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Global asymmetries in the rise of solar power: An LCA-based account of ecologically unequal exchange between Germany and China 2002–2018
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economics, which considers development and growth as biophysical processes contingent upon matter-energy throughput. From this perspective, the development of high-technological infrastructure in industrial nations should not be understood as separate from their matter-energy requirements and the global social structures influencing the geographical distribution of their social-environmental impacts (Hornborg, 2001; Hornborg et al., 2019).

The theory of ecologically unequal exchange shows great potential to explain the distribution of the burdens and the benefits of the nascent solar PV industry from a global perspective. Ecologically unequal exchange posits that the uneven distribution of human development and environmental harms occurs through unreciprocated exchange of embodied resources in international trade (Hornborg, 2009; Hornborg and Martinez-Alier, 2016; Jorgenson, 2016). Ecologically unequal exchange has been applied to demonstrate the uneven distribution of a wide range of human developments and environmental harms (Givens and Huang, 2021). So far, however, only two studies have applied this theory to measure the globally uneven distribution of the burdens and benefits of "green" technologies (Bonds and Downey, 2012; Hornborg et al., 2019). This gap is significant because renewable energy technologies are not merely commodities for consumption but also the presumed socio-metabolic foundation of future societies in the absence of fossil fuels.

The challenge of existing studies is how to empirically test the relation between ecologically unequal exchange and the development of specific "green" technologies. This study relies on a life cycle analysis (LCA) based accounting of ecologically unequal exchange to understand how an uneven flow of embodied resources between China and Germany effected Germany's prospects of installing large amounts of solar PV modules. I introduce an evaluative element to this approach through which it becomes possible to assess how a commodity's (in this case a solar PV module's) monetary price and biophysical efficiency is effected by environmental load displacement. This evaluative part consists of two measures, which I call the "displacement-adjusted price" and "displacement-based efficiency." Through these measurements it will be possible to estimate and evaluate the financial and biophysical implications of exchange in two commodities traded on the world market.

The purpose of this study is to better understand the global distributive dimension of large-scale solar PV development and the increasing metabolic reliance upon such development. The aims are to a) provide an empirically grounded assessment of environmental load displacement in trade with two focal commodities of the solar industry and b) to provide an understanding of large-scale solar PV development relevant for ecological economics. The significance of the study is that it challenges, or complements, the conventional immaterial interpretations of solar PV commercialization. Its significance also lies in build bridges between local and global perspectives on the extractivism and environmental injustices now observed throughout the supply-chain of solar technologies. Methodologically, its significance lies in further developing the LCA-based approach to ecologically unequal exchange.

The study attempts to answer and discuss the following questions:

- Was the German-Chinese trade in solar PV equipment and solar PV modules characterized by ecologically unequal exchange 2002–2018?
- How was Germany's prospects of installing large amounts of solar PV modules effected by displacement of environmental loads in the abovementioned trade?
- Based on the results, how likely is it that the continued mass-installation of solar PV technology is contingent on ecologically unequal exchange?

In the following section I describe the theory of ecologically unequal exchange and provide a description of the international relation between Germany and China. This is followed by a section in which I present the LCA-based method for measuring ecologically unequal exchange. Here I provide a scope definition, discuss the study's limitations, and present the two measures "displacement-adjusted price" and "displacement-based efficiency." I then present the results of the study and determine the presence of ecologically unequal exchange in the German-Chinese trade with solar PV modules and solar PV equipment 2002–2018. This provides an answer to the study's first research question. In the discussion I first consider Germany's solar PV module's "displacement-adjusted price" and "displacement-based efficiency" and then discuss how Germany's prospects of installing large amounts of solar PV modules was effected by environmental load displacements to China. I then discuss how likely it is that large-scale development of solar PV technology is generically contingent on ecologically unequal exchange. I conclude with new insights on the role of ecologically unequal exchange for the rise of solar power and its significance for contemporary and future efforts to transition away from fossil fuels by means of solar PV technology.

2. The theory of ecologically unequal exchange

2.1. Ecologically unequal exchange and the ontology of technology

The theory of ecologically unequal exchange (EUE) explains how

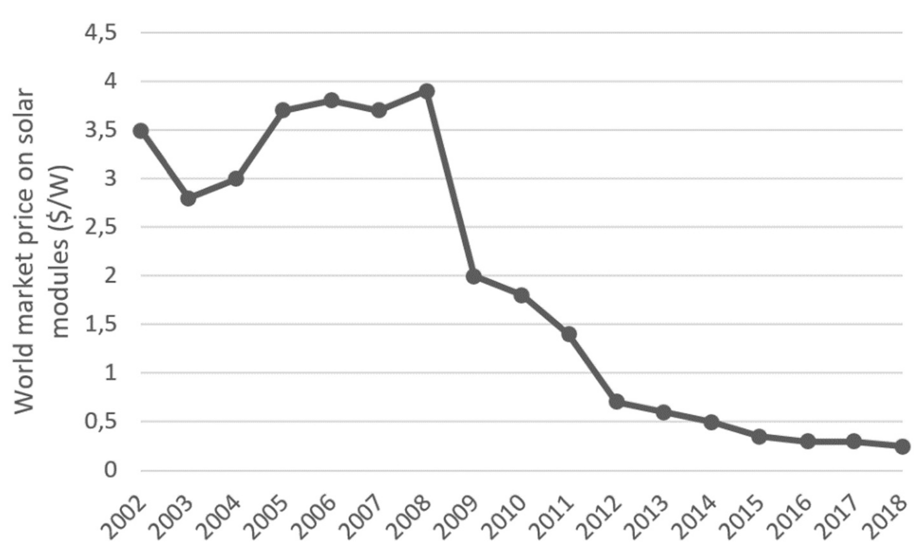

Fig. 1. Average world market PV prices, 2002–2018 (Nemet, 2019; Haegel et al., 2019).

wealthier nations rely on net imports of resources to sustain their high levels of consumption and technological development, while displacing a significant amount of work and environmental loads to poorer nations (Giljum and Eisenmenger, 2004; Jorgenson et al., 2009; Dorninger and Hornborg, 2015; Hao, 2020; Dorninger et al., 2021). This theory has been applied to demonstrate the uneven distribution of several crucial factors of production, including energy, labor, and land (Lawrence, 2009; Dorninger et al., 2021), as well as deforestation (Noble, 2017), loss of biodiversity (Shandra et al., 2019), fish stock depletion (Clark et al., 2019), greenhouse gas emissions (Roberts and Parks, 2007; Prell and Sun, 2015; Warlenius, 2016), human health and zoonic diseases (Austin, 2021) and more (see e.g. Givens and Huang, 2021).

