Net zero electricity systems in global economies by life cycle assessment (L.C.A.) considering ecosystem, health, monetization, and soil CO₂ sequestration impacts

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Abstract

The electricity sector supporting all sectors accounts for 38% of the global annual energy-related greenhouse gas emissions (GHG) of 34Gt CO₂eq. With this trajectory, the global mean temperature will rise by 2.7°C by 2100 (at 50% probability). There is no consensus approach to sustainability analysis of net zero electricity (NZE) scenarios or systems. This study has developed a novel, rigorous, holistic LCA-based methodology for robust NZE roadmap/pathway analyses. It identifies the leading fifteen countries with the highest gross domestic products with over 90% GHG. It compiles Ecoinvent life cycle inventory for NZE systems and country mixes and calculates their life cycle impacts using *ReCiPe*, *Impact 2002+*, and *Environmental Prices* methods. The global mean ranking of non-fossil systems is (kg CO₂eq/GJ, US\$/GJ): hydro-run-of-river (1.49, 0.73), hydro-reservoir (7.77, 0.91), wind:1-3MW (7.37, 3.9), solar-20MW (13.94, 4.18), solar-50MW (15.29, 4.84), wind:>3MW (9.55, 9.68), geothermal (19.99, 9.84), and bioenergy (12.09, 36.28). To hit NZE, Brazil, the U.S.A., Spain, Germany, France, Canada, Japan, Italy, and the U.K. need 52-95% decarbonization. Russia, Indonesia, Mexico, and Turkey can achieve 61%, 31%, 6%, and 4% decarbonization, while with 0.52 and 0.65 kg CO₂eq/kWh, China and India are unlikely to make any difference by this time. NZE relies on improving health in developing countries, de-fossilized resource-technology diversification, and soil organic carbon sequestration, enhancing biodiversity and forestation. Deemed life cycle sustainability tradeoffs are land use, particulate emission, terrestrial-human-freshwater toxicity, and ecosystem quality (e.g., bioenergy amongst fossil-independent systems), and ionising radiation (e.g., nuclear).

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25 **Keywords:** net zero roadmaps, consequential life cycle assessment, weighted costing or monetization
26 of environmental impact, land use GWP human health ecosystem and sustainability, hydropower wind
27 solar geothermal bioenergy nuclear, natural CO₂ sink carbon sink such as forestation, soil and
28 biodiversity.

29 **Introduction**

30 The net zero greenhouse gas emissions (GHG) by neutralizing GHG are needed to constrain the global
31 temperature rise to 1.5°C by 2100 compared to pre-industrial levels, according to the Intergovernmental
32 Panel on Climate Change (I.P.C.C.) [1] and the International Energy Agency (IEA) [2]. Electricity is a
33 ubiquitous driver for all sectors for all products across all supply chains between countries.
34 Electrification of large parts of the energy demand of all sectors is a crucial assumption towards the net
35 zero targets [3]. Renewable resources, such as hydro, wind, solar and geothermal, can de-fossilize or
36 decarbonize the electricity sector. Bioenergy that responds to changing supply-demand conditions can
37 meet any deficit of renewable energy supplies [4], [5]. The net residual GHG must be neutralized by
38 GHG capture and sequestration for the net zero GHG targets. Soil and root carbon storage is a natural
39 sink to sequester GHG to mitigate climate impact consequences [6] following the United Nations
40 Sustainable Goals 7, affordable and clean energy, and 13, climate action.

41 With the prominent emergence of the climate crisis at the Conference of the Parties, COP26, holistic and
42 whole-system methodologies such as life cycle assessment (L.C.A.) are timely to deploy to refresh
43 renewable and biomass strategies to hit the net zero targets. L.C.A. has long been applied to bioenergy
44 [7], [8], and biorefinery systems [9], [10], with carbon capture and storage [11], [12]. Studies have
45 applied L.C.A. to rank renewable energy systems against bioenergy, nuclear power, and fossil-based
46 power systems [5], [13]. Significant environmental impacts are fossil, abiotic resource and land use,
47 global warming potential (GWP), acidification, urban smog, and eutrophication potentials. These studies
48 have also conducted social L.C.A. and economic life cycle costing [5], [14]. There are multiple
49 competing factors, such as land use for bioenergy [15], [16], health and safety risks of nuclear waste
50 disposal from decommissioning of nuclear power plants [17], power price rise from hydropower during
51 drought [18], and power supply/price instability due to renewable resource supply intermittency [19]. A
52 net zero system must mitigate such potential adverse consequences of technology on the ecosystem,
53 health, and economy. Studies have shown that incorporating storage systems to resolve supply

54 intermittency of renewable resources can result in a higher environmental footprint than fossil power
55 plants [13]. These competing factors or tradeoffs call for wide-ranging sustainability indicators of the
56 electricity sector, considering L.C.A. to benchmark and compare against future studies. Provided such
57 default or standard characterizations of emerging net zero systems existed, the most influential global
58 economies wishing to demonstrate their compliance could lay down specific transitioning pathways in
59 their policy directives. Therefore, energy legislation and regulations must provide default sustainability
60 characterizations of de-fossilized clean energy systems to avoid a disproportionate administrative burden
61 on energy system operators [20].

62 The world must have a consensus approach and appropriate measures for developed economies to allow
63 developing countries to grow within planetary boundaries socio-economically. Nine planetary
64 boundaries signpost absolute sustainability [21], [22]. Two of them, biodiversity loss and nutrient flows,
65 exceed the safe operation of the earth system. The food system primarily influences these two planetary
66 boundaries [23]. However, an in-depth, comprehensive L.C.A. can show energy systems impacting these
67 planetary boundaries due to intrinsic interactions between systems [13] and the fundamental energy-
68 food-water and wider nexus [23], [24]. As the primary means to energy and nexus provisions, the
69 electricity sector must attain a net zero as a priority for global economies [25]. The decarbonization
70 target is more imminent in developed countries. The most significant economies have a 90% share of
71 the GHG impact globally [2], [26]. These countries must achieve decarbonization of sectors, a paradigm
72 shift in behavior, and building energy efficiency to reduce demand and carbon capture and sequestration
73 [27]. Net zero's in developed countries can allow developing countries to grow economically equitably
74 with developed economies (the United Nations Sustainable Development Goal 10, reduced inequalities).
75 Also, protecting the health of humans and the environment in developing nations is the greatest challenge
76 to sustainability [28], often overlooked in GHG analysis-focused studies [29], [30] or studies with fewer
77 than necessary competing tradeoffs [31], [32]. To overcome such obstacles, whole system holistic
78 L.C.A. is imperative to apply for *net zero electricity* (NZE) across developed and developing countries.

Literature is very scarce on comparative L.C.A. of the electricity sector between countries. There are only two such research publications in the literature. Coupled energy system models, land use frameworks, integrated assessment models, and macro-economic models have been applied for insights into emission, energy, and economic systems in eleven global regions [33]. An optimized fractional nonlinear grey Bernoulli model has been developed to estimate renewable energy mix in other top global economies [34]. Landscape research covering more than one geographic region or system is imperative and timely to standardize these systems' characterizations for evidence-based decision-making, such as areas to pay attention to or improve through region-specific policymaking. Thus, the methodology developed to compare the top fifteen countries' electricity systems and the results generated in this study are novel and make substantial new contributions to the existing scientific knowledge.

The paper is structured as follows. The top fifteen global economies and the LCA-based methodology developed are discussed in the following section. The novel method consists of interacting and complementary *life cycle environmental impact assessment* (L.C.I.A.), *life cycle environmental price analysis* (E.P.A.), and *soil organic carbon sequestration analysis* (S.O.C.). Comprehensive L.C.A. results between technologies and countries are then discussed before concluding the study.

Methodology

This section has four subsections 1) identification of the top global economies, 2) L.C.I.A., 3) E.P.A., and 4) S.O.C. as follows.

