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Review

The hidden costs of energy and mobility: A global meta-analysis and research synthesis of electricity and transport externalities

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ABSTRACT

What is the range and scope of externalities associated with electricity supply, energy efficiency, and transport? What research methods and techniques of valuation does the community use to monetize these externalities? What policy implications arise in terms of better governing energy and mobility systems? To answer these questions, this study offers a comprehensive and global research synthesis of externalities for energy and mobility. It synthesizes data from 139 studies with 704 distinct estimates to examine the hidden social and environmental costs. The mean external cost for electricity supply is 7.15¢/kWh. When correlating this with the actual amount of electricity generated per year, the amount is $11.644 trillion. This likely exceeds both the reported revenues for electricity sales, oil and gas production as well as the levelized costs of energy. The mean external cost for mobility is 17.8¢/km. Using differentiated estimations of the externalities associated with aviation, road travel for passengers and freight, rail, and coastal water/marine modes of travel, transport's global externalities amount to another $13.018 trillion. When combined, this $24.662 trillion in externalities for energy and transport is equivalent to 28.7% of global Gross Domestic Product. Energy efficiency or demand response by contrast has net positive externalities of approximately 7.8¢/kWh. When put into the context of global efficiency and demand management efforts, this approaches an annual positive value of $312 billion. The fundamental policy question is whether we want global markets that manipulate the presence of externalities to their advantage, or a policy regime that attempts to internalize them.

1. Introduction

There may perhaps be no more vexing a conundrum than externalities. Many externalities result from extracting, producing, and using energy fuels or consuming mobility services. Yet these costs are not always reflected in electricity rates and transport prices. Markets often "externalize" negative environmental and social costs (e.g., hazardous working conditions) and fail to provide or adequately value public goods (e.g., clean air). Consumers become shielded from the true costs of energy extraction, conversion, supply, distribution or use, or from driving their cars, making the immense ecological or community impacts from existing systems less discernable.

A variety of studies have grappled with the problem of externalities, but done so in a partial and often limited fashion, i.e. by focusing only on a small number of externalities, or a small number of locations, or a small number of technologies. By contrast, a multitude of different externalities affect many locations across an array of technologies. Indoor and outdoor air pollution, largely from fossil-fueled power plants, household cookstoves, and the tailpipes of conventional cars and trucks, is responsible for 4.9 million deaths and 147 million years of healthy life lost each year [1]. In comparison, pollution kills three times more people than HIV-AIDS, tuberculosis, and malaria combined [2]. Climate risks could cost some countries as much as 19 percent of their GDP by 2030, with the biggest impacts falling on developing countries; some states, such as Maharashtra, India, could be prone to drought that wipes out 30 percent of food production, inducing $7 billion in damages among 15 million small and marginal farmers [3]. Low-lying islands and coastal areas could be submerged in sea level rise to the point where some entire countries—such as the Maldives, Kiribati, or Tuvalu—could no longer exist, converting their populations into dispersed climate refugees [4]. Reduced rainfall could aggravate water and food security so that hundreds of millions of people could die of disease epidemics and starvation

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attributable to climate change—with one study projecting 175 million people at prone to heightened zinc deficiency due to climate change, as well as 122 million people to be protein deficient and 1.4 billion women of childbearing age (and young children) to be iron deficient and at risk of anemia [5]. In the realm of mobility, traffic congestion costs the United Kingdom economy an estimated £6.9 billion a year in lost time, or about £900 per every driver [6]. Adding to the toll from transport, the World Health Organization estimates that every year 1.25 million people are killed and 20 to 50 million injured in traffic road crashes involving cars or motorcycles; globally, road traffic injuries are also the leading cause of death for those between the age of 15 and 29 years old [7].