The theory of EUE builds on insights from dependency theory (Prebisch, 1962; Frank, 1966; Amin, 1972), world-systems analysis (Wallerstein, 2004, 2011), Marxist theory of unequal exchange (Emmanuel, 1972) and ecological economics (Odum, 1971; Bunker, 1985; Odum and Arding, 1991; Hornborg, 1998). Research on EUE distinguish between the culturally determined "values" of commodities and the physical factors of production (or, "low entropy") dissipated in their production (Hornborg, 1998). This distinction is pivotal because the asymmetric transfers of resources occur when the exchange value of commodities is not proportional to the biophysical resources required for their production. The result of such exchange is an asymmetric transfer of embodied labor and resources typically flowing from peripheral to core regions of the world economy.

The underlying cause of EUE is the uneven wages and unevenly priced resources in the core and its peripheries (including the semi-periphery).[2] These differences can be ascribed to a range of factors, of which technology is one (Hornborg, 1998, 2001; Pérez-Rincón, 2006). Conventional wisdom suggests that technological progress increases productivity and reduces prices on commodities. But the fruit of technological progress is expressed differently in the world periphery and in its core (see Prebisch, 1962; Wallerstein, 2004). The result of this difference may be "deteriorating terms of trade" whereby ever more commodities need to be produced and exported to maintain the same export income flow in the peripheries (Pérez-Rincón, 2006). In the core, the higher prices and wages lead to a net import of embodied resources that is used to further develop its social metabolism. Thus, while technology may increase the rate of exploitation in the peripheries, technological productivity tends to beget access to more technological infrastructure in the core (Hornborg, 1998, 2009).

The theory of EUE implies that the wealth and human development accrued in the world's core is inseparable from the impoverishment and human underdevelopment in the world's peripheries. As such, a global asymmetric transfer of resources is essential for the concentration and function of modern technological infrastructure in the world's core (Hornborg, 2001, 2019). Technologies cannot be separated from the biophysical resources needed for their production and, by extension, cannot be separated from the global social relations through which such biophysical resources are accessed. The concept of "machine fetishism" refers to the modern cultural difficulty to understand how the productive potential of technology is therefore not inherent to technical artifacts but granted through previous dissipation of low-entropy resources elsewhere in the world system (Hornborg, 1992, 2001, 2009). This suggests that we cannot fully understand technological development without considering it from a global lens attentive to material extraction and international trade.

One question following from this literature is to what degree the *perceived* efficiency of technological artifacts in the world's core (e.g. solar PV modules) is dependent on environmental load displacements to the world's peripheries. Measures such as energy return on energy investment (EROEI) and power density (W/m2) have been applied to understand the biophysical efficiencies of a range of energy technologies (Hall et al., 2009; Murphy and Hall, 2010; Smil, 2015; de Castro and Capellán-Pérez, 2020). However, no study has considered how these measures may be fundamentally altered through environmental load displacements (e.g., displacements of energy dissipation and land-intensive production processes) in the world economy. Georgescu-Roegen (1978: 19) hypothesized early that "the direct use of solar energy is a 'parasite,' as it were, of the current technology, based mainly on fossil fuels." But he did not consider that such "parasiting" – which can be understood as a biophysical subsidy – may be accessed also through ecologically unequal exchange.

This study focuses on whether global asymmetries in resource transfers is foundational for the financial and biophysical viability of the large-scale development of solar PV technology envisioned to form the energetic basis of a low-carbon social metabolism. The case of the German-Chinese relation in the rise of solar power may provide an initial understanding of the global social relations implied in such a social metabolism. Thus, this study asks how Germany's prospect of installing large amounts of solar PV modules was effected by environmental load displacements in trade with China and how likely it is that the continued mass-installation of solar PV technology is contingent on ecologically unequal exchange? Aiming to answer these questions, I calculate the presence of EUE in the rise of the global solar PV market and analyze its significance for Germany's large-scale solar PV development.

2.2. *Ecologically unequal exchange between Germany and China*

From a world-economic perspective, Germany is a core country and China is a semi-peripheral country. Ranked by the World Bank as a high-income economy, Germany is known for its internationally strong vehicle industry, medical industry, and the production of machinery for export. Several studies have documented how Germany as a core, high-income country, relies upon a net import of matter-energy in the world economy (Giljum and Eisenmenger, 2004; Jorgenson, 2009; Dorninger and Hornborg, 2015). Germany's ambitious environmental politics is thereby associated with an environmental load displacement whereby Germany exports a considerable amount of the environmental degradation resulting from its metabolism to other countries.

According to the World Bank, China ranks as an "upper middle income" country. Currently, China is the largest exporting nation in the world, exporting machinery, textiles, and a vast range of other commodities. One study assessing the physical trade between China and 186 other countries found that developed regions (including the EU) displace their environmental loads to China through trade (Yu et al., 2014). This environmental load included embodied greenhouse gas emissions (CO_2 and SO_2) as well as embodied water and embodied land. The same study concluded that China in turn exports some of its environmental loads to less developed regions, including Southeast Asian and Africa. Several other studies reveal the Chinese role as semi-periphery, as it simultaneously *exports* embodied greenhouse gas emissions, embodied energy, embodied land, and embodied material *importing* embodied forests, embodied land, and embodied water (Yu et al., 2014; Peng et al., 2016; Tian et al., 2017; Shandra et al., 2019).[3]

Given their respective roles in the world economy, it is not surprising that direct trade relations between China and Germany have been shown to facilitate an ecologically unequal exchange whereby embodied matter-energy is transferred to Germany (Tian et al., 2017). Notably, the most relevant trade sectors between China and Germany, considered in physical measurements, included the German export of "machinery" (secondary industry, heavy machinery) to China and the Chinese export of "electrical and optical equipment" (secondary industry, light

[2] At another level of analysis, Hornborg (2009) has pointed out "general purpose money" as the core determinant of EUE.