Identification of top powerful global economies

The most significant economies have a 90% share of GHG from the electricity sector globally [2], [26]. So, the top economies must move away from fossil-dominated electricity generation. These countries must follow clean electricity transitioning pathways. The countries with the highest gross domestic products (G.D.P.) through to 2050 are identified, as shown in Table 1. These countries are India, Indonesia, China, Japan, Russia, Germany, U.S.A., U.K., Italy, Spain, Brazil, Canada, and France. Turkey and Mexico are selected as two more countries with a similar G.D.P., G.D.P. growth potential,

104 and high primary energy consumption. Since its currency shock after the third quarter in 2018, Turkey
 105 has shown impressive G.D.P. progress [35]. Turkey is thus included in the list of top economies. Mexico
 106 has also been included as one of the top ten primary energy-consuming countries with a similar G.D.P.
 107 as the other selected countries [36], [37]. South Korea's G.D.P. is declining [38]; however, united Korea
 108 is expected to be among the top fifteen strongest economies in 2050 [39]. Because of Korea's unclear
 109 position, future studies can address united Korea's net zero roadmaps.

110 Table 1. List of the top global economies with the highest G.D.P. identified from [2] and [26].

Countries with the highest G.D.P. in 2019	Countries with the highest G.D.P. in 2050	Highest primary energy- consuming countries
USA	China	China
China	USA	USA
Japan	India	India
Germany	United Kingdom	Russia
India	France	Japan
United Kingdom	Germany	Canada
France	Russia	Germany
Italy	Indonesia	South Korea
Brazil	Japan	Brazil
Canada	Spain	Mexico

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112 ***Life cycle environmental impact assessment (L.C.I.A.)***

113 L.C.A. is a powerful methodology for analyzing the environmental impacts of a product or service in a
 114 change-oriented model [40]. It applies fundamental systemic interdependencies to assess the
 115 consequences of a change in a system on other systems. LCA based on the ISO14040-44 [41], [42], [43],
 116 [44], [45] is conducted in four interactive stages, goal and scope definition, inventory analysis, impact

117 assessment and interpretation [40]. Although L.C.A. is the most comprehensive and holistic
118 methodology for robust strategic planning and policymaking to date [40], the roadmap studies to NZE
119 are yet to use the methodology, as seen in the roadmap studies [46], [47]. Thus, for the first time, this
120 paper applies L.C.A. based on a novel integrated framework to evaluate a roadmap to NZE in top global
121 economies.

122 The first stage of the four interactive stages of L.C.A. is the goal and scope definition. In the goal and
123 scope definition, objectives and system boundaries are defined. Life cycle inventory databases are
124 examined and selected. Potential impact characterizations for the studied system are identified. This
125 study analyzes and compares L.C.I.A., E.P.A. and S.O.C. between energy technologies and the
126 electricity mixes for net zero GHG in the top fifteen global economies. This study conducts L.C.A. of
127 renewable and bioenergy systems in the top fifteen global economies identified in Table 1. A bottom-up
128 analysis starts with collecting life cycle inventory data (Ecoinvent 3.0) in a change-oriented model. This
129 study identifies the electricity mixes in the countries and life cycle impact characterizations of the
130 technologies in change-oriented scenarios relevant for NZE within the supply-demand constraints. 1
131 kWh of electricity output from each type of energy system and 1 kWh of electricity mix of each chosen
132 country forms the basis (functional unit) for this comprehensive comparative L.C.A. study. The results
133 table's final summary presents the multidimensional environmental impact assessments for 1 G.J.
134 electricity output from the various energy systems under change-oriented NZE scenarios. Figure 1 shows
135 the novel integrated LCA-based methodology developed and applied in this study. The LCIA methods
136 applied are ReCiPe Midpoint (M) Hierarchist (H) [40], [48] and Impact 2002+ damage weighting [49].
137 Furthermore, the E.P.A. using the Environmental Prices v1 weighted costing of characterization [50]
138 and the S.O.C. [51], [52] are applied for more holistic analyses, discussed in the latter two sub-sections.
139 The ReCiPe (M) (H) and the Impact 2002+ damage weighting methods, which are focused on L.C.I.A.,
140 are discussed in this sub-section.

Figure 1. Integrated framework with L.C.I.A., E.P.A., and S.O.C.

Inventory analysis involves acquiring appropriate inventory data for each system under consideration from a standard life cycle inventory database. In this study, Ecoinvent 3.0 has been the primary source of inventory database for the functional units (1 kWh or 1 G.J. of electricity output from each type of energy system and 1 kWh of electricity mix of each chosen country). The L.C.I.A. and the Environmental Prices v1 [50] have been analyzed using SimaPro 9. Amongst the top fifteen global economies, India, China, Canada, the U.S.A., and Brazil have granular life cycle inventory data at zonal or supplier levels. Otherwise, for all other countries, life cycle inventory data on energy systems relevant for NZE are collected at the country level for the L.C.A. The technology and life cycle inventory choices made for the L.C.A. are shown in Table 2. This dataset includes underlying activities from raw material acquisition through electricity generation to transmission into high voltage networks over aerial lines and cables. Thus, the activities are electricity self-generation within a given country, infrastructure life cycles including transmission, operation, maintenance, transmission loss, direct atmospheric emissions such as ozone and nitrous oxides, etc. Different technology bases or assumptions are shown in Table 2.

Table 2. Renewable and bioenergy technology for NZE.

Name	Ecoinvent 3.0 consequential life cycle inventory database
Hydro run-of-river	<p>Electricity, high voltage {COUNTRY-CODE} electricity production, hydro, run-of-river</p> <p>These are hydropower plants without reservoirs. More commonly than high or medium pressure systems, the dataset includes low-pressure systems (including river power stations and canal power plants). The dataset also contains alpine run power stations. The structural part of the overall system (including cement, reinforcing steel, electricity, transportation, etc.) has a life of around 80 years, while the rest of the materials has a life span of 40 years. The inventories are estimated based on an annual net electricity output is 15484 GWh. A modern hydro run-of-river system has 88% energy efficiency.</p>
Hydro reservoir	<p>Electricity, high voltage {COUNTRY-CODE} electricity production, hydro, reservoir, region</p> <p>The inventories are estimated based on annual gross production output of 17.8 TWh and an installed capacity of 9130 MW. The lifetime is 150 years for the dam and 80 years for the rest of the materials. A modern system has 91% energy efficiency.</p>
Wind turbine 1-3MW	<p>Electricity, high voltage {COUNTRY-CODE} electricity production, wind, 1-3MW turbine, onshore</p> <p>This dataset represents the production of high voltage electricity at grid-connected onshore wind power plants (2MW) in {COUNTRY-CODE}. It includes operation and maintenance as well as infrastructure inputs. Wind load hours have been adapted to local conditions. A modern system has 93% energy efficiency.</p>

Wind turbine >3MW	Electricity, high voltage {COUNTRY-CODE} electricity production, wind, >3MW turbine, onshore This dataset represents the production of high voltage electricity at grid-connected onshore wind power plants (4.5 MW) in {COUNTRY-CODE}. It includes operation and maintenance as well as infrastructure inputs. Wind load hours have been adapted to local conditions. A modern system has 93% energy efficiency.
Solar photovoltaic 20 M.W.	Electricity, high voltage {COUNTRY-CODE} electricity production, solar tower power plant, 20 M.W. The dataset includes the generation of high voltage electricity with a 20 M.W. concentrated solar tower plant of a lifetime of 30 years. Local irradiance has been adjusted to local conditions.
Solar photovoltaic 50 M.W.	1 kWh Electricity, high voltage {COUNTRY-CODE} electricity production, solar thermal parabolic trough, 50 M.W. The dataset includes the generation of high voltage electricity with a 50 M.W. concentrated solar tower plant of a lifetime of 30 years. Local irradiance has been adjusted to local conditions.
Geothermal	Electricity, high voltage {Global} electricity production, deep geothermal
Bioenergy	Electricity, high voltage {Global} electricity production, wood, future This dataset co-generation system with a capacity of 6667 kW using wood chips. The overall efficiency is 60%, while the electricity generation efficiency is 35%.

