Supplemental Materials

LCA Modeling of Electricity Systems: Critical impact of database selection

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This document provides additional details on the methods and results for this paper to provide greater transparency than appropriate in a standard manuscript.

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Supplementary S1. Estimating NPCC Electricity Mixes

Materials related to section 2.1.1 and 2.2 Electricity mix (2022 & 2040)

2022 Electricity Mixes

The analysis focused on the NPCC U.S. region, specifically combining the following eGRID subregions:

- NEWE: New England (Connecticut, Massachusetts, Maine, New Hampshire, Rhode Island, Vermont)
- NYCW: New York City and Westchester County, New York
- NYUP: New York Upstate
- NYLI: New York Long Island

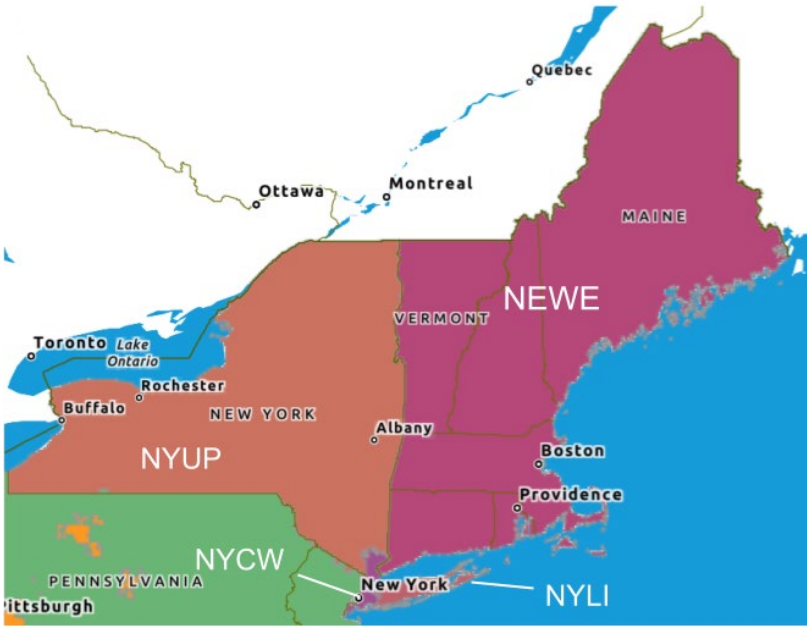


Figure S1. *Map of eGRID Subregions.* Adapted from U.S. Environmental Protection Agency. (2023), *eGRID web map (ArcGIS)*, https://www.arcgis.com/apps/mapviewer/index.html?layers=d6e1591d9a424f1fa6d95a02095a06d7

These subregions represent the major electricity markets within the NPCC U.S. boundary. The electricity generation mix data were obtained from the U.S. Environmental Protection Agency's eGRID 2010 and 2022 databases, specifically the 'Subregion Resource Mix' sheet from the downloadable excel spreadsheets. The data for each subregion were combined into a single NPCC electricity mix using a weighted average.

$$NPCC\ Total\ (j)\ (\%) = \sum_{regions\ (i)} \frac{Generation(i)\ (MWh)}{Generation\ Total\ (MWh)} \times Resource\ Fraction\ (i,j)\ (\%) \qquad [S1]$$

Where *j* is the resource mix and *i* denotes the subregion.

Table S1 shows the eGRID generation and resource mix percentages for each subregion and the calculated mix for the NPCC region in 2022. The combined NPCC electricity mix was used as input data for a customized electricity supply model built, utilizing Ecoinvent datasets.

Table S1. Regional Generation and Resource Mix (2022)

eGRID subregion acronym	Net Generation (MWh)	Resource Mix (%)							
		Gas	Nucl.	Hydro	Wind	Solar	Coal	Oil	Other
NEWE	100,011,791	49.3	29.8	7.3	3.7	1.5	0.5	0.2	0.1
NYCW	41,509,809	58.3	40.2	0.0	0.0	0.0	0.0	0.5	0
NYLI	8,943,357	85.5	0.0	0.0	0.0	2.1	0.0	2.5	0
NYUP	87,477,873	25.0	32.2	34.9	5.1	0.4	0.5	0.1	0
NPCC Total	**237,942,830**	**43.2**	**31.3**	**15.9**	**3.4**	**0.9**	**0.4**	**0.3**	**<0.1**

2040 Electricity Mix

The projected 2040 electricity mix for the NPCC region was constructed by combining projections for New York State (NYS) and New England (NEWE) using a weighted average approach (Eq. [S1]) based on projected net electricity generation (MWh) in each region (Table S2).

For NYS, generation data by technology was extracted from **Table 4-3 of the NYSERDA Zero Emissions Pathways Study** (New York Independent System Operator [NYISO], 2021), which lists projected annual electricity generation (in GWh) for 2040 under the "Mitigated Demand Scenario." which represent a scenario of deep decarbonization. From this table, technology shares were calculated by dividing generation per technology by the total projected electricity generation (~210 TWh).

For NEWE, projections were based on **Scenario 3 (S3 – "Deep Decarbonization")** from the **ISO-NE Future Grid Reliability Study Phase 1**. As this scenario's mix is presented only graphically (Figure 5-3), each technology share was approximated using the annual generation in TWh for each technology based on measured bar height. "Imports" (~28 TWh) were assumed to be hydroelectric and were combined with modeled hydro. This assumption is based on ISO-NE's documentation, which indicates that nearly all electricity imports into New England originate from Canadian hydroelectric resources.

The final NPCC mix was obtained by calculating the weighted average of technology shares between NEWE and NYS based on their projected 2040 generation.