[3] China is a net exporter of raw materials, embodied energy, and embodied labor, but a net importer of embodied land (Dorninger et al., 2021).

machinery) to Germany (Tian et al., 2017). This means that the German export of machinery, such as cars, PV equipment, and similar products, has a notable biophysical significance for the Chinese economy, while electrical equipment, such as computers and solar PV modules, have a high significance for the German economy.

3. Method and materials

3.1. LCA-based method for calculating ecologically unequal exchange

This study applies an LCA-based method for assessing the significance of ecologically unequal exchange in the rise of solar power. Many quantitative studies on ecologically unequal exchange focus on specific nations or world economic regions corresponding to the international division of labor described in world-system analysis (e.g., Giljum and Eisenmenger, 2004; Pérez-Rincón, 2006; Jorgenson et al., 2009; Dorninger and Hornborg, 2015; Dorninger et al., 2021). As we have already seen how the world economic relation between Germany and China was characterized by ecologically unequal exchange, the goal here is to calculate the presence of unequal exchange in the trade with focal commodities of the global solar PV market. Through an LCA-based method, it is possible to assess ecologically unequal exchange in trade with specific commodities (Oulu, 2015). This method gives a detailed understanding of the extent to which trade in specific commodities is involved in asymmetric flows of resources in the world economy and is therefore a suitable method for the aim of this study.

LCA-based calculations on ecologically unequal exchange have two parts. First is to calculate the embodied resources and impacts of the individual commodities traded and second is to calculate the bulk exchange of these commodities in the world economy relative to a fixed market price. This includes four sub-phases.

- First, a scope definition should be provided wherein the functional unit, system boundaries, and units of measurements are articulated.
- This is followed by an inventory analysis wherein the resource intensity per functional unit is determined and presented. This study relies on secondary data gathered from previously published LCA studies.
- Third, an impact assessment is made wherein unequal exchange is determined via a comparison of the resource intensity per unit of exchange value.
- Finally, the implications of the results are discussed.

Apart from including a sub-section on limitations and methodological developments (3.3), I will follow this systematization.

3.2. Scope definition

To compare the ecological exchange implicated in two focal commodities in the solar PV market, the functional units were defined as follows: One Chinese solar multi-crystalline silicone solar photovoltaic module[4] and one German solar photovoltaic manufacturing machine.[5] The system boundaries were set to include measurements traced from the extraction of the necessary matter-energy to the assembly of the final product (Fig. 2 and Fig. 3). Since this study is focusing on the exchange of finished products, environmental impacts associated with the usage, disposal, and recycling phases are considered outside the system boundaries. Only domestic resources and greenhouse gas emissions are considered, even if the commodity chains extend internationally to a lesser degree (for solar PV, see Dong et al., 2015). The units of measurement include embodied land, embodied labor, embodied energy, and embodied CO_2-eq. emissions. These units of embodiments are then related to quantities and monetary exchange values (USD) of the respective commodities, derived from the UN database COMTRADE (2021) and the Trend Economy (2020) database on commodity exchanges.

[4] Properties: 1482 × 992 × 35 mm (1,47 m^2), 16.8 kg, 54 cells (6 × 9), lifespan 25 years, 200 Wp.

[5] Properties: 2500 kg, lifespan 30 years (OpenLCA, 2020).

3.3. Limitations and methodological developments

The study design has potential limitations related to the method and the reliability of data. The LCA-based method is suitable for calculating the asymmetric flows of embodied resources in trade with specific commodities. But this method has hitherto not been used to explain whether such asymmetric flows influence the financial or biophysical viability of the commodities traded.[6] In theory, even if the trade in solar PV modules and solar PV manufacturing machines involve an asymmetric transfer of resources, the financial and biophysical viability of solar PV modules might still be high if other industrial sectors provide the means for a (biophysical or monetary) subsidy. I address this issue by providing an estimate of what the solar PV modules would cost if they had been produced with German wages and energy prices. As such, I assume that market prices (USD/W) influence the cost-effectiveness of solar PV development.[7] I propose that an LCA-based assessment of EUE may be used to understand the extent to which a commodity's price – and so financial viability – is influenced by the geographical location of production.

To measure this, I introduce the notion of a "displacement-adjusted price," which denotes the price of a commodity if the displaced environmental loads (through EUE) were to be supplied with domestic wages and prices. I also introduce the notion of "displacement-based efficiency," which denotes the physical efficiency of a technology after the associated environmental load displacements have been analytically excluded as necessary inputs.[8] For this study, I employ the concepts of EROI and power density for assessing the displacement-based efficiency of solar PV technology. By comparing the displacement-adjusted price with the market price and the displacement-based efficiency with the actual efficiency, it is possible to evaluate the significance of ecologically unequal exchange for the financial and biophysical viability of one or two commodities – in this case solar PV modules.

4. Results

4.1. Embodied resources in Chinese solar PV modules

Let us now turn to the inventory analysis wherein the resource intensity of the functional unit is determined and presented. Table 1 summarizes the resource intensity of a Chinese solar PV module. Methodologically, the resource intensity in the life-cycle inventory table is presented as if it is static in time, which means that variations in resource intensity associated with changes in the manufacturing process have not been taken into consideration. To avoid portraying the resource intensity as larger than it was during the last years of consideration, the inventory table is based on LCA-analyses published as recently as possible (typically from 2013 onwards). Some LCA analyses show that resource efficiencies in PV manufacturing may not have changed considerably over the last twenty years (Ludin et al., 2018).

