typical	15%	2018
	Small scale chillers	Typical	10%	
	Heat pumps	Typical	6%	
Impacts of Leakage from Refrigerants in Heat Pumps	Heat pumps	Lower	n/a	2014
		Typical non-domestic	3.80%	
		Typical domestic	3.5%	
		Upper	n/a	

continued overleaf

APPENDICES | A4 REFRIGERANT LEAKAGE

Hamot, L., Dugdale, H., & Boennec, O. (2020, September 1). Refrigerants & Environmental Impacts: A Best Practice Guide. Integral Group.
https://www.integralgroup.com/news/refrigerants-environmental-impacts/

Embodied Carbon
Heat Pumps

Leakage Rates

Reference	Type of plant	Annual leak rate		date of paper
Cold Hard Facts 3	Small AC sealed-	Theoretical leak rate	2.5%	2016
	HW heat pump: domestic-	Service rate	2%	
	Small AC: Split:	Theoretical leak rate	3.5%	
	Single split: non-ducted	Service rate	2%	
	Medium AC	Theoretical leak rate	2.7%	
	Split system: ducted	Service rate	2%	
	VRV/VRF split system	Service rate	2%	
	Multi split	Service rate	2%	
	Large AC	Theoretical leak rate	4.5%	
	Large AC <350 kWr	Service rate	4%	
	Large AC >350 & <500 kWr	Service rate	4%	
March (1991) as cited in BNCR36: Direct Emission of Refrigerant Gases	Heat pumps	Lower	3%	1991
		Upper	10%	
Haydock et al (2003) as cited in BNCR36: Direct Emission of Refrigerant Gases	Heat pumps	Lower	3%	2003
		Upper	5%	
ETSU (1997) as cited in BNCR36: Direct Emission of Refrigerant Gases	Heat pumps	Typical	4%	2007
Evaluation of the leakage rates of 11,000 refrigeration systems in Hungary (34) cited by Schwarz	Stationary refrigeration and air conditioning equipment >3 kg.	Average	10%	2010
2013 Annual Conference of the Institute of Refrigeration LEC Leakage & Energy Control System by VDFK	74,000 refrigerant units in different applications	Average	3.16%	2013
International Institute of Refrigeration	Commercial chillers	Upper	15%	<2017
	Residential & light systems	Upper	10%	

Hamot, L., Dugdale, H., & Boennec, O. (2020, September 1). Refrigerants & Environmental Impacts: A Best Practice Guide. Integral Group. https://www.integralgroup.com/news/refrigerants-environmental-impacts/

Embodied Carbon
Heat Pumps

ATMOsphere x FGN FUTURE GREEN NOW

Impact of Refrigerants: Fact Sheet #1 (V.1.1.)

Real GWP: 20 years vs.100 years

Refrigerant	Type	Composition	GWP 100 years	"Real" GWP 20 years
R404A	HFC	44% R125 / 4% R134a / 52% R143a	4,200	6,600
R22	HCFC	100% R22	1,780	5,310
R407A	HFC	20% R32 / 40% R125 / 50% R134a	2,100	4,500
R410A	HFC	50% R125 / 50% R32	2,100	4,400
R407C	HFC	23% R32 / 25% R125 / 52% R134a	1,700	4,100
R134a	HFC	100% R134a	1,360	3,810
R448A (Solstice N40)	HFC/ HFO	26% R32 / 26% R125 / 21% R134a / 7% R1234ze / 20% R1234yf	1,400	3,100
R449A (Opteon XP40)	HFC/ HFO	24,3% R32 / 24,7% R125 / 25,7% R134a / 25,3% R1234yf	1,400	3,100
R449C (Opteon XP20)	HFC/ HFO	20% R32 / 20% R125 / 29% R134a / 31% R1234yf	1,200	2,900
R32	HFC	100% R32	704	2,530
R452B (Opteon XL55)	HFC/ HFO	67% R32 / 7% R125 / 26% R1234yf	710	2,100
R513A (Opteon XP10)	HFC/ HFO	44% R134a / 56% R1234yf	600	1,700
R454B	HFC/ HFO	68.9% R32 / 31.1% R1234yf	490	1,700
R450A (Solstice N13)	HFC/ HFO	42% R134a / 58% R1234ze	570	1,600
R744	Natural	CO_2	1	1
R600a	Natural	Isobutane	<1	<1
R290	Natural	Propane	<1	<1
R1270	Natural	Propylene	<1	<1
R717	Natural	NH_3	0	0
R718	Natural	H_2O	0	0
R729	Natural	Air	0	0