Table S2. Regional Generation and Resource Mix (2040)

Region	Net Generation (MWh)	Resource Mix (%)				
		Natural Gas	Nuclear	Hydro	Wind	Solar
NEWE	108,539,000	16.0	17.6	20.1	34.2	12.1
NY	210,591,000	0.5	13.1	23.1	43.0	20.3
NPCC Total	**319,130,000**	**5.8**	**14.6**	**22.1**	**40.0**	**17.5**

Supplementary S2. Calculation of Grid Length per Unit of Electricity (m/kWh) for NPCC U.S. Region

Details for materials in section 2.1.2 Inventory Datasets Selection and Customized Model Construction

To incorporate grid infrastructure into the customized electricity model, it was necessary to calculate the length of transmission and distribution networks per unit of electricity delivered (m/kWh). This enabled the application of infrastructure-related processes from the Ecoinvent database in a consistent and regionally representative manner.

Transmission and distribution were treated separately due to their distinct infrastructure types. For distribution, a weighted average was calculated based on state-level electricity consumption and estimated network lengths, in order to better reflect spatial variability within the NPCC U.S. region. These values are needed to assign infrastructure burdens in the Life Cycle Inventory, with the following Ecoinvent processes:

- Transmission: '*market for transmission network, electricity, high voltage*'
- Distribution: '*market for distribution network, electricity, low voltage*'

Both processes were implemented in the customized model with their respective m/kWh values, ensuring a transparent and differentiated treatment of electricity infrastructure in the NPCC region.

Data for transmission network length was sourced from regional planning reports provided by ISO New England and NYISO, which oversee high-voltage transmission planning and operations across state lines in the Northeast U.S. (ISO New England, 2024; NYISO, 2024). These sources offer consolidated estimates of total transmission line mileage for the region, supporting the use of a single regional average for transmission grid length per unit of electricity.

For distribution networks, utility-specific reports and state-level electricity consumption data from the U.S. Energy Information Administration (2023) and EPA's eGRID database (EPA, 2025) were used to estimate total distribution line lengths and enable a state-weighted average calculation of distribution grid length per kWh (Table S3).

Assumptions & Considerations

- Utilities operate distinct distribution networks with no overlapping infrastructure, as each serves exclusive service territories regulated by state public utility commissions.
- Transmission grid lengths were taken from ISO-NE and NYISO summaries, accounting for high-voltage infrastructure only (NYISO, 2023; ISO-NE, 2023).
- Distribution lengths were compiled from major utility reports, representing the bulk of infrastructure within NPCC U.S.
- Implementation of additional future T&D infrastructure to accommodate increasing decarbonization and electrification were not included in the LCA model for 2040.

Table S3. Electricity Consumption and T&D Grid Lengths in NPCC U.S. Region (2022)

State	Electricity Consumption (MWh)	Distribution Grid Length (m)	Transmission Grid Length (m)
New York	143,210,517	278,346,618	14,484,000
Massachusetts	50,983,440	42,808,444	17,712,000
Connecticut	27,767,146	28,968,120	
Maine	11,875,708	47,958,332	
New Hampshire	10,818,130	31,985,633	
Rhode Island	7,576,284	9,656,040	
Vermont	5,470,471	26,389,957	
Total	257,701,696		32,196,000

The separate infrastructure modeling of transmission and distribution networks reflects the real-world structural, operational, and environmental differences between high-voltage transmission systems and lower-voltage distribution systems.

Transmission Grid Length per MWh (Regional Average)

Transmission infrastructure in the NPCC region is centrally planned and operated across state lines by ISO New England and NYISO (ISO New England, 2024; NYISO, 2024). It primarily consists of high-voltage lines that connect major power generation sites with regional distribution networks. Because this infrastructure is planned and managed at a regional level rather than on a state-by-state basis, it is appropriate to use a single, regional transmission grid length per unit of electricity. This avoids artificial allocation based on political boundaries and more accurately reflects how transmission infrastructure operates in practice.

Note: Each utility operates exclusive service territories; therefore, there is no overlap or double counting in transmission grid lengths. The total consumption (**257,701,696 MWh/y)** and transmission grid length (**32,186,800 m**) were used to determine the *Transmission Grid Length per MWh* ≈ ***0.125 m/MWh/y***

To account for the infrastructure lifetime, the value used in the LCI was divided by 40 years, resulting in a new value of ***0.003 m/MWh.***

Distribution Grid Length per MWh (State-Weighted Average)

In contrast to transmission, distribution infrastructure is more localized and varies significantly across states due to differences in urbanization, customer density, and utility service areas. To more accurately reflect this variability, the distribution grid length per MWh was calculated using an average by state. The calculation used state-level electricity consumption (MWh) and estimated distribution network lengths (m) (Table 4)

Each state's contribution to the regional average was weighted by its share of total electricity consumption. The weighted average was then calculated:

$$Regional\ Distribution\ length\ \left(\frac{m}{MWh}\right)$$

$$= \sum_{states\ (j)} \left[\frac{Dist.Length_j(m)}{Elec\ Cons._j\ (MWh/y)}\right] \times \left[\frac{Elec\ Cons._j\ (MWh)}{\sum_j\ Elec\ Cons._j\ (MWh)}\right] \times \frac{1}{40\ y}$$

To account for the infrastructure lifetime, the value obtained was divided by 40 years, resulting in a value of ***0.045 m/MWh.***

Supplementary S3. Residential Heating LCA Case Study - Methods

Materials referenced from section 2.32 Case Study: Implications of LCI database selection for electrification and grid decarbonization

The functional unit for the residential heating case study was defined as the useful thermal energy required to meet the winter heating demand of an average single-family household in the NPCC region. The calculation was based on typical housing characteristics and heating energy intensity values (Table S5)