[6] In this study, viability refers to the ability to function, to succeed, or to be sustained. Financial viability refers to a commodity's (in this study, a solar PV module's) ability to succeed financially within the logic of capital accumulation. Biophysical viability refers to the commodity's ability to physically function as intended and to be sustained within a social metabolism.

[7] I acknowledge that market prices are in turn determined by a range of social-ecological factors.

[8] The displacement-based efficiency represents the physical efficiency of a technology such as it is experienced in the world core.

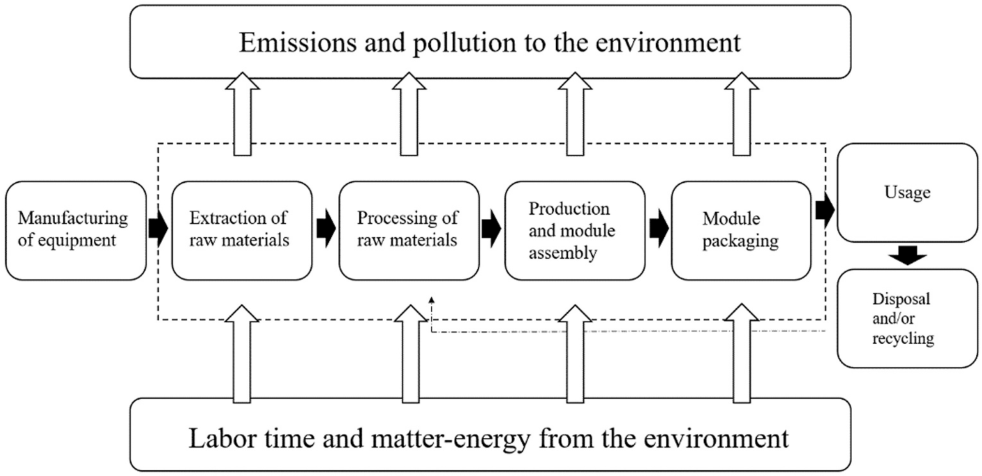

Fig. 2. System boundary for a Chinese multi-crystalline silicone (m-Si) solar PV module.

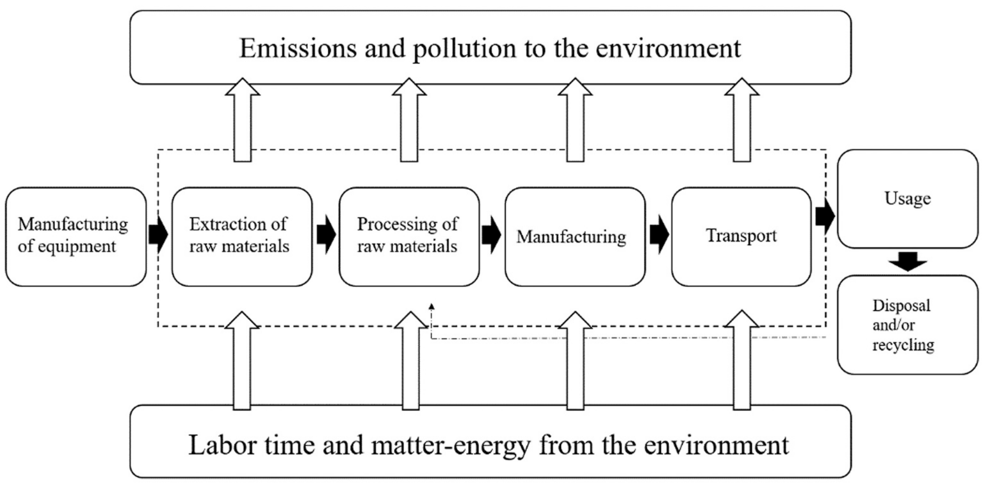

Fig. 3. System boundary for a German solar photovoltaic manufacturing machine.

Table 1
Life-cycle inventory for a Chinese solar multi-crystalline silicone (m-Si) solar photovoltaic module.

Process/input	Energy (MJ)	Land (m^2)[c]	Labor (h)[d]	CO_2-eq. (kg)
Extraction of raw materials	2,552[a]	57	0.35	0.6[b]
Processing of materials	2,071[a]	44	0.87	186.1[b]
Production and assembly	1382[a]	29	3.26	88.9[b]
Module packaging	1,512[b]	31.5	N/A	167.6[e]
Total	7517	161.5	4.47	443.2

[a] Data from Wong et al. (2016).
[b] Data from Dong et al. (2015).
[c] Calculations based on energy values from Wong et al. (2016) and Dong et al. (2015) converted into land hectares with a coefficient (1.56 W/m^2) calculated from land requirements of China's solar PV industry (Roos, 2021: 159). The coefficient includes indirect land requirements of the necessary labor and capital, but excludes the land for carbon sequestration.
[d] Data from Llera et al. (2013). Considering a 1800 h work year in China.
[e] Data from Dong et al. (2015). Includes some emissions associated with assembly of the aluminum frame not previously included.

This may be linked to observations that efficiencies may be offset by indirect energy dissipation and "diseconomies of space" (Bunker and Ciccantell, 2005; Ciccantell and Smith, 2009; Hagens, 2020). This study relies on conservative estimations of the resources intensities, i.e., low resource intensities for Chinese solar PV modules and high resource intensities for German solar PV equipment. Future studies could attempt to provide uncertainty ranges for more accurate results.

4.2. Embodied resources in German solar PV manufacturing machines

Table 2 summarizes the resource intensity of a German solar PV manufacturing machine. As previously mentioned, it is notoriously difficult to access LCA data on machinery, perhaps because there is a limited interest in understanding machines as material artifacts (Hornborg, 1992; Stivers, 1999). The most significant exception to this trend can be found in research on energy flows in agricultural systems (e.g., Fluck, 1992; Pimentel, 2006; Bochtis et al., 2019). In these studies, energy embodiments associated with the manufacture of machinery are considered relevant for the overall energy expenditure of a particular food product or a particular agricultural system. Usually, such measurements are based on energy intensities per kg of machinery. In literature on ecological footprints, it is also possible to find coefficients concerning land embodiments for different industrial sectors (e.g., Hubacek and Giljum, 2003). The life-cycle inventory for the German manufacturing machine draws upon these studies.