Table 1: The "real" impact of refrigerants on the environment over the next 20 years. Source: UNEP[1]

ATMOsphere/Future Green Now. (2021, August 5). Impact of refrigerants: Fact sheet #1 (v.1.1.) real GWP: 20 ... - r744.com. Impact of Refrigerants: Fact Sheet #1 (V.1.1.). Retrieved June 13, 2022, from https://r744.com/wp-content/uploads/sites/3/2021/06/ATMO_future_green_V.1.1_final.pdf

Embodied Carbon
Heat Pumps

Model Search: Search Products Submit

HOME | NOMENCLATURE | ACCESSORIES | CONTROLS | M-SERIES | P-SERIES | SMART MULTI |
S-SERIES | Y-SERIES (VRF HEAT PUMP) | R2-SERIES (VRF HEAT RECOVERY) | VENTILATION | JET TOWEL |
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Embodied Carbon
Heat Pumps

P-Series R410A Outdoor Units

H2i Hyper-heating Heat Pump

Slim and compact, INVERTER-driven compressor, quiet, Pulse Amplitude Modulation (PAM), Pulse Wave Modulations (PWM): Vector Wave Eco INVERTER, low ambient cooling operation down to 0 deg F (with wind baffle), A-control connection. Same indoor units used with both cooling-only and heat pump outdoor models, auto cool/heat changeover.

Production: 2021 - Current

- PUZ-HA24NHA1
- PUZ-HA30NKA
- PUZ-HA36NKA
- PUZ-HA42NKA1

M-Series R410A Outdoor

SUZ Single-zone Hyper-heating Universal Heat Pump

Single-zone, H2i hyper-heating heat pump Universal Outdoor unit. Pairs with M-Series ceiling cassettes, horizontal-ducted or air handler. Blue Fin anti-corrosion treatment on heat exchanger. Most models Energy Star certified. SEER up to 20.3

Production: 2020 - Current

- SUZ-KA09NAHZ.TH
- SUZ-KA12NAHZ.TH
- SUZ-KA15NAHZ.TH
- SUZ-KA18NAHZ.TH
- SUZ-KA24NAHZ
- SUZ-KA30NAHZ
- SUZ-KA36NAHZ

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Embodied Carbon
Heat Pumps

M-SERIES | **SUBMITTAL DATA: SEZ-KD09NA4 & SUZ-KA09NAHZ**
9,000 BTU/H HORIZONTAL-DUCTED HEAT PUMP SYSTEMS | MITSUBISHI ELECTRIC

Job Name:	
System Reference:	Date:

APPLIES TO INDOOR UNIT: □ SEZ-KD09NA4.TH □ SEZ-KD09NAR1.TH □ SEZ-KD09NA4R1.TH	Outdoor Unit: SUZ-KA09NAHZ

INDOOR UNIT FEATURES

- Concealed horizontal-ducted unit for applications with short duct runs
- Quiet operation
- Ultra-thin body: 7-7/8" high
- Built-in condensate lift mechanism (lifts to 21-21/32")
- Multiple control options available:
  - kumo cloud® smart device app for remote access
  - Third-party interface options
  - Wired or wireless controllers
- Static capability up to 0.20 in. WG

OUTDOOR UNIT FEATURES

- The outdoor unit powers the indoor unit, and should a power outage occur, the system is automatically restarted when power returns
- INVERTER-driven compressor and LEV provide high efficiency and comfort while using only the energy needed to maintain maximum performance
- H2i® hyper heat performance offers 100% heating capacity at 5°F
- Hot-Start Technology: no cold air rush at equipment startup or when restarting after Defrost Cycle
- Quiet operation
- Blue Fin anti-corrosion treatment applied to the outdoor unit heat exchanger for increased coil protection and longer life
- Built-in base pan heater
- Innovative Joint Lap DC Motor leads to high efficiency and reliability
- Pulse Amplitude Modulation technology