Table S5. Assumptions and Parameters for Residential Heating Case Study

Parameter	Value	Unit	Source
Reference floor area	2,000	ft^2	DOE Building Energy Codes Program
Converted floor area	185.8	m^2	Conversion (1 ft^2 = 0.092903 m^2)
Annual heating demand intensity	120	kWh/m^2/year	DOE / NYSERDA / Padovani et al., (2021)
Total annual heating demand	22,296	kWh/year	185.8 m^2 × 120 kWh/m^2/year
Converted to MJ	80,266	MJ/year	1 kWh = 3.6 MJ
Share of demand occurring in winter	92%	–	DOE Building Energy Codes Program
Functional Unit	**73,850**	**MJ**	80,266 MJ/year × 0.92MJ winter/MJ annually

Table S6 summarizes the main characteristics and lifecycle datasets used for the heating technologies considered. Between the two databases for heat pump (HP) heating systems, the inventory datasets presented here were the closest we found as possible to each other in terms of capacity (10 - 30 kW).

Table S6. Technical characteristics and modeling details of heat pump heating technologies

Technology	Description	Sphera Process	Ecoinvent Process
Heat Pump	Coefficient of Performance (COP) = 3 Includes the production of the heat pump, including materials, energy, transportation, and emissions of refrigerant (R134a) during production and end of life.	"electric heat pump (air-water) 10 kW"	"heat pump production, 30 kW – RoW (R134a)" (rest of world)
Sources	Sphera Documentation Portal (2023); Ecoinvent 3.11 ecoQuery (2025)		

Heat Pump Production and Refrigerant Inventory

To represent the capital equipment of the electrified heating system, the dataset *"heat pump production, 30 kW – RoW (R134a)"* (Rest of World) was used for Ecoinvent 3.11, and the dataset "*electric heat pump (air-water) 10 kW*" for Sphera. As used, these datasets account for material and energy requirements during manufacturing of one unit, as well as refrigerant consumption and end-of-life releases, but not the use lifecycle stage. To align with the functional unit (73,850 MJ useful heat ≈ 20,480 kWh) that describes annual average winter season heating load in the NPCC region, the datasets were scaled relative to the lifetime energy service of a comparable system. Following Lin et al. (2021), one residential heat pump is assumed to provide 252,000 kWh of space heat over 20 years. The corresponding allocation is:

$$HP\ Units\ = \frac{20{,}480\ kWh/FU}{252{,}000\ kWh/unit} = 0.0812\ unit/FU$$

Because the Ecoinvent dataset already includes refrigerant use and end-of-life management, only refrigerant leakage during the use-phase was added separately. Based on Lin et al. (2021), total lifetime leakage is approximately 3.42 kg over 252,000 kWh. Scaled to the functional unit:

$$Leakage\ during\ use\ = 3.42\ kg/unit\ x\ 0.0812\ units/FU = 0.278\ kg\ R134a/FU$$

A coefficient of performance for the HP was assumed to be 3.0 over the heating system.

Table S7. Summary - Additional inputs and outputs for the life cycle inventory of heating technologies to generate 73,850 MJ useful heat (average winter residential heating demand in NPCC region)

Technology	Flow	Quantity		
Heat Pump	Electricity (for COP = 3)	24,617	MJ	Input
	Capital equipment	0.0812	units	Input
	Refrigerant leakage (R134a)	0.278	kg	Output

Supplementary S4. LCIA Results: Generation and distribution of 1 MWh electricity, NPCC, 2022

Materials to support results and discussion in Section 3.1 Comparison of the LCI Database and LCIA Methods for 2022

This section presents the LCIA results for electricity supply modeling for the year 2022, including results from the Sphera electricity dataset, the default Ecoinvent - "market for electricity, low voltage–US-NPCC" dataset, and the customized NPCC model developed in this study using individual Ecoinvent 3.11 processes. Results are included for both the ReCiPe and TRACI LCIA methods.

Table S8a. ReCiPe LCIA Results for Electricity System 2022 (functional unit = 1 MWh)

Impact category	Units	Ecoinvent default	Customized electricity with Ecoinvent databases	Sphera databases
Climate change, excl biogenic carbon	kg CO2 eq.	2.94E+02	3.69E+02	3.41E+02
Climate change, incl biogenic carbon	kg CO2 eq	3.01E+02	3.69E+02	3.41E+02
Fine Particulate Matter Formation	kg PM2.5 eq	1.72E-01	2.67E-01	5.71E-02
Fossil depletion	kg oil eq	1.97E+02	1.96E+02	1.65E+02
Freshwater Consumption	m3	5.57E+00	1.47E+00	4.30E+00
Freshwater ecotoxicity	kg 1,4 DB eq	3.29E+01	2.24E+01	2.21E-02
Freshwater Eutrophication	kg P eq	3.65E-02	6.77E-02	2.86E-05
Human toxicity, cancer	kg 1,4-DB eq	3.26E+01	3.48E+01	1.01E-01
Human toxicity, non-cancer	kg 1,4-DB eq	4.12E+02	3.76E+02	3.85E+00
Ionizing Radiation	kBq Co-60 eq. to air	2.24E+02	1.77E+02	1.23E+01
Land use	Annual crop eq.·y	1.06E+01	2.37E+00	7.12E-01
Marine ecotoxicity	kg 1,4-DB eq	3.98E+01	2.72E+01	4.90E-02
Marine Eutrophication	kg N eq	6.37E-03	8.29E-03	1.08E-03
Metal depletion	kg Cu eq	1.39E+00	1.02E+00	1.71E-01
Photochemical Ozone Formation, Ecosystems	kg NOx eq	4.07E-01	5.14E-01	2.03E-01
Photochemical Ozone Formation, Human Health	kg NOx eq	3.61E-01	4.70E-01	2.01E-01
Stratospheric Ozone Depletion	kg CFC-11 eq	1.39E-04	8.96E-05	2.44E-05
Terrestrial Acidification	kg SO2 eq	4.35E-01	7.93E-01	1.71E-01
Terrestrial ecotoxicity	kg 1,4-DB eq	7.15E+02	5.64E+02	2.45E+01