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158 Among the technologies shown in Table 2, bioenergy and geothermal have a global Ecoinvent 3.0
159 inventory dataset. For the other six technologies in Table 2, Ecoinvent 3.0 inventory datasets calibrate
160 to local conditions. Thus, there are six (technologies) times fifteen (countries) or ninety datasets

161 assimilated from Ecoinvent 3.0. These datasets include the list of activities and their amounts,
 162 contributions, and impact values in each impact category. Furthermore, for each technology in each
 163 country, there are several impact categories under consideration, as shown in Figure 1.
 164 Various L.C.I.A. methods, I.L.C.D. for Europe, T.R.A.C.I. for the U.S.A., CML by Netherlands, and
 165 ReCiPe in the present context etc., suggest over ten life cycle impact categories for evaluation. Each
 166 method gives its own set of values of characterization factors to apply to individual pollutant
 167 inventories to estimate the total impact value in a category. The I.P.C.C. (Intergovernmental Panel
 168 on Climate Change) gives global warming potential characterization factors of unique greenhouse
 169 gas types - these have the worldwide consensus and hence been applied across all the L.C.I.A.
 170 methods. Amongst these L.C.I.A. methods, ReCiPe has global relevance. The Impact 2002+ L.C.I.A.
 171 method is also considered as it complements the ReCiPe L.C.I.A. method, while both make up the
 172 emerging Product Environmental Footprint method. The ReCiPe L.C.I.A. method evaluations can be
 173 monetized using Environmental Prices v1 analysis. Thus, ReCiPe, Impact 2002+ and Environmental
 174 Prices v1 are applied to the life cycle inventory databases sourced from Ecoinvent 3.0.
 175 There are ten ReCiPe (M) (H) impact characterizations, five Impact 2002+ damage categories, and
 176 fifteen Environmental Prices v1 weighted costs of environmental characterizations calculated for each
 177 technology in each country or zone. These datasets organize hotspots (with the highest contribution) in
 178 each impact category for each technology in each country or zone. A sample data for GWP of fifteen
 179 countries' electricity mixes, bioenergy and geothermal (global), and six renewable energy systems in the
 180 rest of the world is exemplified in the Supplementary Information. These granular data are then
 181 aggregated in various ways for transferable results for use in future research, e.g., by calculating global
 182 means, ranges, weighted characterizations, normalized damage categories, and weighted environmental
 183 costs, etc.
 184 The section on results and discussions presents the mean global impacts of the technologies under
 185 consideration (Table 2). Further granularity in data exists, e.g., for the hydro reservoir, Alpine and non-

Alpine regions' inventory datasets represent the range in the impacts. The GWP ranges of the technologies are compared against previously published results. Variations in GWP and land use impact characterizations between countries in the considered NZE scenario are illustrated. Furthermore, the current GWP of the electricity sector in the various countries is established [53]. Percentage decarbonization potentials of the different countries in the change-oriented NZE scenarios from the current GWP of the electricity sector are calculated.

Life cycle impact characterizations and proportion of electricity generation by each energy technology type under each country's resource class in each zone or supplier (where applicable) are analyzed. The product of the life cycle impact characterization and the proportion of electricity generation is the impact characterization by the technology type, under the resource class, in the region, in the country.

Amongst numerous life cycle impact categories, as shown in Figure 1, the most important one for the electricity service is GWP over 100 years in kg CO₂ equivalent. Also, the land use in m² crop equivalent by the ReCiPe (M) (H) method is of global interest. As shown in Figure 1, the other impact characterizations that can differentiate performances between energy systems of choice are also considered. The ReCiPe (M) (H) method has a global consensus, as often applied in scientific models [40]. The ReCiPe (M) (H) method is usually recommended as the default globally relevant L.C.I.A. method. Also, the overall environmental damage assessments recommended by the Impact 2002+ [54], [55] are used for ranking the chosen electricity generation technologies in Table 2. The results can be examined for consistency and robustness by applying the ReCiPe (M) (H) and the Impact 2002+ methods. The damage categories in the Impact 2002+ method are resource depletion, ecosystem quality, and human health, in addition to climate change. The units of GWP, resource depletion, ecosystem quality, and human health are mass (kg) of carbon dioxide equivalent (eq), M.J. of primary fossil resources, potentially disappeared fraction (PDF×m²×year) and disability-adjusted life years (D.A.L.Y.), respectively, for a given functional unit [49]. These damage consequences can be weighted for overall damage, represented concerning damage caused by an average person in Europe in one year

211 (1 Pt). ISO14040-44 recommends presenting multidimensional L.C.I.A. results for tradeoff analysis. In
 212 addition, this study also shows weighted scores or ranks between the technologies and between
 213 electricity mixes of the countries.
 214 The electricity mix data for the top fifteen economies in the change-oriented NZE scenarios collated
 215 from Ecoinvent 3.0 are shown in Figure 2. Table 3 also shows the proportions of less than 1% of the
 216 electricity mix (applicable to India, China, France, and the U.K.) obtained from Ecoinvent 3.0. Such low
 217 proportions are not accessible from Figure 2. Geothermal is an emerging technology with less than 1%
 218 proportion in the electricity mix in the countries. For France, both the hydro run-of-river and hydro
 219 reservoir technologies are emerging with less than 1% proportion in the electricity mix.

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Figure 2. Territorial electricity mix in the top fifteen global economies in consequential life cycle inventory (change-oriented NZE scenarios).

Table 3. Electricity mix in India, China, France, and the U.K.

Power technology	India	China	France	UK
Coal	0.6607	0.4467		

Gas	0.1117	0.1271		
Wind >3MW	0.0697	0.1331	0.6220	0.1807
Wind 1-3MW			0.2185	0.2445
Hydro reservoir	0.0645		0.0010	
Nuclear	0.0551	0.1815		0.2959
Bioenergy	0.0198	0.0275	0.1323	0.2771
Hydro run-of-river	0.0088	0.0808	0.0053	
Oil	0.0075			
Solar 50 MW	0.0008	0.0022		
Solar 20 MW	0.0008	0.0022		
Geothermal	0.0005	0.0008	0.0209	0.0017

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232 *Life cycle environmental price analysis (E.P.A.)*

233 The Environmental Prices v1 [50] is a systemic method applied for weighted costing of environmental
234 impact characterizations of the ReCiPe (M) (H) method into a single cost of a system on the environment,
235 as shown in Figure 1. The Environmental Prices v1 is a method for expressing environmental impacts
236 in the monetary unit. The characterization step is based on the ReCiPe (M) (H) method and is compatible
237 with the L.C.A. results presented. The environmental prices are assigned to the impact characterizations
238 except for natural land transformation and water, metal, and fossil depletion of the ReCiPe (M) (H)
239 method. The methodology uses characterizations based on EU28 [50]. The technique applies weights
240 shown in Table 4 to the various impact characterizations of the ReCiPe (M) (H) method to normalize
241 them into a single score in terms of a monetary cost. This step is a valuation step, as shown in Figure 1.
242 A single score to individual technologies allows a comparison between the various technologies. The
243 greater the monetary cost of technology, the higher is its damage to the environment. Thus, the countries'
244 electricity mixes can be compared in terms of monetary damages on the environment, in \$/kWh or \$/G.J.
245 A similar comparison can be performed between technologies, shown in Table 2. The Environmental
246 Prices v1 method is in synergy with the various life cycle impact characterizations available in SimaPro
247 9. Thus, the scenarios created in SimaPro 9 can be run with the Environmental Prices v1 method to
248 convert environmental impact characterizations into corresponding environmental monetary costs
249 applying the weights shown in Table 4. Every effort has been made in this study to present individual

250 characterization results. However, the normalization and valuation methods such as the Environmental
 251 Prices v1 method can complement the L.C.I.A. results. They compare between systems for a functional
 252 unit (1 kWh or 1 G.J.).