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Embodied Carbon
Heat Pumps

SPECIFICATIONS: SEZ-KD09NA4 & SUZ-KA09NAHZ

		D: In. (mm)	35-7/16 (900)
		H: In. (mm)	14-3/16 (360)
	Unit Weight	Lbs. (kg)	42 (19)
	Package Weight	Lbs. (kg)	64 (29)
Indoor Unit Operating Temperature Range	Cooling Intake Air Temp (Maximum / Minimum)*	°F	90 DB / 72 WB // 68 DB / 61 WB
	Heating Intake Air Temp (Maximum / Minimum)	°F	77 DB // 59 DB
Outdoor Unit	MCA	A	14.0
	MOCP	A	24.0
	Fan Motor Full Load Amperage	A	0.7
	Fan Motor Output	W	77.0
	Airflow Rate	CFM	1,691 / 1,691
	Refrigerant Control		LEV
	Defrost Method		Reverse Cycle
	Heat Exchanger Type		Plate Fin Coil
	Blue Fin Coating on Heat Exchanger		Yes
	Sound Pressure Level (Cooling)[1]	dB(A)	54
	Sound Pressure Level, Heating[2]	dB(A)	55
	Compressor Type		DC INVERTER-driven Twin Rotary
	Compressor Model		SNB130FHBM2T
	Compressor Rated Load Amps	A	13
	Compressor Locked Rotor Amps	A	10
	Compressor Oil Type // Charge	oz.	FV50S // 22
	External Finish Color		Ivory Munsell 3Y 7.8/1.1
	Base Pan Heater		Yes
	Unit Dimensions	W: In. (mm)	38-9/16 (840)
		D: In. (mm)	13 (330)
		H: In. (mm)	34-5/8 (880)
	Package Dimensions	W: In. (mm)	38-9/16 (980)
		D: In. (mm)	16-9/16 (420)
		H: In. (mm)	39 (990)
	Unit Weight	Lbs. (kg)	129 (58.5)
	Package Weight	Lbs. (kg)	148 (67)
Outdoor Unit Operating Temperature Range	Cooling Air Temp (Maximum / Minimum)*	°F	115 / 14
	Cooling Thermal Lock-out / Re-start Temperatures**	°F	-1 / 3
	Heating Air Temp (Maximum / Minimum)	°F	75 / -13
	Heating Thermal Lock-out / Re-start Temperatures**	°F	-18 / -14
Refrigerant	Type		R410A
	Charge	Lbs, oz	3, 9

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Embodied Carbon
Heat Pumps

SPECIFICATIONS: SEZ-KD09NA4 & SUZ-KA09NAHZ

		D: In. (mm)	35-7/16 (900)
		H: In. (mm)	14-3/16 (360)
	Unit Weight	Lbs. (kg)	42 (19)
	Package Weight	Lbs. (kg)	64 (29)
Indoor Unit Operating Temperature Range	Cooling Intake Air Temp (Maximum / Minimum)*	°F	90 DB / 72 WB // 68 DB / 61 WB
	Heating Intake Air Temp (Maximum / Minimum)	°F	77 DB // 59 DB
Outdoor Unit	MCA	A	14.0
	MOCP	A	24.0
	Fan Motor Full Load Amperage	A	0.7
	Fan Motor Output	W	77.0
	Airflow Rate	CFM	1,691 / 1,691
	Refrigerant Control		LEV
	Defrost Method		Reverse Cycle
	Heat Exchanger Type		Plate Fin Coil
	Blue Fin Coating on Heat Exchanger		Yes
	Sound Pressure Level (Cooling)[1]	dB(A)	54
	Sound Pressure Level, Heating[2]	dB(A)	55
	Compressor Type		DC INVERTER-driven Twin Rotary
	Compressor Model		SNB130FHBM2T
	Compressor Rated Load Amps	A	13
	Compressor Locked Rotor Amps	A	10
	Compressor Oil Type // Charge	oz.	FV50S // 22
	External Finish Color		Ivory Munsell 3Y 7.8/1.1
	Base Pan Heater		Yes
	Unit Dimensions	W: In. (mm)	38-9/16 (840)
		D: In. (mm)	13 (330)
		H: In. (mm)	34-5/8 (880)
	Package Dimensions	W: In. (mm)	38-9/16 (980)
		D: In. (mm)	16-9/16 (420)
		H: In. (mm)	39 (990)
	Unit Weight	Lbs. (kg)	129 (58.5)
	Package Weight	Lbs. (kg)	148 (67)
Outdoor Unit Operating Temperature Range	Cooling Air Temp (Maximum / Minimum)*	°F	115 / 14
	Cooling Thermal Lock-out / Re-start Temperatures**	°F	-1 / 3
	Heating Air Temp (Maximum / Minimum)	°F	75 / -13
	Heating Thermal Lock-out / Re-start Temperatures**	°F	-18 / -14
Refrigerant	Type		R410A
	Charge	Lbs, oz	3, 9