Table S8b. TRACI LCIA Results for Electricity System 2022 (functional unit = 1 MWh)

Impact category	**Ecoinvent Default**	**Customized electricity with Ecoinvent databases**	**Sphera databases**
Global Warming Air, incl. biogenic carbon [kg CO2 eq.]	284	358	331
Resources, Fossil fuels [MJ surplus energy]	5.23E+02	6.12E+02	566
Human Health Particulate Air [kg PM2.5 eq.]	0.123	0.145	0.0174
Ecotoxicity (recommended) [CTUe]	6.21	4.304	0.425
Human toxicity, cancer (recommended) [CTUh]	1.70E-08	1.42E-08	8.14E-08
Human toxicity, non-canc. (recommended) [CTUh]	2.46E-07	1.60E-07	1.42E-08
Eutrophication [kg N eq.]	0.0163	0.0302	0.0203
Acidification [kg SO2 eq.]	0.539	0.957	0.244
Ozone Depletion Air [kg CFC 11 eq.]	2.28E-06	2.51E-06	4.54E-11
Smog Air [kg O3 eq.]	8.27	11	4.96

Supplementary S5. LCIA Results - Residential Heating Case Study

Materials to support section 3.2 Electricity Mix Projections (2022-2040) and Implications for Heating Electrification

Table S9. LCIA results for the residential heating inventory - heat pump scenario.

	Customized Model		Sphera Model	
Impact category	**2022**	**2040**	**2022**	**2040**
Climate change, excl bio. carbon [kg CO2 eq.]	8.95E+03	2.15E+03	5.61E+03	1.59E+03
Fine Particulate Matter Formation [kg PM2.5 eq.]	5.87E+00	2.54E+00	1.35E+00	1.12E+00
Fossil depletion [kg oil eq.]	4.34E+03	1.55E+03	3.42E+03	2.14E+03
Freshwater Consumption [m3]	3.31E+01	2.70E+01	1.05E+02	1.20E+02
Freshwater ecotoxicity [kg 1,4 DB eq.]	2.81E+02	6.69E+02	1.64E+02	1.64E+02
Freshwater Eutrophication [kg P eq.]	1.49E+00	7.08E-01	2.79E-01	2.79E-01
Human toxicity, cancer [kg 1,4-DB eq.]	9.32E+02	9.32E+02	2.39E+02	2.42E+02
Human toxicity, non-cancer [kg 1,4-DB eq.]	7.98E+03	7.97E+03	3.30E+03	3.30E+03
Ionizing Radiation [kBq Co-60 eq. to air]	3.89E+03	2.79E+03	3.85E+02	4.29E+02
Land use [Annual crop eq.·y]	5.02E+01	1.28E+02	1.14E+01	1.35E+01
Marine ecotoxicity [kg 1,4-DB eq.]	3.47E+02	8.13E+02	2.00E+02	1.99E+02
Marine Eutrophication [kg N eq.]	1.88E-01	1.04E-01	3.07E-02	3.24E-02
Metal depletion [kg Cu eq.]	2.28E+01	2.79E+01	1.34E+01	1.44E+01
Photochem. O3 Form., Ecosystems [kg NOx eq.]	1.14E+01	3.20E+00	3.25E+00	1.37E+00
Photochem. O3 Form., Human Health [kg NOx eq.]	1.04E+01	3.00E+00	3.19E+00	1.33E+00
Stratospheric Ozone Depletion [kg CFC-11 eq.]	2.51E-03	9.68E-04	7.27E-04	6.21E-04
Terrestrial Acidification [kg SO2 eq.]	1.73E+01	6.36E+00	3.84E+00	3.19E+00
Terrestrial ecotoxicity [kg 1,4-DB eq.]	1.19E+04	1.68E+04	5.02E+03	5.05E+03

The heat map in Table 1 of the manuscript shows the relative changes for the heat pump option over the years and differences between the impacts determined with two different inventory databases. Each row represents an impact category, with these loosely organized into related impacts.

The changes over time (2040 compared to 2022) were calculated as a percentage:

$$\%\, change_{i,j} = \frac{(2022\ value_{i,j} - 2040\ value_{i,j})}{2022\ value_{i,j}} \times 100\%$$

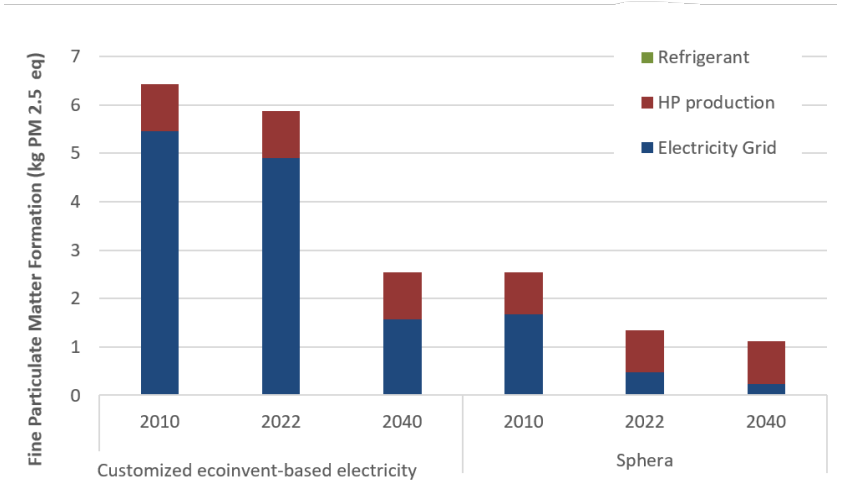
The differences between the databases are simply presented as a ratio (customized/Sphera). With ratios that are typically over two times the value, percentage changes were less meaningful.