Table 2
Life-cycle inventory table for a German solar photovoltaic manufacturing machine.

Process/input	Energy (MJ)[a]	Land (m^2)[b]	Labor (h)	CO_2-eq. (kg)[d]
Extraction and processing	1,286,500	8276	N/A	74,617
Manufacturing	61,000	385	N/A	3538
Transportation	3225	20	N/A	187
Total	1350,725	8681	849[c]	78,342

[a] Data from Bochtis et al. (2019).
[b] Calculations based on energy values from Bochtis et al. (2019) converted into land hectares with a coefficient (4,93 W/m^2) calculated from land requirements of Germany's solar PV industry (Roos, 2021: 163). The coefficient includes indirect land requirements of the necessary labor and capital, but excludes the land for carbon sequestration.
[c] Calculated by dividing the annual turnover of Germany's manufacturing and equipment industry with the amount of jobs focused on export in the sector (Kolbe, 2011; Dauth et al., 2017). Considering a 1350 h work-year in Germany.
[d] Calculated with a coefficient of Germany's carbon intensity (0.058 kg/MJ) (Worldometer, 2020; BP, 2019).

4.3. Determination of ecologically unequal exchange

The next step is to apply the resource intensities associated with each commodity to aggregate trade volumes between Germany and China during the rise of solar power (see Appendix A). The results show an unequal exchange whereby net transfers of embodied energy, embodied land, embodied labor, and embodied emissions are flowing from China to Germany (Fig. 4-Fig. *8*). In all embodiments calculated, the biophysical exchange implicated in trade with these two commodities shows a notable asymmetry as of 2013. Even prior to this period, a notable (yet smaller) asymmetry was present, which accelerated in 2006. Fig. 8 provides a closer look at the trends during the years 2002–2010.

These results indicate that trade in focal solar commodities became increasingly unequal between Germany and China between 2002 and 2018. By trading German solar PV manufacturing machinery (secondary industry, heavy machinery) for Chinese solar PV modules (secondary industry, light machinery), Germany displaced an increasing amount of the environmental loads of its solar PV development to China. Before the global commercialization of solar PV cells, the exchange implied a modest net transfer of embodied resources per monetary unit. Sixteen years later, the same exchange implicated a more significant net transfer of 1459 GJ, 3.2 ha of embodied land, 866 embodied labor-hours, and embodied greenhouse gases equivalent to 86 t of CO_2-eq. from China to Germany per 10,000 USD exchanged (Table 3).

The continued fall in the price on solar PV modules in China relative to the comparatively stable price on solar PV manufacturing machine in Germany exemplifies a "deterioration in terms of trade," whereby China needed to export an ever-increasing quantity of solar PV modules to balance the import of solar PV machinery (Figs. 4-7). This is reflected more clearly in how EUE was intensifying during the rise of solar power 2002–2018 (Table 3). To maintain a regular export income flow in the solar PV market, Chinese and foreign manufacturers in China were likely compelled to produce ever more solar PV modules at an increasing rate of natural resource extraction, pollution, and with lower salaries.[9]

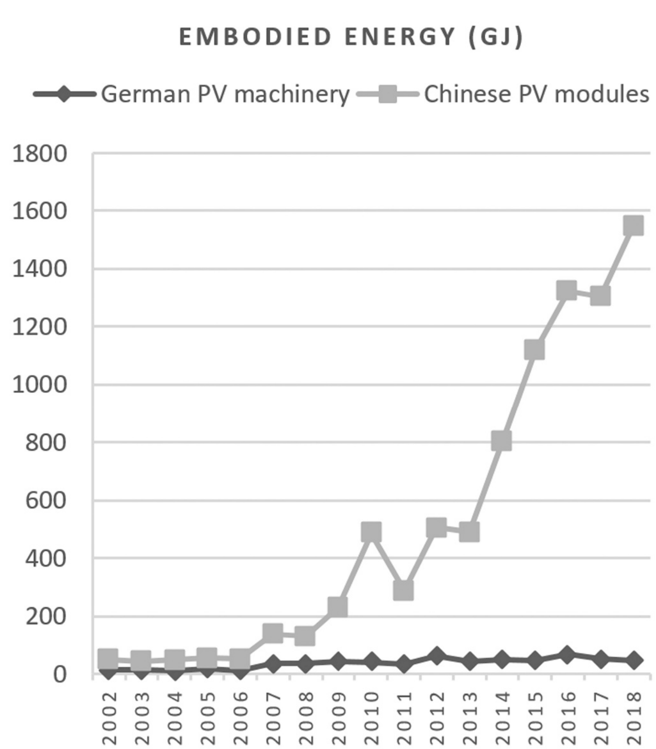

Fig. 4. Exchange of embodied energy per 10,000 USD.

5. Discussion

5.1. The significance of ecologically unequal exchange for Germany's solar PV development

The results confirm the previously reported EUE between Germany and China (Tian et al., 2017). Since LCA-based accounting of EUE only measures resource transfers implicated in two commodities, the result of this study is best understood as a focal example of a broader pattern of EUE between the countries. Seen from this perspective, the results suggest that Germany's solar PV installation would have implied much higher financial costs and domestic environmental loads if Germany had

Table 3
Net transfer of embodied resources from China to Germany per 10,000 USD, 2002–2018.