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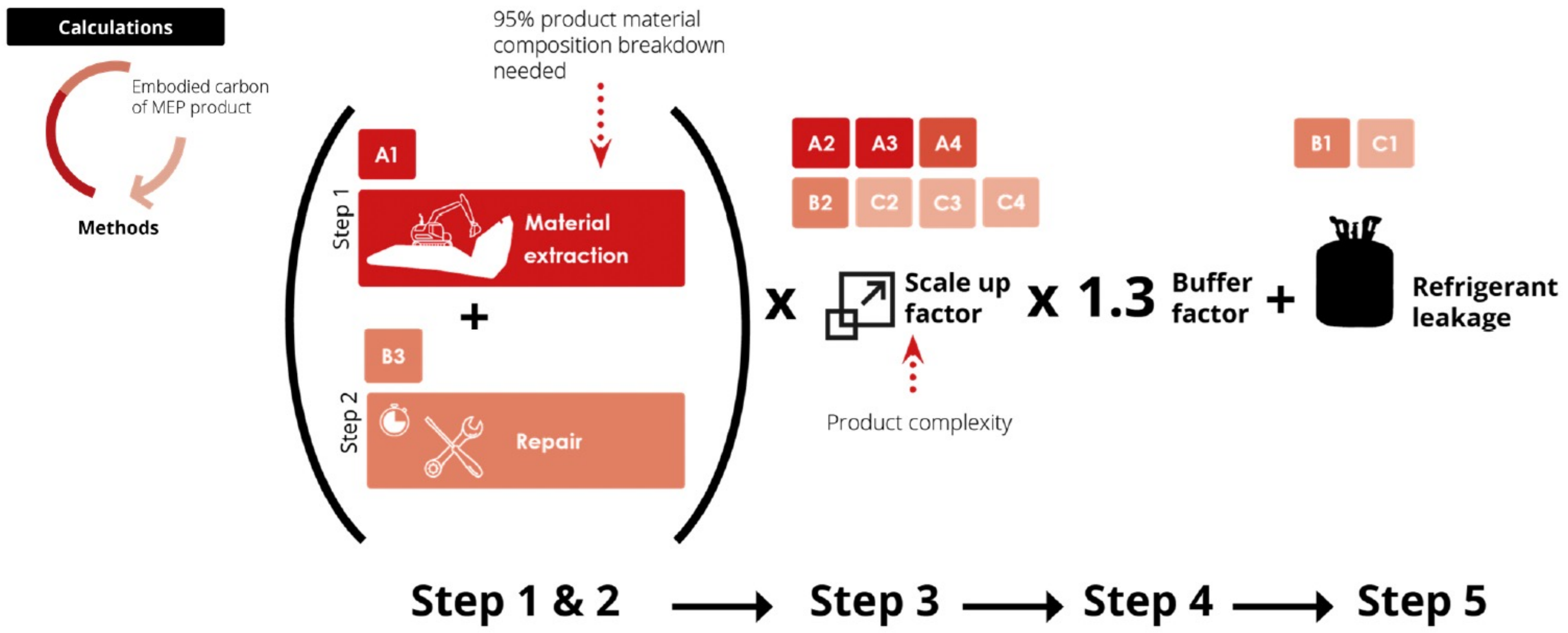
Embodied Carbon
CIBSE TM65