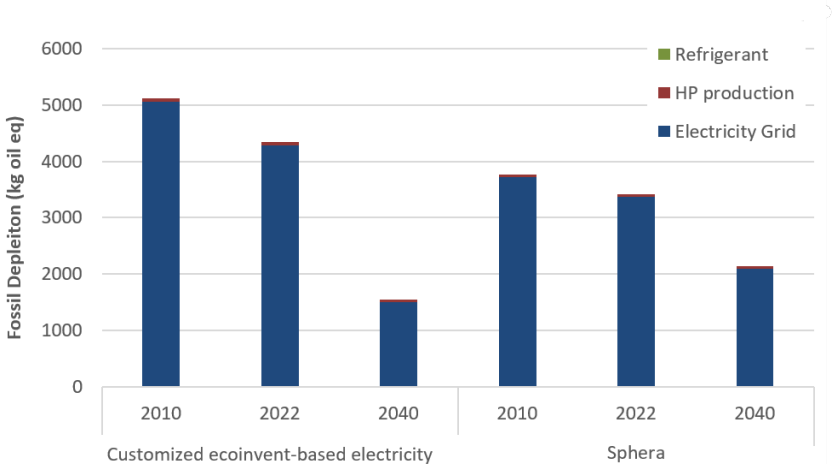
As we consider the question - Does decarbonization of the grid help substantially to reduce the impacts of heat pump heating systems between 2022 and 2040:

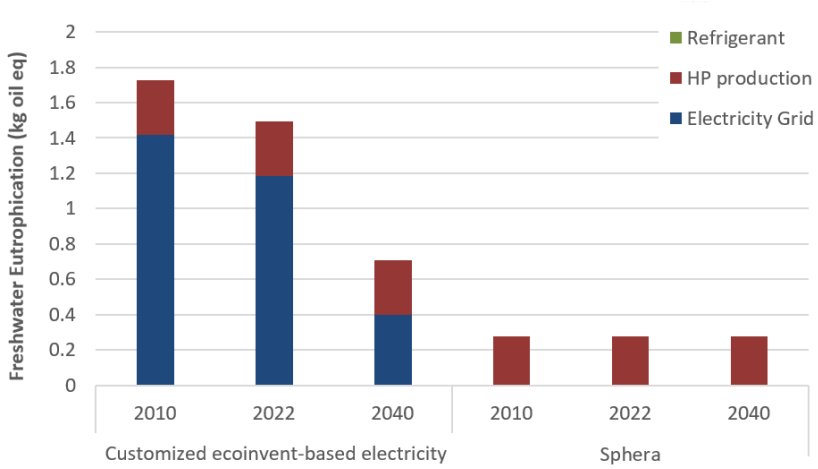
- For most impact categories, use of both inventory data bases both show that the 2040 impacts are far less than the 2022 impacts (blue shading, negative values)

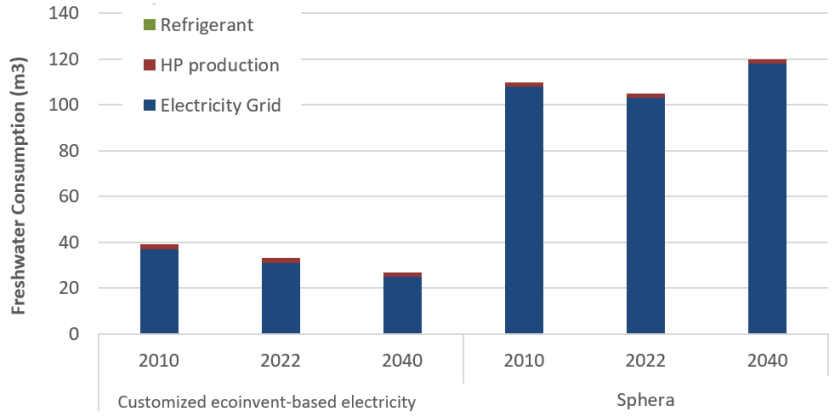
- For a few impact categories - the impacts are increased (red shading: land use, metal depletion, ecotoxicity). These are related to the increased use of metal and space with renewable energy infrastructure
- In a few cases, the answer to this question depends on the inventory database used:
    - for freshwater consumption, the customized model with Ecoinvent component inventories is greatly reduced, but the impacts increase some based on results with Sphera.
    - for freshwater and marine ecotoxicities, the customized model shows significant increases in impacts between 2022 and 2040, yet Sphere shows no change in the impacts. As described in the main paper, uncertainty in the electric grid infrastructure assumptions, especially material end-of-life result in high toxicity scores with Ecoinvent inventory databases.