A seminal work in energy studies analyzing externalities did so for individual electricity generators to determine the extent that negative externalities were not reflected in electricity prices [8,9]. They found that these costs, when averaged across studies, represented an additional 0.29 to 14.87 ¢/kWh. However, their study relied on data that is now more than 20 years old (from 1998). When surveying externalities, they did not include *any* value for CO_2 and climate change, nor did they account for land use impacts, water, or impacts on property values. They focused on electricity only, excluding energy efficiency or mobility, and they used a comparatively small sample size of studies (38 studies with 132 observations). They lastly focused only on negative externalities. Another seminal work in energy studies revealed that the social cost of the electricity, heat and cold demand with 100% wind, water, and sunlight supply is one-fourth the social cost of business-as-usual [10], and the Green New Deal could reduce aggregate social costs (private plus health plus climate) from $76.1 to $6.8 trillion/year [11].

By contrast, this study presents an up-to-date, more comprehensive and more rigorous assessment of the global externalities—the scope of externalities around the world, even if they occur at different scales—associated with electricity supply and energy efficiency as well as transport and mobility (for more on how we define externalities, see Section 2.1). It asks three central questions: What is the range and scope of externalities—positive and negative—associated with electricity supply, energy efficiency, and transport? What research methods and techniques of valuation does the community use to monetize these externalities? What policy implications arise? It answers these questions by offering a meta-analysis and research synthesis of 139 studies with 704 distinct estimates of externalities: 83 studies (with 318 observations) for electricity supply, 13 studies (with 13 observations) for energy efficiency, and 43 studies (with 373 observations) for transport. It explores positive and negative externalities, and it includes a broader corpus of impacts, including a host of externalities that were excluded from Sundqivist and Soderholm, notably climate change and greenhouse gas emissions, which means the social cost of carbon is accounted for as an external cost.

2. Research design: conceptual approach and methods

Our core approach is that of meta-analysis and research synthesis, a process that combines quantitative results across a set of studies to draw synthetic and crosscutting conclusions. This began by defining externalities and compiling an original dataset of externalities studies to examine.

2.1. Defining and conceptualizing positive and negative externalities

Generally, economic theorists have determined that for markets to function properly, all costs and benefits associated with exchanges (or negative and positive externalities) must be born solely by the participants of the transaction, or internalized in prices so that all assets in the economic system are adequately priced. An externality is a term used to describe an unintended "side effect without compensation" – that is, an unexpected cost or benefit resulting from an economic activity that affects people other than those engaged in that activity, and there's no proper compensation [12–14]. As the National Academies of Science put it, "An externality, which can be positive or negative, is an activity of one agent (for example, an individual or an organization, such as a company) that affects the well-being of another agent and occurs outside the market mechanism [15]."

When the principles of neoclassical economics were being formulated by Alfred Marshall in the 1890s and Arthur Cecil Pigou in the 1910s, one of their central arguments was that externalities *had* to be internalized (or taxed, to use Pigou's language) [16,17]. The reason is because rational firms will usually overproduce negative externalities (since somebody else pays for them) but under-produce positive externalities (since they are prone to free riders) [18]. While these economists were very cognizant of the virtue of the market as an efficient mechanism for the allocation of scarce resources, they understood that it could only operate satisfactorily within a framework of legal, political, and moral restrictions. Left to their own devices, firms would inevitably produce externalities in the interest of profit and growth [19].

This may all sound rather dry and theoretical, but it has very real implications for the energy and transport sectors. In the domain of energy, states will often require higher smokestacks on fossil-fueled power plants as a way to minimize the environmental harms of air pollution within their domain, shifting the pollution instead to a broader geographic area encompassing other states, a problem known as "state line syndrome [20]." Importers of LNG and oil have little incentive to change the nature of their imports to improve energy security (a positive externality, or public good) since the benefits of doing so are distributed to all companies and importers, including their competitors [21].