Basic level calculation:



https://www.beama.org.uk/static/db8d64d0-e519-498c-beac29e6e99ff3b7/TM65-Tool-BEAMA-webinar-Carl-Collins-Slides.pdf

Embodied Carbon Ventilation

Ventilation | TM65 Calculation

MITSUBISHI ELECTRIC

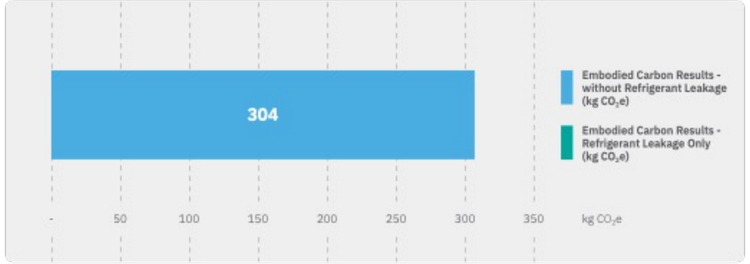
VL-250CZPVU-R/L-E

CIBSE TM65 Embodied Carbon Mid-level Calculation

Assesment Date:	22nd June 2021
Assessor / Organisation:	Mitsubishi Electric
Contact:	embodied.carbon@meuk.mee.com

Embodied Carbon Result with 'Mid-level TM65 Calculation' Method Total:

304 (kg CO_2e)



VL-250CZPVU-R/L-E - Product Information

Type of product	MVHR
Capacity of equipment (kW)	N/A
Product weight (kg)	26
Material breakdown for at least 95% of the product weight? (Y/N)	Y
Service life of the product (years)	15
Type of refrigerant	N/A
Refrigerant GWP	N/A
Energy consumption of the factory per unit of product (kWh)	5.15
Location of manufacture	Japan
Product Complexity	Category 3: High

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$$\frac{304\ kgCO_2e}{26\ kg} = 11.7\ kgCO_2e/kg$$

Embodied Carbon Ventilation

Ventilation | TM65 Calculation

MITSUBISHI ELECTRIC

VL-250CZPVU-R/L-E

CIBSE TM65 Embodied Carbon Mid-level Calculation

Embodied Carbon Results Breakdown (kg CO_2e)	
A1: Material extraction	174
A2: Transport	21
A3: Manufacturing	9
A4: Transport to Site	7
B1: Use	-
B3: Repair	21
C1: Deconstruction	-
C2: Transport	0.3
C3: Waste Processing	1
C4: Disposal	0.1

Embodied Carbon Results - without Refrigerant Leakage (kg CO_2e)	
A1-C4 (excluding B1,C1)	234
A1-C4 with Buffer Factor (excluding B1, C1)	304

Embodied Carbon Result - Refrigerant Leakage Only (kg CO_2e)	
B1 (Refrigerant leakage during use) + C1 (Refrigerant leakage end of life)	-

Assumptions	
A1: Material carbon coefficient source	TM65 Table 2.1 & The ICE Database
B1: Refrigerant annual leakage rate (%)	N/A
C1: Refrigerant end of life recovery rate (%)	N/A
B3: Materials replaced as part of repair (%)	10 (TM65 Assumption)
C4: Percentage of product going to landfill (%)	60 (TM65 Assumption)

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UNITED KINGDOM Mitsubishi Electric Europe Living Environment Systems Division, Travellers Lane, Hatfield, Hertfordshire, AL10 8XB, England. Telephone: 01707 282880 Fax: 01707 278881
IRELAND Mitsubishi Electric Europe, Westgate Business Park, Ballymount, Dublin 24, Ireland. Telephone: (01) 419 8800 Fax: (01) 419 8890 International code: (003531)

Note: The fuse rating is for guidance only. Please refer to the relevant databook for detailed specification. It is the responsibility of a qualified electrician/electrical engineer to select the correct cable size and fuse rating based on current regulation and site specific conditions. Mitsubishi Electric's air conditioning equipment and heat pump systems contain a fluorinated greenhouse gas, R410A (GWP:2088), R32 (GWP:675), R407C (GWP:1774), R134a (GWP:1430), R513A (GWP:631), R454B (GWP:466), R1234ze (GWP:7) or R1234yf (GWP:4). *These GWP values are based on Regulation (EU) No 517/2014 from IPCC 4th edition. In case of Regulation (EU) No.626/2011 from IPCC 3rd edition, these are as follows. R410A (GWP:1975), R32 (GWP:550), R407C (GWP:1650) or R134a (GWP:1300).