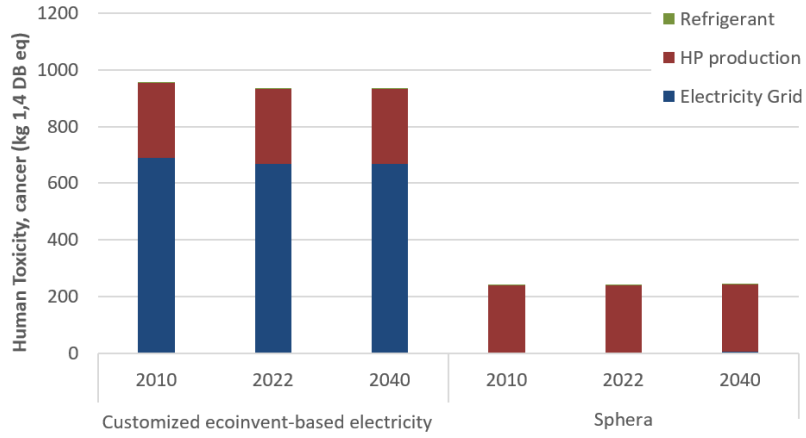
The complete results of the residential heating case study are included in Figure S2. Note: values for analysis with 2010 electricity mix are also included here. They did not add any value to the interpretation of results so are not described in the manuscript.

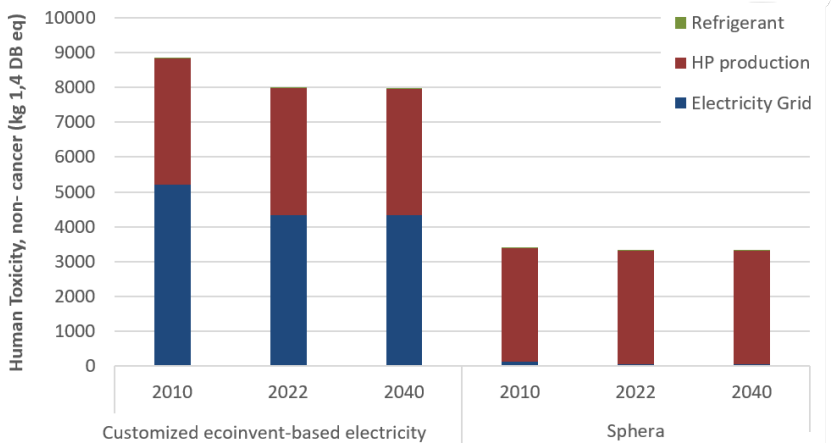

Fine Particulate Matter Formation (kg PM 2.5 eq)
7
6
5
4
3
2
1
0
Refrigerant
HP production
Electricity Grid
2010
2022
2040
2010
2022
2040
Customized ecoinvent-based electricity
Sphera

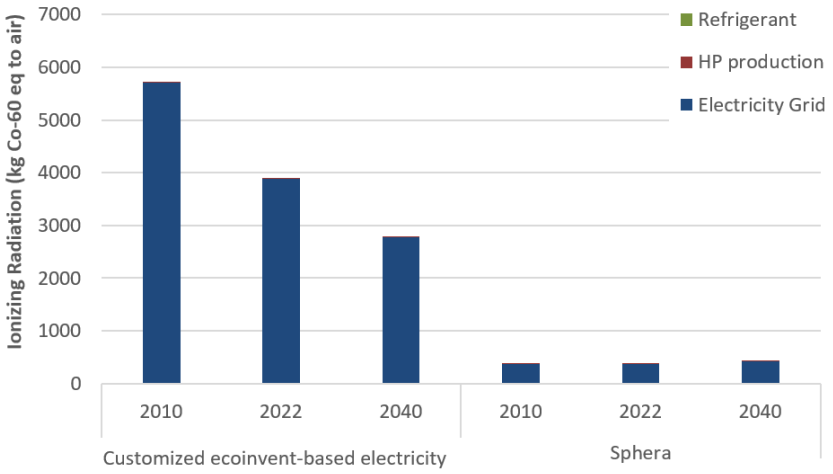

Fossil Depleiton (kg oil eq)
6000
5000
4000
3000
2000
1000
0
Refrigerant
HP production
Electricity Grid
2010
2022
2040
2010
2022
2040
Customized ecoinvent-based electricity
Sphera

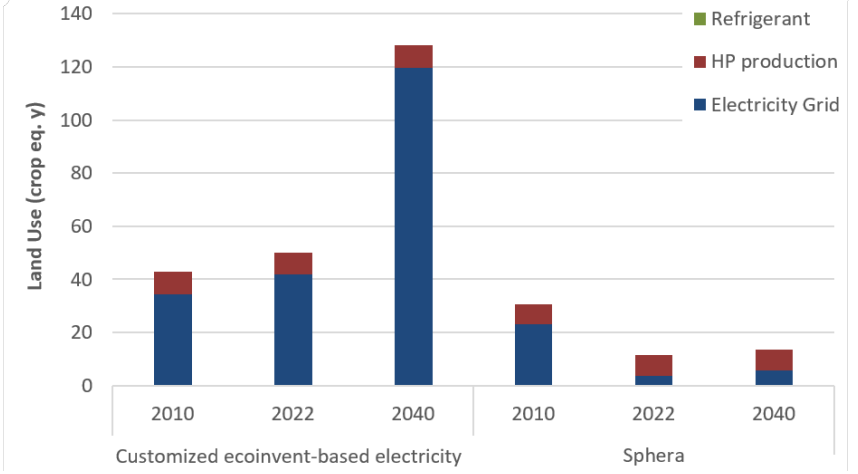

Freshwater Eutrophication (kg oil eq)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Refrigerant
HP production
Electricity Grid
2010
2022
2040
2010
2022
2040
Customized ecoinvent-based electricity
Sphera