Year	Energy (GJ)	Land (ha)	Labor (h)	CO_2-eq. (t)
2002	19	0.1	10	1
2003	14	0.1	8	1
2004	28	0.1	16	2
2005	21	0.1	12	1
2006	27	0.1	15	2
2007	66	0.2	38	4
2008	58	0.2	33	3
2009	146	0.4	85	9
2010	405	0.4	105	11
2011	224	0.5	132	13
2012	382	1	244	23
2013	403	1	238	24
2014	703	1.6	416	41
2015	1028	2.3	610	61
2016	1185	2.7	702	70
2017	1201	2.7	712	71
2018	1459	3.2	866	86

[9] The cause of this deterioration in terms of trade cannot be explained by increased "knowledge" or "innovation" in Chinese solar PV manufacturing. For example, the gap in manufacturing costs between Germany and China were so large that even the world's most established solar PV companies – such as German Q-Cells – who had been leading PV manufacturing for decades and had maximized opportunities for low-cost manufacturing within Europe, still could not scale up manufacturing to saturate the growing German demand (Nemet, 2019: 118–123). However, it can potentially be explained by the asymmetries in the functioning of the labor markets and the political economy of environmental regulations in Germany and China respectively (Pérez-Rincón, 2006).

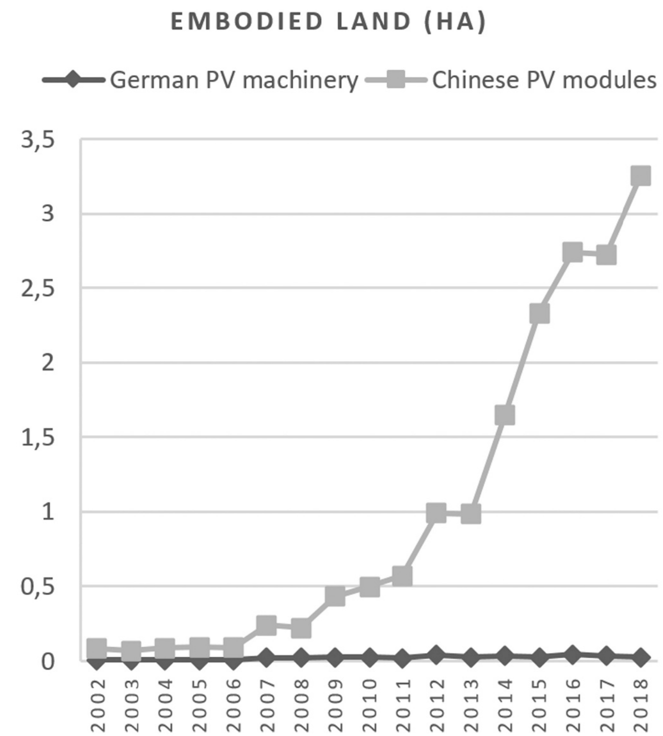

Fig. 5. Exchange of embodied land per 10,000 USD.

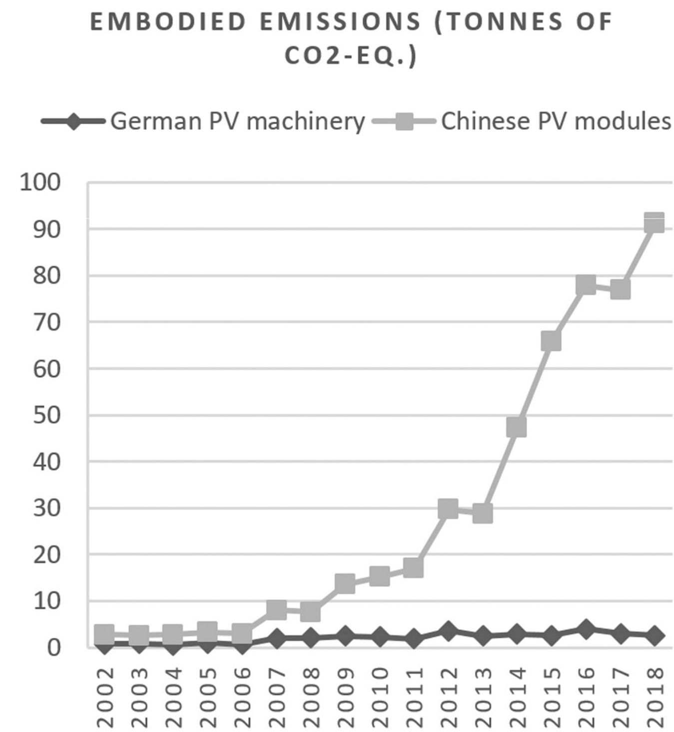

Fig. 7. Exchange of embodied emissions per 10,000 USD.

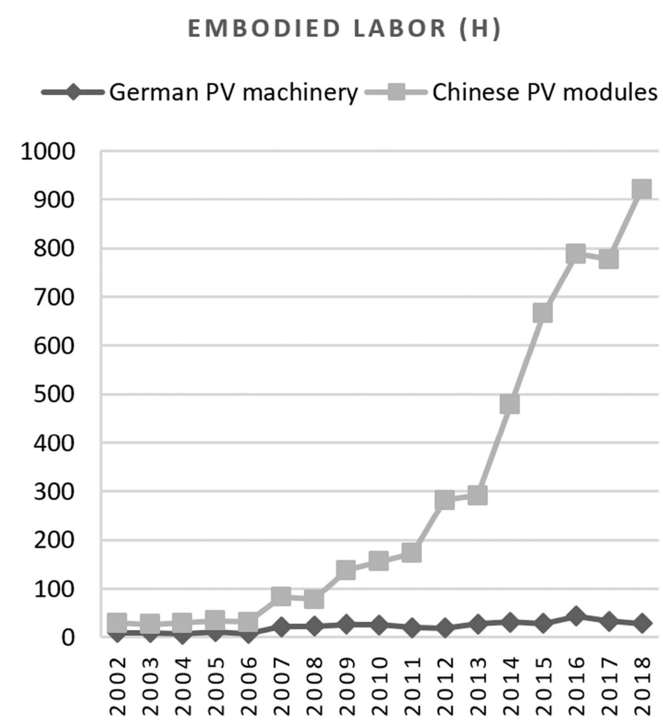

Fig. 6. Exchange of embodied labor per 10,000 USD.