Effective as of July 2021

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Embodied Carbon Ventilation

Ventilation | TM65 Calculation

MITSUBISHI ELECTRIC

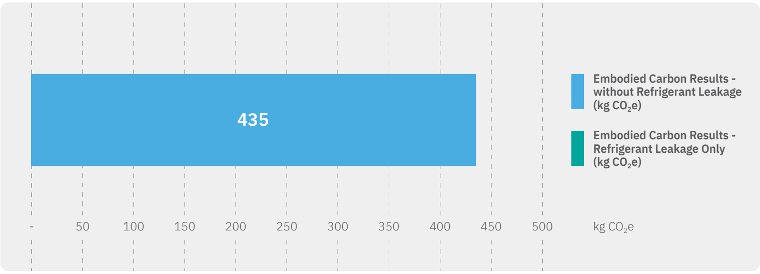
LGH-100RVX-E

CIBSE TM65 Embodied Carbon Mid-level Calculation

Assesment Date:	22nd June 2021
Assessor / Organisation:	Mitsubishi Electric
Contact:	embodied.carbon@meuk.mee.com

Embodied Carbon Result with 'Mid-level TM65 Calculation' Method Total:

435 (kg CO_2e)



LGH-100RVX-E - Product Information

Type of product	**MVHR**
Capacity of equipment (kW)	**N/A**
Product weight (kg)	**54**
Material breakdown for at least 95% of the product weight? (Y/N)	**Y**
Service life of the product (years)	**15**
Type of refrigerant	**N/A**
Refrigerant GWP	**N/A**
Energy consumption of the factory per unit of product (kWh)	**5.15**
Location of manufacture	**Japan**
Product Complexity	**Category 3: High**

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$$\frac{435\ kgCO_2e}{54\ kg} = 8\ kgCO_2e/kg$$

Embodied Carbon Ventilation

Ventilation | TM65 Calculation

LGH-100RVX-E

CIBSE TM65 Embodied Carbon Mid-level Calculation

Embodied Carbon Results Breakdown (kg CO_2e)	
A1: Material extraction	237
A2: Transport	43
A3: Manufacturing	9
A4: Transport to Site	13
B1: Use	N/A
B3: Repair	30
C1: Deconstruction	N/A
C2: Transport	1
C3: Waste Processing	1
C4: Disposal	0.23

Embodied Carbon Results - without Refrigerant Leakage (kg CO_2e)	
A1-C4 (excluding B1,C1)	334
A1-C4 with Buffer Factor (excluding B1, C1)	435

Embodied Carbon Result - Refrigerant Leakage Only (kg CO_2e)	
B1 (Refrigerant leakage during use) + C1 (Refrigerant leakage end of life)	-

Assumptions	
A1: Material carbon coefficient source	TM65 Table 2.1 & The ICE Database
B1: Refrigerant annual leakage rate (%)	N/A
C1: Refrigerant end of life recovery rate (%)	N/A
B3: Materials replaced as part of repair (%)	10 (TM65 Assumption)
C4: Percentage of product going to landfill (%)	60 (TM65 Assumption)

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Embodied Carbon
Outdoor Unit

Heating | TM65 Calculation

MITSUBISHI ELECTRIC

PUZ-WM60VAA

CIBSE TM65 Embodied Carbon Mid-level Calculation
Including Operational Carbon Benchmark Estimate