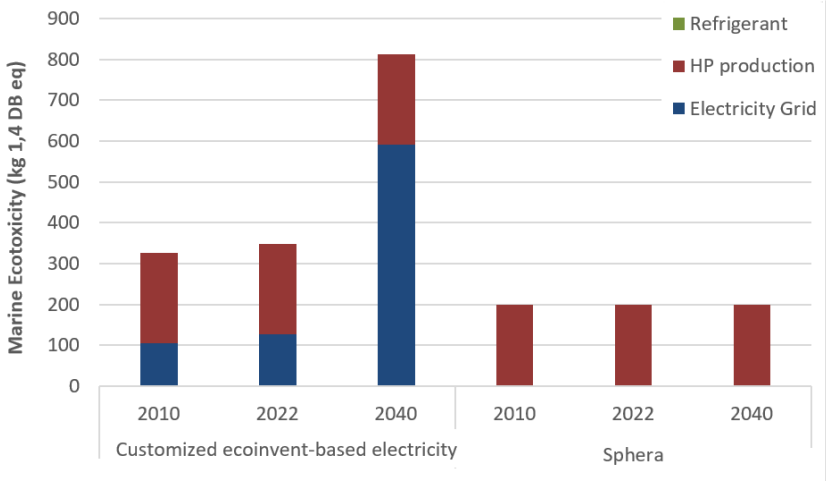

Freshwater Consumption (m3)
140
120
100
80
60
40
20
0
Refrigerant
HP production
Electricity Grid
2010
2022
2040
2010
2022
2040
Customized ecoinvent-based electricity
Sphera

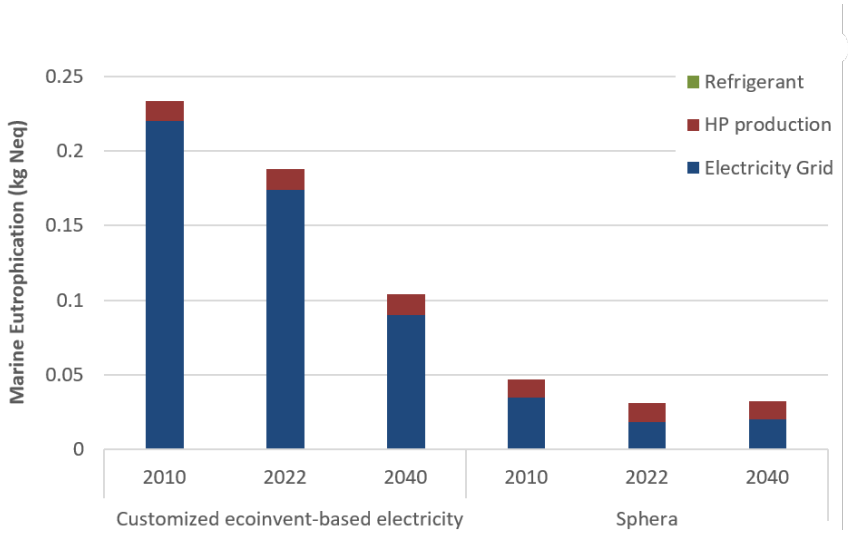

Human Toxicity, cancer (kg 1,4 DB eq)
1200
1000
800
600
400
200
0
Refrigerant
HP production
Electricity Grid
2010
2022
2040
2010
2022
2040
Customized ecoinvent-based electricity
Sphera

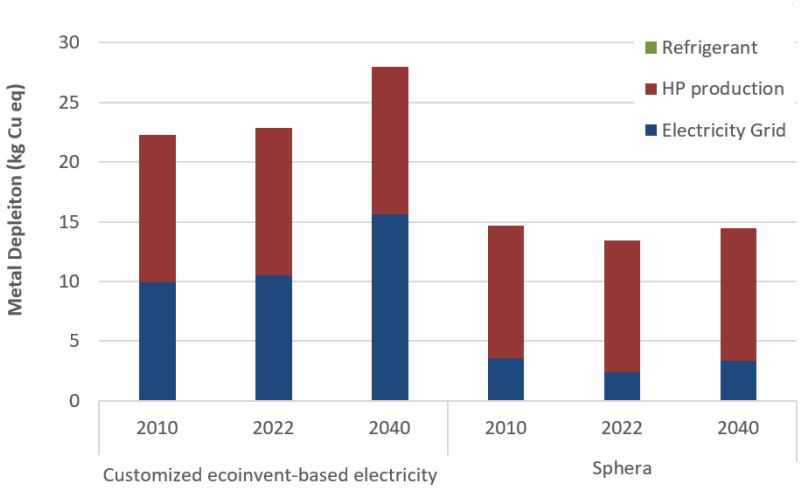

Human Toxicity, non- cancer (kg 1,4 DB eq)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Refrigerant
HP production
Electricity Grid
2010
2022
2040
2010
2022
2040
Customized ecoinvent-based electricity
Sphera

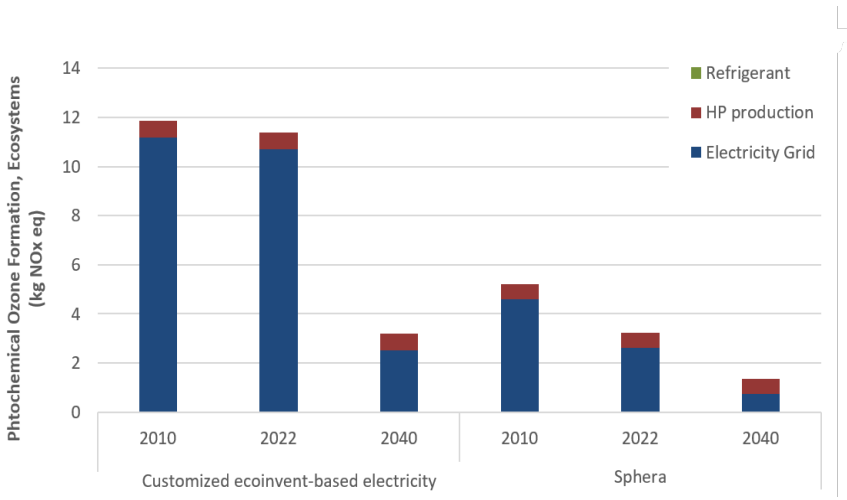

Ionizing Radiation (kg Co-60 eq to air)
7000
6000
5000
4000
3000
2000
1000
0
Refrigerant
HP production
Electricity Grid
2010
2022
2040
2010
2022
2040
Customized ecoinvent-based electricity
Sphera