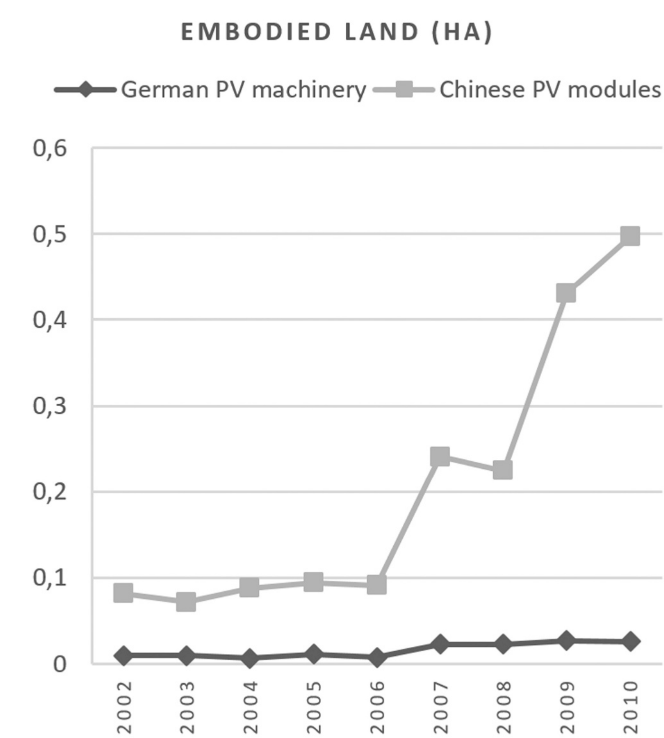

Fig. 8. Exchange of embodied land per 10,000 USD, 2002–2010.

not engaged in the abovementioned trade with China 2002–2018. But how significant was this ecologically unequal exchange for Germany's prospect to develop its solar PV capacity? This can be tested by calculating the displacement-adjusted price and displacement-based efficiencies of the solar PV modules.

Let us first turn to the monetary costs of the solar PV modules. At the peak of asymmetry in 2018, China exported solar PV modules to Germany at a total exchange value of 463,406,970 USD (Appendix A). The total amount of labor-hours embodied was 41,436,627. With Chinese manufacturing wages of 6.2 USD/h, these labor-hours cost 256,907,087 USD (Trading economics, 2021). With German manufacturing wages of 28 USD/h, the same amount of labor hours costs 1,160,225,556 USD (Salary explorer, 2021). The total price on the solar PV modules installed by Germany would have increased to

1,366,725,439 USD (0.74 USD/W) if they were manufactured with German wages. The embodied energy to manufacture the solar PV modules amounted to 69,682,131 GJ (Appendix A). With Chinese electricity prices of 0.08 USD/kWh and German electricity prices of 0.38 USD/kWh (Statista, 2021), the prices on the solar PV modules would increase by 5,806,844,250 USD if they were manufactured in Germany.[10] This means that the solar PV modules that Germany imported from China at an exchange value of 463,406,970 USD would cost 7,173,569,689 USD if they were manufactured with German wages and energy prices. This shows that the price on the solar PV modules would be at least 15 times higher if they were produced in Germany rather than China.[11] The displacement-adjusted price is 3.87 USD/W, which is a price equivalent to the market price of the year 2000.

Let us now turn to the biophysical efficiencies of Germany's solar PV modules. Considering a capacity of 200 Wp for each solar PV module, the results (Table 1) indicate that one solar PV module requires 37.5 MJ, 0.81 m^2, 0.02 labor-hours, and 2.2 kg CO_2-eq. per watt installed. In 2018, a given proportion of these resources were appropriated by Germany in trading solar equipment for Chinese solar PV modules. Figs. 3-6 show the environmental load displacement per 10,000 USD. Considering a price of 0.25 USD/W (Fig. 1), this environmental load displacement amount to 36 MJ, 0.81 m^2, 0.022 labor-hours and 2.22 kg CO_2-eq. per watt installed in 2018. This means that it would have required 40 times more energy, 115 times more land, 32 times more labor, and 34 times more CO_2-eq. for Germany to install the solar PV modules if they were produced domestically rather than in China.

While the aggregate resource demand would not greatly affect Germany's economy if supplied domestically, the biophysical requirements had a notable influence on the prospects of Germany's large-scale solar PV development by 2018. Let us take the energy efficiency and land efficiency of the solar PV modules as examples to illustrate this. On an average, German solar power generates roughly 3.38 MJ/W per year.[12] Over the course of the 25-year long lifespan of a solar PV cell, it would generate roughly 85 MJ/W. Considering the biophysical expenditures per watt (Table 4), the solar PV module's EROI would be roughly 2.2:1 (85 MJ/W ÷ x). This is not high enough to sustain modern industrial societies as suggested by the "law of minimum EROI" (Hall et al., 2009). In contrast, the displacement-based efficiency suggests that the EROI experienced in Germany was closer to 77:1 (85 MJ/W ÷ z). This EROI is well over the minimum EROI required to sustain modern industrial societies and can largely be attributed to the displacements of energy dissipation to China.

In terms of land, the results show that the solar PV modules required 0.8075 m^2 per watt (Table 4). Dividing this by the 25-year long lifespan of the solar PV cells (0.8075 ÷ 25) yields 0.0323 m^2 per watt. Previous studies have estimated that the annual direct land requirement of solar PV utility parks is approximately 5 W/m^2, i.e., 0.2 m^2 per watt (Smil, 2015; Capellán-Pérez et al., 2017). Adding these annual direct land requirements (0.0323 m^2 + 0.2 m^2) yields 0.2323 m^2 per watt, which translates to a power density of 4.3 W/m^2. This is a power density that is too low for sustaining industrial societies without significant pressures on domestic food supplies, notable habitat loss, and probably increases in land rent (Smil, 2015). In contrast, by displacing most of the land requirements to China the demand on land experienced in Germany was closer to 0.007 m^2 per watt, i.e., a displacement-based power density of 143 W/m^2.