Similarly, in the transport sector, in Europe some 40 million people across 115 of the largest cities in the European Union are exposed to air exceeding health guidelines (for at least one pollutant) and children in particular residing close to roads with heavy-duty vehicle traffic have twice the risk of respiratory problems as those living near less congested streets [22]. Transport systems also create pernicious negative externalities including traffic congestion (traffic jams), physical inactivity, and noise. They can engender "community severance," and lack of fair access to education, health services, markets and shops, require land use for parking, and are prone to additive pollution associated with automotive manufacturing [23].

Externalities are not always negative, and can be positive. There are clear and compelling links between energy access and health, given that clean water and sewage disposal require modern sources of energy [24]. This means electricity access often creates positive externalities and cobenefits such as more reliable heath care, warm water, and street lights that enhance safety and wellbeing [25]. It has similarly been shown that the electrification of schools has positive externalities including extended studying hours, better skills development for computers, higher school completion (graduation rates), better exam scores and even gender equality, measured as a higher ratio of girls to boys [26]. The National Renewable Energy Laboratory noted in their survey of American electricity markets that low-carbon technologies were not adequately valued for at least six of the positive externalities that they provided, including risk management, environmental performance, investment, reduced resource use, improved public image, and economic spillover effects [27]. Another study concluded that the "risk management" benefits of clean power sources amounted to at least 0.5 ¢/kWh that were not reflected in traditional electricity markets [28].

In the domain of transport, studies frequently discuss the positive externalities of air pollution benefits of electric vehicles alongside their carbon savings and even social benefits such as higher status or "less guilt" when driving [29]. One study examining four low-carbon transition in Europe—including electric vehicles in Norway—even catalogued 128 distinct positive externalities, framed as "co-benefits," ranging from fuel savings and less water consumption to enhanced community democracy and less anxiety [30].

Despite this body of evidence, a more complete and balanced picture of these vast and differing impacts across different energy or mobility systems, by type of externalities, temporalities and locations is elusive. We sought to tackle this gap head on by offering a meta-analysis and research synthesis of hundreds of studies and observations looking closely at externalities. We use the terms “meta-analysis” and “research synthesis” because the research design straddles the two: it does comprehensively quantify estimations of externalities (a form of meta-analysis, even when we do not fully weight differentiations, see Section 3) but it also integrates a vast body of research across many disciplines and approaches (a form of research synthesis which does indeed have qualitative elements, see especially Sections 4 and 5).

2.2. Analytical protocol and coding strategy

To provide as comprehensive overview of externalities as possible, we searched the literature for studies on electricity and energy supply, energy efficiency, and transport and mobility. This included all fuels (nuclear, wind, coal, hydrogen, etc.), forms of efficiency (audits, retrofits, labels, demand side management), and transport modes (passenger travel, public transit/bus, rail, freight, aviation, marine shipping).

We first searched ScienceDirect, Taylor and Francis Online, Emerald Insight, ProQuest Central, JSTOR, and Google Scholar for the following keywords in English in the past thirty years (i.e. from 1990 to 2019): the search strings “external cost” and “externality” with “electricity,” “energy,” “renewable,” “efficiency,” “transport,” “mobility,” “fuel cycle,” “economic valuation,” “monetization,” and “quantifying.” This resulted in a corpus of 10,651 possible articles. We then as a team scanned all abstracts, titles, and keywords to check the relevance of each candidate study, with each study coded by at least two researchers, to minimize potential bias and mitigate coding fatigue. This process, which took four months, narrowed the candidates down to 447 articles. These candidates all had to address the estimation of externalities associated with electricity supply, transport, and/or energy efficiency in the abstract or summary. Ending our search protocol in 2019 did mean we miss a few very recent 2020 studies, including Bielecki et al. [31] and Vlachokostas et al. [32].