Land Use (crop eq. y)
140
120
100
80
60
40
20
0
Refrigerant
HP production
Electricity Grid
2010
2022
2040
2010
2022
2040
Customized ecoinvent-based electricity
Sphera


Marine Ecotoxicity (kg 1,4 DB eq)
900
800
700
600
500
400
300
200
100
0
Refrigerant
HP production
Electricity Grid
2010
2022
2040
2010
2022
2040
Customized ecoinvent-based electricity
Sphera


Marine Eutrophication (kg Neq)
0.25
0.2
0.15
0.1
0.05
0
Refrigerant
HP production
Electricity Grid
2010
2022
2040
2010
2022
2040
Customized ecoinvent-based electricity
Sphera


Metal Depleiton (kg Cu eq)
30
25
20
15
10
5
0
Refrigerant
HP production
Electricity Grid
2010
2022
2040
2010
2022
2040
Customized ecoinvent-based electricity
Sphera


Phtochemical Ozone Formation, Ecosystems (kg NOx eq)
14
12
10
8
6
4
2
0
Refrigerant
HP production
Electricity Grid
2010
2022
2040
2010
2022
2040
Customized ecoinvent-based electricity
Sphera

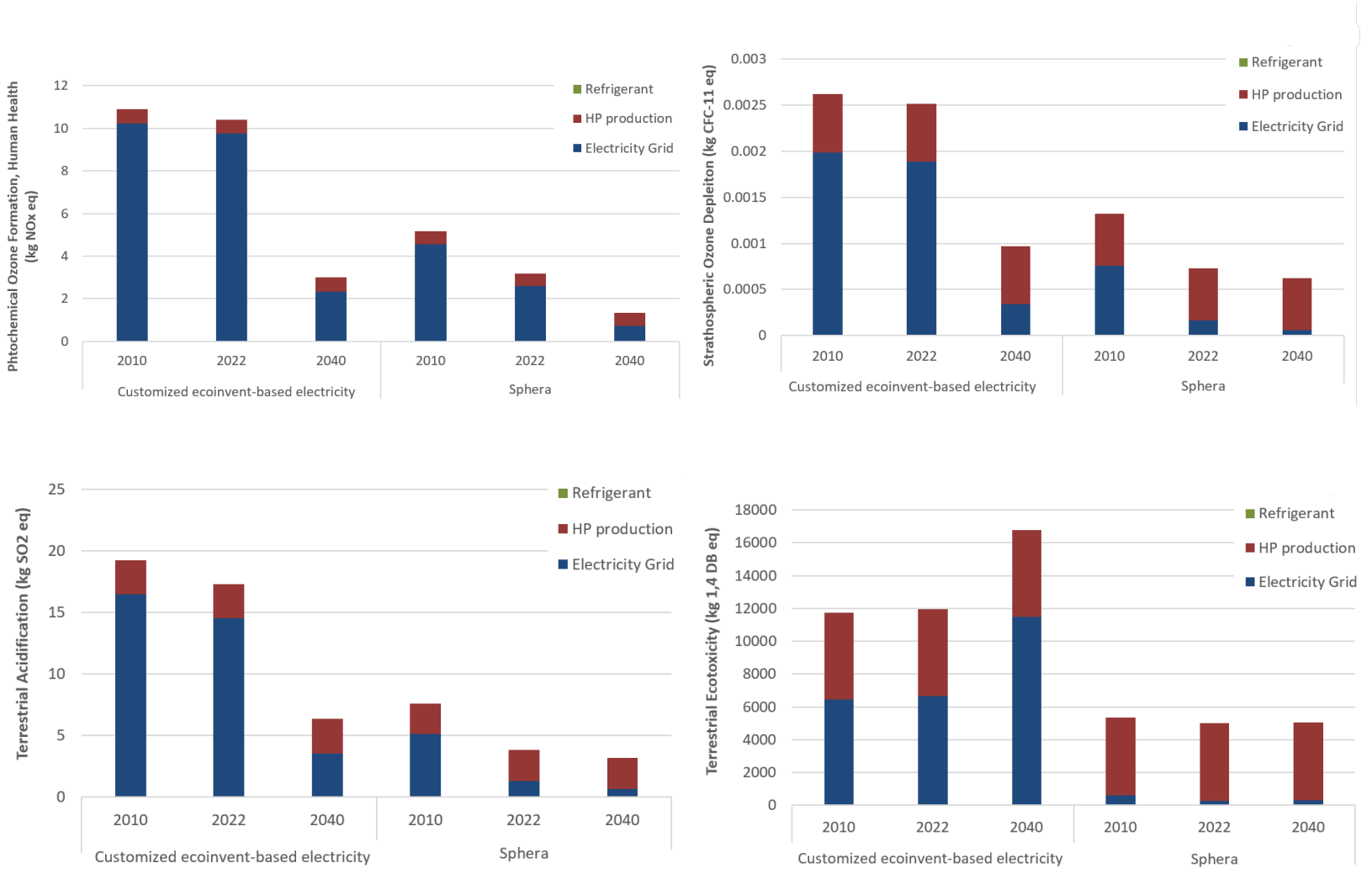


Figure S2. Breakdown of impact categories for heat pumps estimated with the customized LCA model using Ecoinvent 3.11 dataset components versus with the Sphera dataset (four other impact categories are included in the main paper).

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