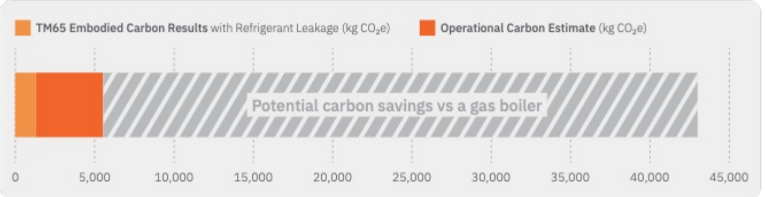
ecodan
Renewable Heating Technology

Assessment date: 29th of September 2021
Assessor: Residential Product Marketing
Organisation: Mitsubishi Electric
Contact: embodied.carbon@meuk.mee.com

Embodied Carbon Result with 'Mid-level TM65 Calculation' Method: 1,362 (kg CO_2e)

Operational Carbon Result: 4,078 (kg CO_2e)

Total = 5,440 (kg CO_2e)



Operational carbon data for heating requirements, according to heat pump ErP fiche at medium temperature (55°C), average climate conditions and equivalent boiler heat output. Gas boiler assumptions: embodied carbon of 300kg CO_2e, efficiency of 93%, service life of 15 years.

Carbon factors sources:
Electrical grid according to Greenbook forecast for residential use. (source: gov.uk, IAG spreadsheet toolkit for valuing changes in greenhouse gas emissions, sheet conversion CO_2). Gas network according to SAP 10.1 carbon emissions factor (source: BRE Group, SAP-10.1-01-10-2019, Page 171).

PUZ-WM60VAA - Product Information

Type of product	A2W Heat pump
Capacity of equipment (kW)	6
Product weight (kg)	95.8
Material breakdown for at least 95% of the product weight? (Y/N)	Y
Service life of the product (years)	15
Type of refrigerant	R32
Refrigerant GWP	675
Refrigerant charge (kg)	2.2
Energy consumption of the factory per unit of product (kWh)	66.66
Location of manufacture	UK
Product Complexity	Category 3: High

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$$\frac{1{,}362\ kgCO_2e}{96\ kg} = 14.2\ kgCO_2e/kg$$

Embodied Carbon Outdoor Unit

Heating | **TM65 Calculation**

MITSUBISHI ELECTRIC

PUZ-WM60VAA

CIBSE TM65 Embodied Carbon Mid-level Calculation
Including Operational Carbon Benchmark Estimate

Embodied Carbon Results Breakdown (kg CO_2e)	
A1: Material extraction	456
A2: Transport	76
A3: Manufacturing	77
A4: Transport to Site	1
B1: Use	446
B3: Repair	63
C1: Deconstruction	15
C2: Transport	1
C3: Waste Processing	19
C4: Disposal	0

Embodied Carbon Results - without Refrigerant Leakage (kg CO_2e)	
A1-C4 (excluding B1,C1)	693
A1-C4 with Buffer Factor (excluding B1, C1)	901

Embodied Carbon Result - Refrigerant Leakage Only (kg CO_2e)	
B1 (Refrigerant leakage during use) + C1 (Refrigerant leakage end of life)	460

Assumptions	
A1: Material carbon coefficient source	TM65 Table 2.1 & The ICE Database
B1: Refrigerant annual leakage rate (%)	2 (TM65 Assumption)
C1: Refrigerant end of life recovery rate (%)	99 (TM65 Assumption)
B3: Materials replaced as part of repair (%)	10 (TM65 Assumption)
C4: Percentage of product going to landfill (%)	30 (TM65 Assumption)

Operational Carbon

Year*1	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12	Y13	Y14	Y15	Cumulative Total
Heat Pump (kg CO_2e)	355	371	346	349	327	349	331	305	275	242	203	188	164	136	136	4,078

Note: kg CO_2e calculation results are rounded to the nearest whole number. *1 Y1 = starting from 2022

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UNITED KINGDOM Mitsubishi Electric Europe Living Environment Systems Division, Travellers Lane, Hatfield, Hertfordshire, AL10 8XB, England. Telephone: 01707 282880 Fax: 01707 278881
IRELAND Mitsubishi Electric Europe, Westgate Business Park, Ballymount, Dublin 24, Ireland. Telephone: (01) 419 8800 Fax: (01) 419 8890 International code: (003531)