Nevertheless, the research team fully read all 447 of these studies. Exploring a whole document, we selected the articles for in-depth review according to the following protocol:

- **Detail**: it had to provide estimates of externalities detailed or disaggregated by fuel source, technology, or mode of transport, e.g. excluding studies such as Button[33] and Kammen and Pacca[34] (this lowered our sample to 313);
- **Valuation**: it had to use a valuation technique to actually monetize such damages, meaning we excluded studies that only estimated purely physical emissions or impacts, e.g. excluding Musso and Rothengatter [35], or studies that presented ratio/percentage estimates, e.g. Davis [36] (this lowered it to 264);
- **Rigor**: it had to be peer reviewed, that is published in an academic peer-reviewed journal or confirmed that it was peer reviewed via a conference, a PhD committee, or an institution. This means we can in some cases include PhD theses/dissertations, conference proceedings, and reports, but only if we could verify they were peer reviewed, e.g. excluding McAuley [37] (this lowered it to 201);
- **Originality**: it had to provide its own estimates of externalities. We excluded review papers and studies that only refer to the other research results, e.g. excluding the National Research Council [38], or older versions of studies that were replaced by a newer update, e.g. excluding Parry and Small [39] as it was updated by Parry et al. [40] (this lowered it to 139).

Thus, 308 articles were excluded by these criteria (see Appendix I), and 139 studies were closely reviewed (see Appendix II): 83 papers for the externalities from electricity generation, 13 for energy efficiency, and 43 for transport.

With these studies collected, we then began an iterative or recursive process of cataloguing externalities at the same time we expanded our coding categories to reflect the findings of the research. Meta-analyses can each be distinguished between *a priori* reviews that start with fixed criteria or search strings that do not change once the search begins, and *iterative* reviews that modify search strings based on ongoing results, leading to repeated searches. We chose the *iterative* approach. This meant we cover a far broader range of externalities than most other studies, including climate, health, and environment but also aesthetics, noise, vibration, insurance, and accidents. We also sought to examine the methods utilized by studies to estimate and monetize such externalities, arriving at a classification scheme of 12 distinct approaches (including contingent valuation and hedonic valuation to abatement costs, shadow costs and choice experiments). As a final methodological point, our analysis collated all the resulting costs by category, with no other weighting or methodological breakdown. For more details, see Section 4.1.

2.3. Strengths

The prime strength of our meta-analysis and research synthesis approach is that it offers a more comprehensive and robust examination of a topic that is not confined to a single study, its focus, its assumptions, or its methods. Research synthesis is especially useful for statistically aggregating quantitative results from a number of similar studies to increase the statistical power of tests and the precision of parameter estimates [41,42]. Aggregate results can be pooled and analyzed with a meta-regression technique that estimates an overall effect size, while also explaining variations across studies (e.g. different samples or methods).

Weighting the estimates could be an option for the research synthesis of the externalities. We cover three decades of studies, and there have been continuous technological improvements in electricity generation and transport. Thus, one could think the recent estimates deserve more weight. Also, studies that quantify a countries’ externalities with better data or large externalities could have more attention than others. However, the basis of the weights could be debatable [43]. The better data or large externalities do not guarantee the importance of estimates, and, even if they could, the size of externalities does not represent a weight. We decided not to apply various weighting schemes considering an effect size in a meta-analysis because many articles reviewed in this paper present deterministic estimates. We therefore present an unweighted assessment of externalities but publish our full dataset and accompanying data tables (see Appendices I, II and Appendix B) so that others wishing to design weighted estimations can do so. Same with those wishing to run more complicated regressions or models of national, regional, or global externalities, whom we welcome to build on our work and our dataset.

While the method of meta-analysis and research synthesis is powerful, it is only appropriate for clear and precise research questions that have previously been addressed by a large pool of comparable quantitative studies. Put another way, meta-analyses may not be possible for some study types, and they do not always yield more useful results (for example if the included studies are too heterogeneous). They are common in fields such as medicine, but much less common within energy social science. There are exceptions, however, such as estimates of energy price elasticities [44], social influence effects for alternative fuel vehicle purchases [45], and the success of demand response programs [46]. This is explicitly why we coupled or meta-analysis approach with a research synthesis.