Germany's prospect to install large amounts of solar PV modules was greatly improved by trading solar PV machinery for solar PV modules with China. This effect was not immediate, but gradual, with a notable improvement between 2006 and 2018. The displacement-adjusted price shows that this improvement was highly significant as the falling price on solar PV modules on the world market would have been reset to the market price of 2002 if the modules were manufactured in Germany in 2018. The displacement-based efficiencies also show this by revealing that Germany's solar PV development became a biophysically feasible net energy strategy and required significantly less land per watt capacity due to the environmental load displacements to China. These results could be further nuanced by considering the ecological exchange implicated in whole industrial sectors, including a range of associated materials and commodities.

Table 4
Displacement-based efficiency as the difference between biophysical requirements and environmental load displacement.

Indicator (per watt)	Energy (MJ)	Land (m^2)	Labor (h)	CO_2-eq. (kg)
Biophysical requirement (x)[a]	37.6	0.8075	0.02235	2.22
Environmental load displacement (y)[b]	36.5	0.8005	0.02165	2.15
Displacement-based efficiency (z) = (x − y)	1.1	0.007	0.0007	0.07

[a] Derived from Table 1.
[b] Derived from Figs. 4-7.

5.2. Implications and future directions

This study shows how the rise of the solar power may have been contingent on international price differences facilitating an ecologically unequal exchange between Germany and China. Without this global asymmetry, the solar PV module prices would probably be much too high and the solar PV module efficiencies much too low to be viable in Germany. These results validate the theory of EUE suggesting that a global asymmetric transfer of resources is essential for the concentration and function of modern technological infrastructure in the world's core and should not be understood as distinct from technological progress and efficiency improvements.

From the perspective of ecological economics, this material prerequisite of technological progress can be explained by the fact that an increase in scale (or "growth," or "complexity", or "development") can only occur with an absolute increase in matter-energy throughput in highly ordered structures (Georgescu-Roegen, 1975; Tainter, 1988; Hall and Klitgaard, 2012). In turn, such an increase mandates lower prices on matter-energy inputs for ventures bound within the cycle of capital accumulation. In the case of the rise of solar power, the relative difference in wages and prices on energy, raw materials, and emissions between China and Germany served the purpose of allowing such higher energy-matter throughput at lower prices and lower domestic environmental pressures. The importance of this asymmetry for the financial and biophysical viability of solar PV technology shows that it is possible that the continued mass-installation of solar PV technology will be implicated in ecologically unequal exchange.

This study confirms Georgescu-Roegen's (1978) suspicion that the metabolic reliance on energy generated from solar technology is "parasitic" and may necessitate biophysical subsidies (notably fossil fuels). This study develops this insights by demonstrating that ecologically unequal exchange may serve as a principal mechanism for appropriating such subsidies in the absence of fossil fuels. In such a scenario,

[10] The price of the Chinese electricity was 1,548,491,800 USD (69,682,131 GJ * 0.08 USD/kWh) and the price of the Germany electricity was 7,355,336,050 USD (69,682,131 GJ * 0.38 USD/kWh). The difference between them is 5,806,844,250 USD.

[11] We should bear in mind that these figures do not include prices on carbon emissions or expenses associated with the land requirements. If these were calculated, it would likely imply that the prices of the solar PV modules would be even higher if they were manufactured in Germany.

[12] Considering a net installed solar capacity of 54,07 GW in 2020 (Fraunhofer, 2021) and an annual solar electricity generation of 50,7 TWh the same year (Burger, 2021).

the environmental depredations and environmental distribution conflicts along the PV commodity chain may both intensify and increase in quantity. Future studies on ecologically unequal exchange in other renewable energy sectors, including waterpower, wind power, and biomass, could further substantiate or nuance this hypothesis.

The LCA-based method for studying ecologically unequal exchange proved useful, yet it can be improved. The limited interest in considering machines as material artifacts seem to effect the availability and reliability of data for LCA-based inventory analyses of manufacturing machinery. I have nevertheless demonstrated that it is possible to employ the LCA-based method to understand changes in the financial and biophysical viability of a technology resulting from environmental load displacement. The notion of a “displacement-adjusted price” and “displacement-based efficiency” proved useful to this end. Future studies might find it helpful to also consider the notion of a “displacement-adjusted resource requirement,” which denotes the resources necessary for accruing a particular commodity (or technology) after the displaced resources have been excluded as an input. Such a measure could be used to further understand the biophysical importance of ecologically unequal exchange for the continuation of high-energy modernity among the wealthy nations of the world. This notion could be relevant beyond the LCA-based approach. Future studies could also attempt to analyze and discuss the changes in the displacement-adjusted prices and displacement-adjusted efficiencies over a given period for a *dynamic* understanding of the significance of ecologically unequal exchange.

6. Conclusion

This study has shown that ecologically unequal exchange may have been an important mechanism for the rise of solar power 2002–2018. By trading German solar PV manufacturing machinery for Chinese solar PV modules, Germany displaced increasing volumes of environmental loads to China during this period. In the absence of such environmental load displacement, it is unlikely that Germany would have developed its solar PV capacity without higher financial and biophysical costs. The calculations of the displacement-adjusted price and the displacement-based efficiencies suggest that Germany installed solar PV panels at considerably lower prices and notably higher efficiencies by engaging in trade with China. This shows that environmental load displacement may be a precondition for employing solar PV technology as a viable net energy strategy in the absence of fossil fuels. This result validates the theory that a net transfer of embodied resources, flowing from one social group to another, may be a global social condition inherent to the pursuit to maintain modern high-energy societies in the absence of fossil fuels. As world leaders push for an ever-faster installation of ever-more solar PV technology, ecologically unequal exchange may therefore become an increasing concern for attempts to create a socially just and ecologically sustainable world. Further studies employing a variety of methods are needed to substantiate and nuance these findings.

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Declaration of Competing Interest

I (Andreas Roos) hereby declare no conflict of interest pertaining to the paper entitled “Global asymmetries in the rise of solar power: An LCA-based account of ecologically unequal exchange between Germany and China 2002-2018.”

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2022.107484.

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