253 Table 4. European Environmental Prices weights for the impact characterizations (EURO per unit
 254 characterization) [50].

Impact characterization	Environmental Price (EURO per unit characterization)
Climate change	0.0566
Ozone depletion	123
Terrestrial acidification	7.48
Freshwater eutrophication	1.86
Marine eutrophication	3.11
Human toxicity	0.0894
Photochemical oxidant formation	1.15
Particulate matter formation	39.2
Terrestrial ecotoxicity	8.69
Freshwater ecotoxicity	0.0361
Marine ecotoxicity	0.00739
Ionising radiation	0.0461
Agricultural land occupation	0.126
Urban land occupation	0.126

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256 ***Soil organic carbon sequestration analysis (S.O.C.)***

257 The land requirement for GHG capture and sequestration has been conducted for 1 kWh electricity mix
 258 of the countries under consideration (Table 1) and for 1 kWh electricity from energy systems (Table 2)
 259 under change-oriented scenarios to achieve NZE in each case. While there are *integrated biorefinery*
 260 *with carbon capture and storage* (B.E.C.C.S.) technologies [40], [56], this study is solely considering
 261 S.O.C. for neutralizing GHG resulting from electricity generation systems. The potential of soil carbon
 262 sequestration by crops has also been estimated in the literature. The results are given in kg C per Ha as
 263 follows: sugarcane (1102), sugar beet (692), cassava (503), rice (401), corn (292), wheat (272), potato
 264 (270), barley (247), rye (220), cotton (170), soybean (153), rapeseed (144), oat (138), sorghum (133)
 265 and millet (71) [51]. This range of soil carbon sequestration by crops (1102-71) is equivalent to 4040-
 266 260 kg CO₂ removal per Ha. The forest carbon sequestration is estimated at 280 kg CO₂ per Ha [52].

267 These factors, 4040-260 kg CO₂ removal per Ha by crops and 280 kg CO₂ per Ha by forest, form the
268 basis to estimate the land requirement to neutralize GHG for NZE.

269 **Results and discussions**

270 This section has four subsections analyzing the L.C.I.A., E.P.A., and S.O.C. results and summary results.
271 These analyses are conducted for both the electricity mixes of the countries (Figure 2 and Table 3) and
272 the energy systems (Table 2).

273 *L.C.I.A. results*

274 The technologies of choice for NZE, as shown in Table 2, are analyzed for L.C.A. using the ReCiPe (M)
275 (H) and the Impact 2002+ damage categories. The results of the two methods in terms of mean impact
276 characterization values are shown in Table 5 and Figure 3. The GWP impacts results of the technologies
277 are compared against the previous study [5], which shows the following GWP in kg CO₂ equivalent per
278 kWh as follows: hydro: 0.004, wind: 0.021, bioenergy: 0.062, geothermal: 0.068, and solar: 0.076.

279 The technologies are organized in increasing GWP from left to right in Table 5. In the increasing order
280 of GWP, these are hydro run-of-river, wind 1-3MW, hydro reservoir, wind >3MW, bioenergy, solar 20
281 M.W., solar 50 M.W. and geothermal, respectively. Their ranking from the most to the least preferred
282 land use is the hydro reservoir, hydro run-of-river, wind >3MW, wind 1-3MW, geothermal, solar 50
283 M.W., solar 20 M.W., and bioenergy. Furthermore, there are variations (minimum-maximum) in the
284 mean GWP and land use impact characterizations (Table 5), as follows:

- 285 • hydro run-of-river (GWP: 0.0052-0.0064 kg CO₂ equivalent; land use: 0.0003-0.003 m²a crop
286 equivalent)
- 287 • wind 1-3MW (GWP: 0.012-0.13 kg CO₂ equivalent; land use: 0.0007-0.009 m²a crop equivalent)
- 288 • hydro reservoir (GWP: 0.007-0.082 kg CO₂ equivalent; land use: 0.00028-0.00035 m²a crop
289 equivalent)
- 290 • wind >3MW (GWP: 0.007-0.082 kg CO₂ equivalent; land use: 0.022-0.045 m²a crop equivalent)

291 These reinstate the need for the consideration of local level characterizations of the technologies.

292 Notably, the deemed impact characterizations are ionising radiation, terrestrial ecotoxicity, human
293 toxicity, freshwater ecotoxicity, fossil resource scarcity and water consumption. Because these impact
294 characterizations differ substantially from one technology to another.

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296 Table 5. ReCiPe (M) (H) characterizations per kWh of the technologies in Table 2. (eq: equivalent, 1,4-DCB: 1,4-Dichlorobenzene, PM: particulate
297 matter, Bq: Becquerel, C.F.C.: chlorofluorocarbon).

Impact category (ReCiPe (M) (H))	Unit per kWh	Hydro run- of-river	Wind 1- 3MW	Hydro reservoir	Wind >3MW	Bioenergy	Solar 20 M.W.	Solar 50 M.W.	Geothermal
Water consumption	m ³	0.000050	0.000233	0.029291	0.000331	0.000147	0.000294	0.000388	0.000410
Fossil resource scarcity	kg oil eq	0.001096	0.006857	0.001265	0.008217	0.011205	0.015353	0.016851	0.018669
Mineral resource scarcity	kg Cu eq	0.000115	0.001033	0.000121	0.001283	0.000486	0.000820	0.000801	0.000920
Land use	m ² a crop eq	0.000340	0.001665	0.000288	0.001565	0.436052	0.006945	0.005773	0.002241
Human non-carcinogenic toxicity	kg 1,4-DCB eq	0.003916	0.072447	0.005726	0.390593	0.227551	0.030599	0.036397	0.083243
Human carcinogenic toxicity	kg 1,4-DCB eq	0.000505	0.004842	0.000487	0.006266	0.002365	0.003339	0.002465	0.005086
Marine ecotoxicity	kg 1,4-DCB eq	0.000277	0.013317	0.000312	0.089891	0.003617	0.003908	0.004403	0.003705
Freshwater ecotoxicity	kg 1,4-DCB eq	0.000210	0.010810	0.000230	0.073607	0.002282	0.003087	0.003504	0.002807
Terrestrial ecotoxicity	kg 1,4-DCB eq	0.023321	0.328365	0.030637	1.436297	0.969987	0.158329	0.151834	0.142040
Marine eutrophication	kg N eq	1.32E-07	1.69E-06	1.32E-07	2.70E-06	1.06E-06	1.07E-06	2.08E-06	3.11E-06
Freshwater eutrophication	kg P eq	1.78E-06	1.51E-05	2.11E-06	4.84E-05	1.06E-05	9.43E-06	1.10E-05	4.56E-05
Terrestrial acidification	kg SO ₂ eq	1.43E-05	7.74E-05	1.63E-05	1.42E-04	7.63E-04	1.32E-04	1.38E-04	1.95E-04
Ozone formation, Terrestrial ecosystems	kg NO _x eq	1.87E-05	7.47E-05	2.06E-05	1.16E-04	9.97E-04	7.92E-05	1.50E-04	1.47E-04
Fine particulate matter formation	kg PM _{2.5} eq	1.18E-05	5.67E-05	1.25E-05	9.11E-05	2.44E-04	6.26E-05	6.85E-05	1.78E-04
Ozone formation, Human health	kg NO _x eq	1.80E-05	7.00E-05	1.99E-05	1.10E-04	9.83E-04	7.48E-05	1.45E-04	1.42E-04
Ionizing radiation	kBq Co-60 eq	-7.37E-07	-3.70E-05	7.30E-05	1.78E-04	-4.40E-05	-2.54E-04	-2.70E-04	4.51E-03
Stratospheric ozone depletion	kg CFC11 eq	1.44E-09	9.65E-09	3.99E-09	1.84E-08	2.71E-07	8.07E-09	3.67E-08	2.00E-08
Global warming	kg CO ₂ eq	0.005351	0.026539	0.027984	0.034379	0.043509	0.050196	0.055027	0.071948