Note: The fuse rating is for guidance only. Please refer to the relevant databook for detailed specification. It is the responsibility of a qualified electrician/electrical engineer to select the correct cable size and fuse rating based on current regulation and site specific conditions. Mitsubishi Electric's air conditioning equipment and heat pump systems contain a fluorinated greenhouse gas, R410A (GWP:2088), R32 (GWP:675), R407C (GWP:1774), R134a (GWP:1430), R513A (GWP:631), R454B (GWP:466), R1234ze (GWP:7) or R1234yf (GWP:4). *These GWP values are based on Regulation (EU) No 517/2014 from IPCC 4th edition. In case of Regulation (EU) No.626/2011 from IPCC 3rd edition, these are as follows. R410A (GWP:1975), R32 (GWP:550), R407C (GWP:1650) or R134a (GWP:1300).

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$$\frac{456+76+77+1=610}{96\ \text{kg}}$$

$$= 6.35\ kgCO_2e/kg$$

Embodied Carbon
Indoor Unit

Air Conditioning | TM65 Calculation

MITSUBISHI ELECTRIC

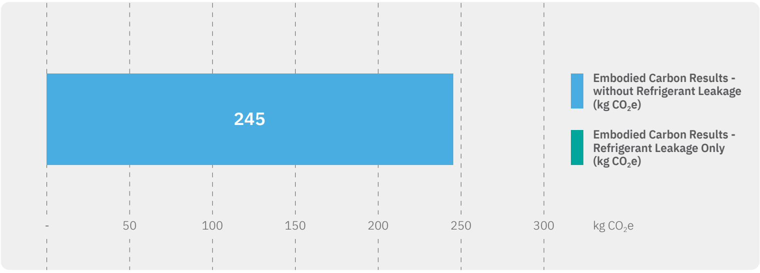
PEFY-P15VMS1-E

CIBSE TM65 Embodied Carbon Mid-level Calculation

Assesment Date:	14th July 2021
Assessor / Organisation:	Mitsubishi Electric
Contact:	embodied.carbon@meuk.mee.com

Embodied Carbon Result with 'Mid-level TM65 Calculation' Method Total:

245 (kg CO_2e)



PEFY-P15VMS1-E - Product Information

Type of product	**VRF Indoor Unit**
Capacity of equipment (kW)	**1.5**
Product weight (kg)	**19**
Material breakdown for at least 95% of the product weight? (Y/N)	**Y**
Service life of the product (years)	**15**
Type of refrigerant	**R410A**
Refrigerant GWP	**2088**
Energy consumption of the factory per unit of product (kWh)	**9.48**
Location of manufacture	**Asia**
Product Complexity	**Category 3: High**

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$$\frac{245}{19\text{ kg}} = 12.9\ kgCO_2e/kg$$

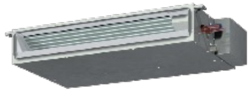
Embodied Carbon Indoor Unit

Air Conditioning | TM65 Calculation

MITSUBISHI ELECTRIC

PEFY-P15VMS1-E

CIBSE TM65 Embodied Carbon Mid-level Calculation



Embodied Carbon Results Breakdown (kg CO_2e)	
A1: Material extraction	117
A2: Transport	15
A3: Manufacturing	32
A4: Transport to Site	5
B1: Use	-
B3: Repair	17
C1: Deconstruction	-
C2: Transport	0.3
C3: Waste Processing	3
C4: Disposal	0.1

Embodied Carbon Results - without Refrigerant Leakage (kg CO_2e)	
A1-C4 (excluding B1,C1)	189
A1-C4 with Buffer Factor (excluding B1, C1)	245

Embodied Carbon Result - Refrigerant Leakage Only (kg CO_2e)	
B1 (Refrigerant leakage during use) + C1 (Refrigerant leakage end of life)	-

Assumptions	
A1: Material carbon coefficient source	TM65 Table 2.1 & The ICE Database
B1: Refrigerant annual leakage rate (%)	6 (TM65 Assumption)
C1: Refrigerant end of life recovery rate (%)	97 (TM65 Assumption)
B3: Materials replaced as part of repair (%)	10 (TM65 Assumption)
C4: Percentage of product going to landfill (%)	30 (TM65 Assumption)

MITSUBISHI ELECTRIC *Changes for the Better*
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