2.4. Limitations

Our approach means we are combining studies with very different units and assumptions. In other words, the study is a research synthesis of the existing already-published evidence, not a single study designed by the authors or one that uses a harmonized technique for monetizing externalities or even consistent units of analysis or boundaries of inclusion and exclusion. Because of the complexity of electricity supply, energy efficiency, and transport, the sources of externalities are multifarious. Also, the estimation methods and units of the externalities are varied: monetary value per kWh, kW, household, year, person-km, vehicle-km, ton-km, etc. Although we classified the externalities by power generation source, transport mode, and monetization method, combining the estimates from various studies in a single meta-study inevitably loses heterogeneity of the estimates, including location factors.

Because our approach is synthetic, we also take at face value whatever monetary value a given study applies to things like the social cost of carbon, or air pollution, or even the statistical value of a human life. These assumptions, of course, are highly debatable. Furthermore, some of the externalities that are monetized in the literature may in fact have a value far beyond their price tag, given they may offer critical ecosystem services or hold significant non-monetary value for some particular groups, i.e. some have argued that the value of a life of a person or a child, an old-growth forest, the protection of an indigenous community, or a quiet and natural space are priceless, and hold infinite value [47–49]. We sidestep this debate by relying instead on how each study within our sample monetizes externalities.

Moreover, scholars may focus on those markets with large externalities, or those markets with better data—the synthesis of published studies may result in biased estimates of the global means reported in the paper. In addition, the large time period covered by this paper—drawing from papers over nearly three decades—may also introduce bias when evaluating subsidies today. For example, since 1990, U.S. power sector SO_2 emissions have fallen 92%, power sector NO_x emissions have fallen 84%, and power sector CO_2 emissions have fallen 12%, while electricity generation was 36% higher in 2019 than in 1990 [50]. The external damages from the power sector have changed significantly over the course of the time period covered by this paper. A study from the 1990s or 2000s would likely yield a much higher estimate of the external costs of power generation than one published in the past few years. It is open for debate whether the best way to summarize the insights of the literature is to simply report external costs as published in these papers or to extract the monetization and apply them to the characteristics of the energy system today.

To help hedge this concern, the study presents summary data per kWh (or for mobility, things like kilometer travelled) so as kWh go up or down researchers and readers can attenuate estimations to take into account particular volumes. While the study also extrapolates global damages from externalities using the statistical mean from the data, we also publish our full dataset (with minimum, maximum, and other ranges) so that others can use this data to show a sensitivity in