298

299

300 Figure 3 shows the overall ranking of the technologies applying the Impact 2002+ weighting method of
 301 the damage categories. Once again, mean values of the damage categories of the technologies (Table 2)
 302 across the world are presented in Figure 3. The damage categories are ecosystem quality, human health,
 303 climate change, and resources. Weightings are applied for aggregated damage categories, and the total
 304 weighted damage can be helpful to compare between systems. The unit of weighted damage is then
 305 presented as 'Point' or 'Pt', where 1 Pt is the damage caused by an average person in Europe in one year.
 306 Applying this method, although the ranking of the technologies under consideration (Table 2) remains
 307 the same for climate change, their overall order differs. The highest to the least priority options are as
 308 follows (measured in μ Pt per kWh electricity output): hydro run-of-river (2.1), hydro reservoir (2.5),
 309 wind 1-3MW (10.7), solar 20MW (16.3), solar 50MW (18.2), wind >3MW (18.5), geothermal (55.7)
 310 and bioenergy (88).

311
 312 Figure 3. Impact 2002+ weighted damage categories in μ Pt per kWh of the technologies in Table 2.
 313 Bioenergy has the highest impact on ecosystem quality, a measure of deforestation, ecosystem
 314 restoration, and biodiversity. B.E.C.C.S. instead of bioenergy is an ecosystem impact mitigating
 315 intervention, albeit at a higher initial investment cost [45], [56].

316 Next, comparisons of GWP and land use between the top global economies for 1 kWh electricity mix
317 are illustrated in Figure 4. The comparisons are based on the Ecoinvent 3.0 life cycle inventory analyses:
318 “Electricity, high voltage {COUNTRY-CODE} | market ... | Consequential”.

319

320

321 Figure 4. Comparisons of GWP (top) and land use (bottom) between the top global economies for 1
322 kWh electricity mix.

323 GWP of greater than 0.2 kg CO₂ equivalent per kWh for countries, India, China, Indonesia, Mexico,
324 Turkey, Canada, and Russia, results from a higher proportion of fossil in the electricity mix than other

325 countries. Land use of greater than 0.03 m² crop equivalent can be explained by a higher proportion of
 326 bioenergy in the electricity mixes in the case of the U.K., Italy, France, and Spain. Notably, Japan's
 327 primary electricity contributor is nuclear, and the U.K. has a substantial proportion of nuclear in the
 328 electricity mix that leaves questions around the safety of waste disposal. A switch from primarily nuclear
 329 (75% in electricity mix) to renewable electricity in France is notable [57].

330 Percentage decarbonization potentials of the different countries in the change-oriented NZE scenarios
 331 from the current GWP of the electricity sector are calculated as follows. The electricity sector accounts
 332 for 38% of energy-related GHG [47]. By applying this factor to an individual country's present GHG
 333 emissions and dividing it by the country's current electricity consumption [53], the country's current
 334 GWP in kg CO₂ equivalent per kWh is obtained. The current GWP is a helpful way to compare against
 335 NZE (Figure 4 (top)) and show decarbonization potential to achieve NZE from the current levels. Figure
 336 5 shows ten countries' percentage decarbonization potential from their present GHG levels on the current
 337 annual GHG versus electricity consumption plot. With 3753 and 878 Gt CO₂ equivalent from 7154 and
 338 1349 TWh electricity consumptions [53], China and India have no improvement potentials when their
 339 current GHG levels and NZE are compared. Their GWP is 0.52 and 0.65 (instead of 0.68 and 1.17 in
 340 Figure 4) kg CO₂ equivalent/kWh calculated using the above techniques from [53]. These two countries
 341 have moved to higher non-fossil renewable proportions in their energy mixes to hit NZE by 2060 and
 342 2070 [58] since the published Ecoinvent 3.0 data. With 1803, 623, and 401 Gt CO₂ equivalent from
 343 4187, 1004, and 1000 TWh electricity consumptions [53], the U.S.A., Russia, and Japan have 63%, 61%,
 344 and 95% decarbonization potential to achieve NZE, also not shown in Figure 5 to avoid overlaps between
 345 bubbles. The developed nations have larger decarbonization targets ahead of the developing countries.
 346 Thus, it is clear that the onus of achieving NZE is with the developed economies to give a chance for
 347 developing economies to grow with de-fossilized renewable clean technologies for an equitable society.

348

349 Figure 5. Percentage decarbonization potential (shown by the size of the bubbles) from the current levels
 350 of GHG to achieve NZE in the various countries.

351 The electricity mixes in the change-oriented NZE scenario of the major global economies are analyzed
 352 using the ReCiPe (M) (H) and Impact 2002+ methods, as shown in Table 6 and Figure 6.

353

354 Table 6. ReCiPe (M) (H) characterizations per kWh electricity generation in the top global economies in Table 1. (eq: equivalent, 1,4-DCB: 1,4-
355 Dichlorobenzene, PM: particulate matter, Bq: Becquerel, C.F.C.: chlorofluorocarbon)

Impact category (ReCiPe (M) (H))	Unit	India	China	Indonesia	Mexico	Turkey	Canada	Russia
Global warming	kg CO ₂ eq	1.171554	0.684530	0.562530	0.490164	0.485880	0.243822	0.236883
Stratospheric ozone depletion	kg CFC11 eq	3.33E-07	1.89E-07	1.84E-07	6.78E-07	1.66E-07	1.60E-07	6.58E-07
Ionizing radiation	kBq Co-60 eq	0.042047	0.127322	0.053633	0.053563	0.053571	-0.000016	0.278305
Ozone formation, Human health	kg NO _x eq	0.002511	0.001765	0.000987	0.000625	0.000718	0.000336	0.000428
Fine particulate matter formation	kg PM2.5 eq	0.002828	0.000978	0.007213	0.001981	0.004662	0.000147	0.000600
Ozone formation, Terrestrial ecosystems	kg NO _x eq	0.002534	0.001774	0.001002	0.000638	0.000731	0.000347	0.000437
Terrestrial acidification	kg SO ₂ eq	0.003551	0.002134	0.001153	0.001380	0.002044	0.000422	0.000825
Freshwater eutrophication	kg P eq	0.000909	0.000125	0.000568	0.000476	0.000513	0.000013	0.000124
Marine eutrophication	kg N eq	0.000056	0.000010	0.000036	0.000030	0.000033	0.000001	0.000013
Terrestrial ecotoxicity	kg 1,4-DCB eq	0.888882	0.661868	0.179769	0.165364	0.168960	0.378131	0.234556
Freshwater ecotoxicity	kg 1,4-DCB eq	0.034150	0.019697	0.015229	0.012932	0.013833	0.015787	0.005615
Marine ecotoxicity	kg 1,4-DCB eq	0.046067	0.025094	0.020914	0.017748	0.018986	0.019345	0.007513
Human carcinogenic toxicity	kg 1,4-DCB eq	0.059220	0.017515	0.027866	0.023447	0.025229	0.002091	0.008170
Human non-carcinogenic toxicity	kg 1,4-DCB eq	1.304247	0.367504	0.592289	0.500319	0.536664	0.096688	0.194518
Land use	m ² a crop eq	0.022798	0.020296	0.007989	0.007962	0.007941	0.022855	0.016998
Mineral resource scarcity	kg Cu eq	0.000518	0.000636	0.000247	0.000246	0.000233	0.000427	0.000496
Fossil resource scarcity	kg oil eq	0.312363	0.148132	0.171577	0.145197	0.146396	0.090742	0.068827
Water consumption	m ³	0.004407	0.002301	0.001938	0.001793	0.001736	0.002194	0.003046

356

Impact category (ReCiPe (M) (H))	Unit	Italy	U.S.A.	Germany	Brazil	Spain	France	UK	Japan
Global warming	kg CO ₂ eq	0.179898	0.157779	0.135691	0.071311	0.043250	0.034265	0.028320	0.019194
Stratospheric ozone depletion	kg CFC11 eq	1.82E-07	1.11E-07	1.13E-07	8.41E-08	1.06E-07	1.07E-07	1.51E-07	1.03E-07
Ionizing radiation	kBq Co-60 eq	0.000097	-0.001298	0.000239	0.042336	-0.000012	0.000137	0.211928	0.542464
Ozone formation, Human health	kg NO _x eq	0.000367	0.000154	0.000181	0.000111	0.000209	0.000216	0.000325	0.000105
Fine particulate matter formation	kg PM2.5 eq	0.000132	0.000074	0.000113	0.000059	0.000095	0.000103	0.000108	0.000058

Ozone formation, Terrestrial ecosystems	kg NO _x eq	0.000378	0.000163	0.000189	0.000114	0.000215	0.000222	0.000331	0.000108
Terrestrial acidification	kg SO ₂ eq	0.000327	0.000189	0.000234	0.000110	0.000207	0.000213	0.000275	0.000097
Freshwater eutrophication	kg P eq	0.000029	0.000019	0.000035	0.000020	0.000026	0.000033	0.000015	0.000012
Marine eutrophication	kg N eq	0.000002	0.000001	0.000002	0.000002	0.000002	0.000002	0.000005	0.000010
Terrestrial ecotoxicity	kg 1,4-DCB eq	0.949970	0.651445	1.053148	0.620882	0.810304	1.039487	0.653447	0.376003
Freshwater ecotoxicity	kg 1,4-DCB eq	0.039547	0.032774	0.050731	0.027920	0.034401	0.044758	0.013847	0.007673
Marine ecotoxicity	kg 1,4-DCB eq	0.048506	0.040003	0.062086	0.034151	0.042143	0.054764	0.017234	0.009592
Human carcinogenic toxicity	kg 1,4-DCB eq	0.004093	0.003092	0.005013	0.002917	0.004191	0.004780	0.003033	0.002346
Human non-carcinogenic toxicity	kg 1,4-DCB eq	0.244761	0.170332	0.267924	0.162056	0.206899	0.266548	0.168615	0.122451
Land use	m ² a crop eq	0.080303	0.000799	0.001325	0.023397	0.053926	0.060631	0.125629	0.026110
Mineral resource scarcity	kg Cu eq	0.000846	0.000675	0.001034	0.000636	0.000944	0.000990	0.000743	0.000759
Fossil resource scarcity	kg oil eq	0.062107	0.053794	0.047612	0.004856	0.011540	0.007964	0.006718	0.004549
Water consumption	m ³	0.001218	0.001099	0.000505	0.019316	0.000545	0.000305	0.001113	0.002787

357

358

359 In addition to GWP and land use, sixteen other mid-point impact characterizations can be examined.
 360 Sensitive impact characterizations are shaded in Table 6. Ionisation radiation is high in Japan, Russia,
 361 the U.K., and China, owing to a high proportion of nuclear in their electricity mix (>18%). Solar in
 362 Spain, and wind and hydro run-of-river in the U.S.A. and Canada help lower ionising radiation impact
 363 from their electricity mixes. Terrestrial ecotoxicity is high for wind >3MW and bioenergy, causing a
 364 higher level of hits in the countries with these systems in their electricity mix. Particulate emissions,
 365 human toxicity and primary energy resource depletion result from fossil use in the electricity mix in the
 366 cases of India, China, Indonesia, Mexico, and Turkey. For Brazil, water consumption is the highest due
 367 to the hydro reservoir's increased share in the electricity mix. Hydroelectricity in Brazil caused electricity
 368 price volatility due to drought [59], [60]. The bioenergy system influences land use impact, as discussed
 369 earlier. The L.C.A. considering multidimensionality beyond GWP is thus proved to be deemed necessary
 370 for tradeoff analysis for sustainable transitioning.

371
 372 Figure 6. Impact 2002+ weighted damage categories in μPt per kWh electricity generation in the top
 373 global economies in Table 1.

Figure 6 shows the Impact 2002+ weighted damage categories in μPt (Pt is overall damage on the environment by an average person in Europe in a year) per kWh electricity generation in the top global economies in Table 1. The human health damage category influences the L.C.I.A. of the electricity sector in Indonesia, Turkey, India, Mexico, China, and Russia. These countries are reliant on gas for electricity. India and Indonesia, with per capita Gross National Income (G.N.I.) of \$1006-3955 belong to the Lower Middle-Income Countries and Territories [61]. Turkey, Mexico, and Brazil, with per capita G.N.I. of \$3956-12235, also fall under the Upper Middle-Income Countries and Territories [61]. Prioritizing human health in driving decisions and policymaking should help the developing countries sustain transitioning into NZE.

Without accounting for human health in Figure 6, the ranking of the top global economies using the Impact 2002+ weighted damage method is quite like that resulted using the ReCiPe (M) (H) method. Considering a more holistic approach, the U.K. and Japan would be placed close to Italy, attributed to their higher proportion of bioenergy and/or nuclear in the electricity mix. For sustainable transitioning for these countries, thus, nuclear should not be a priority option in NZE. Bioenergy should be considered with caution regarding land management to support biodiversity, forestation, and ecosystem services [62]. The environmental damage consequences of the Impact 2002+ method can be shown in decreasing order of $\mu\text{Pt}/\text{kWh}$ for the countries: Indonesia (827), Turkey (536), India (471), Mexico (285), China (226), Russia (130), Japan (84), Canada (68), Italy (61), the U.K. (60), the U.S.A. (41), Germany (41), France (27), Spain (26) and Brazil (22) (Figure 6).

E.P.A. results

Figure 7 illustrates environmental cost in US\$/kWh electricity generation by the countries in increasing order from top to bottom, using the weighting factors given in Table 4. The highest environmental cost incurred by the country towards transitioning is Indonesia (US\$0.83 per kWh). The environmental costs of 1 kWh electricity mixes of the top fifteen global economies are summarized on the map of the world (Figure 8). Particulate matter formation and human toxicity are the key contributors to the environmental

399 costs for developing economies. Notably, the agricultural land occupation has the third most significant
400 attribution in the ranking of the global economies. The ranking of the countries in the order from the
401 most to the least damaging consequences (in US\$ per kWh) of their electricity mixes is: Indonesia (0.83),
402 Turkey (0.57), India (0.53), Mexico (0.3), China (0.23), Russia (0.12), the UK (0.06), Italy (0.06), Japan
403 (0.055), Canada (0.05), France (0.042), Germany (0.04), Spain (0.038), the USA (0.032) and Brazil
404 (0.03). Greater than US\$0.2/kWh damage for a country is due to the usage of fossil resources increasing
405 particulate matter formation and human toxicity. US\$(0.2-0.03)/kWh are due to the agricultural land
406 occupation, climate change, and terrestrial acidification impacts. These medium-range environmental
407 costs owe to the considerable proportions of nuclear (increasing terrestrial acidification), gas (increasing
408 climate change), and bioenergy (increasing agricultural land occupation) in the electricity mix (Figure
409 2). An environmental damage cost of less than US\$0.03/kWh is highly desirable for affordable energy
410 supplies to foster economic growth in developing countries. However, a low damage or damage cost
411 may also cause supply risks. De-fossilized technology diversification is at the heart of sustainable NZE
412 challenges to mitigate renewable supply intermittencies.

413

414 Figure 7. Environmental cost in US\$ per kWh electricity generation by the countries for transitioning to

415 NZE.

416

417 Figure 8. Costs in US\$ of environmental damages due to 1 kWh electricity generation in the top fifteen
 418 global economies studied for the change-oriented NZE scenarios.
 419 A similar environmental monetary analysis is conducted for individual technology options in Table 2
 420 and summarized in Figures 9. Figure 9 (top) is to identify the critical impact characterizations that need
 421 to be improved for sustainable transitioning. These characterizations are particulate matter formation,
 422 agricultural land occupation, human toxicity, climate change, and terrestrial acidification. Figure 9
 423 (bottom) agrees with the previous ranking for the technologies using the Impact 2002+ method in Figure
 424 3.

425

426

427 Figure 9. Environmental cost in US\$ per kWh electricity generation by technologies for transitioning to
 428 NZE. Identification of critical impact characterizations (top) and environmental costs of power
 429 technologies (bottom).

430 *S.O.C. results*

431 For the S.O.C., by taking the ratio between the GWP impact from 1 kWh electricity mix in the various
 432 countries (Table 6) and the S.O.C. range (4040-260 kg CO₂ removal per Ha [51], [52]), additional land
 433 of 0.05-45 m² would be required to neutralize residual GHG from 1 kWh electricity generation in these
 434 countries. In the same way, the renewable system options would need 0.19-2.57 m² (based on 280 kg
 435 CO₂ sequestration per Ha forest) for neutralizing GHG from 1 kWh electricity generation, lowest for
 436 hydro run-of-river highest for geothermal followed from their ranking in GWP in Table 5. Figure 10
 437 shows the land requirements to neutralize GHG from renewable systems. This land requirement is in
 438 addition to the land use by the renewable systems informed by the L.C.A., to achieve NZE. Thus,

439 neutralizing GHG for NZE (consisting of renewable and bioenergy) means additional land-use
440 implications, which can become considerable given the rising demands due to increasing population,
441 urbanization, and competition for land. However, if this other land required is devoted to supporting
442 biodiversity, forestation and ecosystem services, there will be positive steps towards reverting
443 transgressed planetary boundaries in biodiversity and nutrient loss. The scientific research community
444 thus must pay more attention to natural GHG sequestration through ecosystem quality for net zero.

445
446 Figure 10. m² required for GHG neutralization per kWh electricity output from the various energy
447 systems.

448 ***Summary of key results for benchmarking and standardization***

449 The existing regulatory body of knowledge suggests the need for evidence-based policymaking using
450 consequential L.C.A. to underpin the net zero GHG targets agenda. There is a greater depth of coverage
451 of system characterizations needed for the sustainable development of NZE. Table 7 concludes the
452 impact characterizations (global mean values per G.J.) of the electricity generation technologies for
453 sustainable transitioning to NZE. The impact characterizations include ten environmental impact

454 characterizations of the ReCiPe (M) (H) method, five damage categories of the Impact 2002+ method,
455 and fifteen weighted costings of environmental characterizations of the Environmental Prices v1 method.
456 All three ways show consistent ranking between the technologies (from the best to the least preferred):
457 hydro run-of-river, hydro reservoir, wind 1-3MW, solar 20MW, solar 50MW, wind >3MW, geothermal,
458 and bioenergy. These results are transferable to benchmark against in other studies. This study thus
459 standardizes the characterizations of renewable and bioenergy systems to benchmark and compare
460 against, for NZE. Provided such default or standard characterizations of emerging NZE existed,
461 countries wishing to demonstrate their compliance could lay down specific transitioning pathways in
462 their policy directives. Such default values can be embedded in regulations to benchmark or compare
463 against to avoid a disproportionate administrative burden on energy system operators [20]. The final
464 summary Table 7 results serve another essential purpose of informing researchers about important
465 characterizations of critical energy systems for the electricity sector transitioning to enable scalability at
466 a regional, country, or even global scale.

467

468

469 Table 7. Essential life cycle impact characterizations per G.J. electricity output for NZE.

Impact category (ReCiPe (M) (H))	Unit per G.J.	Hydro run-of-river	Hydro reservoir	Wind 1-3MW	Solar 20 M.W.	Solar 50 M.W.	Wind >3MW	Geothermal	Bioenergy
Water consumption	m ³	0.01	8.14	0.06	0.08	0.11	0.09	0.11	0.04
Fossil resource scarcity	kg oil eq	0.30	0.35	1.90	4.26	4.68	2.28	5.19	3.11
Land use	m ² a crop eq	0.09	0.08	0.46	1.93	1.60	0.43	0.62	121.13
Human non-carcinogenic toxicity	kg 1,4-DCB eq	1.09	1.59	20.12	8.50	10.11	108.50	23.12	63.21
Human carcinogenic toxicity	kg 1,4-DCB eq	0.14	0.14	1.35	0.93	0.68	1.74	1.41	0.66
Freshwater ecotoxicity	kg 1,4-DCB eq	0.06	0.06	3.00	0.86	0.97	20.45	0.78	0.63
Terrestrial ecotoxicity	kg 1,4-DCB eq	6.48	8.51	91.21	43.98	42.18	399.0	39.46	269.44
Fine particulate matter formation	kg PM2.5 eq	0.0033	0.0035	5.67E-05	0.0174	0.0190	0.0253	0.0494	0.0678
Ionizing radiation	kBq Co-60 eq	-0.0002	0.0203	-0.0103	-0.0706	-0.0749	0.0493	1.2523	-0.0122
Global warming	kg CO ₂ eq	1.49	7.77	7.37	13.94	15.29	9.55	19.99	12.09
S.O.C.									
Land for neutralizing GHG	m ² a crop eq	53.06	277.45	263.13	497.68	545.59	94.69	713.35	431.39
Damage category (Impact 2002+)									
Resources	MJ primary	14.13	8.63	84.80	191.08	210.92	106.93	261.83	142.09
Climate change	kg CO ₂ eq	1.42	4.45	6.50	13.13	14.30	8.57	18.96	10.74
Ecosystem quality	PDF*m2*yr	0.49	0.41	4.10	4.85	4.51	9.94	103.50	186.56
Human health	DALY	2.25E-06	1.15E-06	1.04E-05	1.14E-05	1.36E-05	2.02E-05	3.03E-05	6.25E-05
Weighted damage category	μPt	352	192	1756	1950	2225	3558	11833	22417
Environmental Prices v1									
Climate change	US\$	0.33	0.10	0.48	0.97	1.07	0.63	1.40	0.83
Ozone depletion	US\$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Terrestrial acidification	US\$	0.05	0.05	0.23	0.42	0.47	0.45	0.63	2.93
Freshwater eutrophication	US\$	0.00	0.00	0.01	0.01	0.01	0.03	0.03	0.02
Marine eutrophication	US\$	0.00	0.00	0.01	0.01	0.01	0.01	0.02	0.06
Human toxicity	US\$	0.09	0.08	0.94	0.54	0.62	4.45	1.92	3.90
Photochemical oxidant formation	US\$	0.01	0.02	0.08	0.09	0.15	0.12	0.15	0.84

Particulate matter formation	US\$	0.23	0.65	1.99	1.98	2.35	3.17	5.43	8.98
Terrestrial ecotoxicity	US\$	0.00	0.00	0.01	0.02	0.02	0.03	0.08	0.15
Freshwater ecotoxicity	US\$	0.01	0.00	0.09	0.03	0.03	0.62	0.02	0.01
Marine ecotoxicity	US\$	0.00	0.00	0.02	0.01	0.01	0.11	0.00	0.00
Ionising radiation	US\$	0.00	0.00	0.00	0.00	0.00	0.01	0.08	0.02
Agricultural land occupation	US\$	0.01	0.00	0.01	0.02	0.03	0.01	0.06	18.42
Urban land occupation	US\$	0.00	0.00	0.02	0.10	0.08	0.02	0.01	0.10
Total	US\$	0.73	0.91	3.90	4.18	4.84	9.68	9.84	36.28

470

471

472 The GWP per unit consequential electricity mix in the top fifteen economies with the world's highest
 473 G.D.P. or energy consumptions is analyzed. These countries in the decreasing order of GWP in kg CO₂
 474 equivalent per kWh are: India (1.17), China (0.68), Indonesia (0.56), Mexico (0.49), Turkey (0.49),
 475 Canada (0.24), Russia (0.24), the USA (0.18), Germany (0.16), Brazil (0.07), Spain (0.04), France (0.03),
 476 the UK (0.03) and Japan (0.02). Lower GWP of <0.2 kg CO₂ equivalent per kWh is desirable, however,
 477 it can be misleading owing to nuclear or bioenergy dominating electricity mix. Nuclear has concerns
 478 over waste disposal. Bioenergy should be deployed with caution to balance changing demand and supply
 479 patterns and avoid unintended consequences on land management. Higher land use >0.03 m²a crop
 480 equivalent can be explained by a higher proportion of bioenergy in the U.K., Italy, France, and Spain,
 481 compared to other countries. Drought or dry weather conditions can impact hydropower supply and
 482 price.

483 The Impact 2002+ method gives an overall ranking depending on the resources, climate change,
 484 ecosystem quality, and human health damage categories, in μ Pt/kWh (1 Pt is the environmental damage
 485 equivalent caused by an average person in Europe in a year). The overall ranking of the countries in the
 486 increasing order of damage consequences is (μ Pt/kWh): Brazil (22), Spain (26), France (27), Germany
 487 (41), the U.S.A. (41), the U.K. (60), Italy (61), Canada (68), Japan (84), Russia (130), China (226),
 488 Mexico (285), India (471), Turkey (536), and Indonesia (827). The overall ranking of the technologies
 489 following Impact 2002+ method is as follows (μ Pt/kWh): hydro run-of-river (2.1), hydro reservoir (2.5),
 490 wind 1-3MW (10.7), solar 20MW (16.3), solar 50MW (18.2), wind >3MW (18.5), geothermal (55.7)
 491 and bioenergy (88). Thus, greater than 88 μ Pt/kWh damage for a country is due to the usage of fossil
 492 resources. These individual technologies' environmental costs in increasing order in US\$/kWh are:
 493 hydro run-of-river (0.0026), hydro reservoir (0.0032), wind 1-3MW (0.14), solar 20MW (0.15), solar
 494 50MW (0.17), wind >3MW (0.035), geothermal (0.035) and bioenergy (0.13). The ranking of the
 495 countries in the increasing order of damage consequences (in US\$ per kWh) is: Brazil (0.03), USA
 496 (0.032), Spain (0.038), Germany (0.04), France (0.042), Canada (0.05), Japan (0.055), Italy (0.06), UK

497 (0.06), Russia (0.12), China (0.23), Mexico (0.3), India (0.53), Turkey (0.57), and Indonesia (0.83).
 498 Greater than US\$0.2/kWh damage for a country is due to the usage of fossil resources. An environmental
 499 damage cost of less than equal to US\$0.03/kWh is the target for global economies for transitioning to
 500 NZE. The primary characterizations influencing the overall environmental damage cost include
 501 particulate matter formation, agricultural land occupation, human toxicity, climate change, and terrestrial
 502 acidification. The overall rankings between the countries' electricity mixes by the Impact 2002+ and the
 503 Environmental Prices v1 methods are the same for Indonesia, Turkey, India, Mexico, China, Russia, and
 504 Brazil. In Impact 2002+, higher weighting is given to resource depletion. Higher weighting to resources
 505 makes Japan and Canada look worse than the U.K. and other countries. The climate impact of NZE for
 506 the U.K. is lower than Italy, owing to the high nuclear proportion in the U.K.'s electricity mix,
 507 influencing their ranking order. In Environmental Prices v1, primary fossil energy resources are assigned
 508 no weighting, and agricultural land occupation is assigned higher weighting. Amongst the NZE systems,
 509 hydropower will suffer from drought, nuclear power will have health and safety risks from nuclear waste
 510 disposal, and bioenergy will have a higher land-use impact. Intermittency in the supply of resources will
 511 be the key energy security challenge in NZE.
 512 Diversification of de-fossilized technologies will be crucial to energy affordability and security.
 513 Affordable energy will allow inclusive growth, leaving no one behind and providing electricity to 785
 514 million people without access to electricity. Notably, 14 million new jobs are estimated to be created by
 515 2030 by NZE [47]. Additional 16 million jobs for workers will come from energy-efficient measures,
 516 buildings, constructions, and electric vehicles [47]. Moving away from fossils also (>US\$0.2/kWh of
 517 damage monetization) can cause job loss in the coal, oil, and gas industry and economic shock that can
 518 be mitigated by training and resources to support new NZE. NZE opportunities like B.E.C.C.S.,
 519 including hydrogen economy, call for a similar skillset and thus can reduce job loss in the coal, oil, and
 520 gas industry [7], [12], [40]. A total annual surge of \$5trillion of investment adding 0.4 percentage point
 521 on G.D.P. will be needed on new energy systems (primarily solar and wind electricity share from 10%

522 to 70%, reducing GHG from 13.5Gt to NZE, by 2050) by 2030 [47]. Given the renewable electricity
523 supply intermittencies and price volatilities, de-fossilized energy diversification is most strategic to
524 sustainable NZE. Clean transition lags in other sectors, road, rail, air, and marine transport, requiring
525 100% decarbonization in the latter three. B.E.C.C.S. providing energy storage, hydrogen, fuels,
526 electricity, and CO₂ sinks such as forestation, soil, and biodiversity are the most powerful strategy for
527 NZE.

528 **Conclusions**

529 A novel, effective, rigorous, and holistic LCA-based methodology consisting of L.C.I.A., environmental
530 monetization, and S.O.C. has been developed and applied for sustainable net zero transitioning of the
531 electricity sector in the top global economies, Indonesia, Turkey, India, Mexico, China, Russia, the U.K.,
532 Italy, Japan, Canada, France, Germany, Spain, the U.S.A., and Brazil. The methodology has also been
533 applied at individual technology levels (hydro, wind, solar, geothermal, and bioenergy). The study has
534 taken a comprehensive bottom-up approach collating technology and regional level life cycle inventory
535 from cradle-to-cradle. Ten ReCiPe-(M)-(H), five Impact-2002+, and fifteen Environmental Prices-v1
536 characterizations are calculated for each technology and each country NZE mix. A sample data for GWP
537 of fifteen countries' electricity mixes, bioenergy and geothermal (global), and six renewable energy
538 systems in the rest of the world (without the U.S.A., the U.K., and E.U.) is given in Supplementary
539 Information. Such granular data are then aggregated in various ways for transferable results in future
540 research, e.g., by calculating global means, ranges, weighted characterizations, normalized damage
541 categories, and weighted environmental costs, etc. ReCiPe characterizes the significant environmental
542 impacts, while Impact-2002+, and Environmental Prices normalize the consequences and damage-
543 monetization. Applying the three methods in a systematic, coherent, and coordinated methodology helps
544 generate robust objective valuable results transferable to other studies. Most impactful characterizations
545 determined are GWP, ionising radiation, terrestrial and freshwater ecotoxicity, human toxicity, land use,
546 fossil resource scarcity, water consumption, particulate matter formation, and agricultural land

547 occupation. The S.O.C. finds land requirements to neutralize GHG for NZE to divert into natural CO₂
548 sinks such as forestation, biodiversity, and ecosystem quality. For sustainable net zero transitioning,
549 decarbonization potentials, technology roadmaps, and impact incentives (ecosystem, health, resources,
550 and climate) are set out.

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