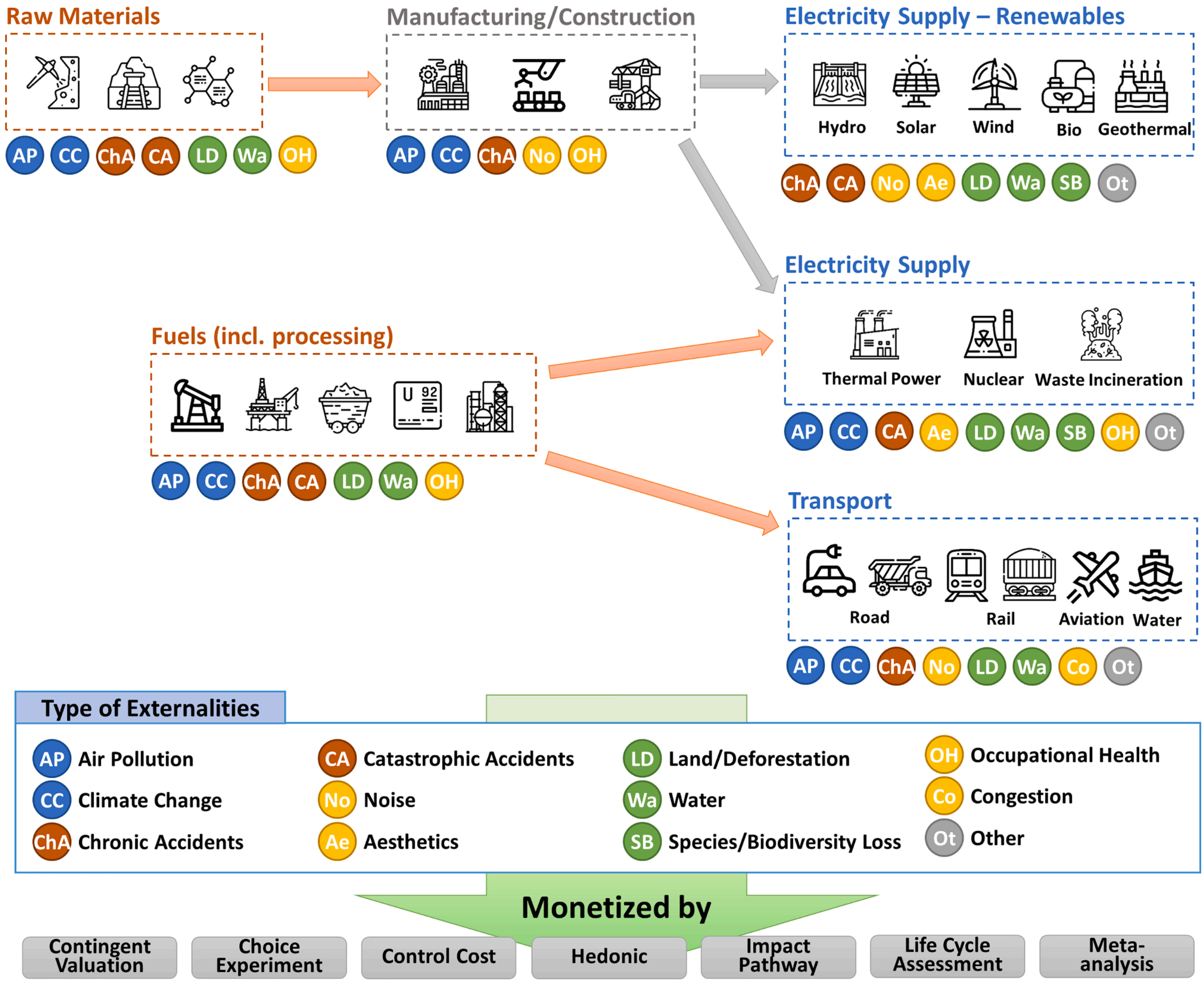

Fig. 1. Sources and pathways of the externalities associated with electricity supply and transport. Our diagram captures all of the lifecycle components of energy and transport systems represented in our analysis, including raw materials extraction, manufacturing and construction, fuel processing, as well as supply and use. We also catalogue seven classes of monetization techniques within the literature, which are described in greater detail in Section 4.

estimations and results. Nevertheless, given our approach does rely on a synthesis of the literature, it is unable to account for particular differences within or across countries, even if a substantial share of the externalities is internalized through taxes or other regulations such as standards. One important aspect of externality studies is their specificity: estimates are highly context-specific and they differ across various technologies. Our calculation of global averages aggregates and therefore in a way hides these variations—but again, this limitation is offset by the publication of the full dataset.

3. The hidden costs (or benefits) of electricity, transport, and energy efficiency

Our meta-analysis and research synthesis reveals that externalities cut across multiple lifecycle stages of energy and transport systems (e.g., raw materials and construction to fuel processing and use, roadbuilding, car crashes) as well as types of impacts (including pollution, accidents, and noise). Fig. 1 provides an overview of our findings, as well as common techniques of monetization (discussed more in Section 4.1), and Appendix II offers the full list of *all* studies we examined. In this section, we focus on monetizing this range of externalities within the available evidence.

3.1. Electricity

Within the sample of 83 studies we analyzed in depth on electricity, we collected 318 different observations of the externalities associated with electricity supply, of which 288 offered monetized estimations of those externalities. The bulk of these externalities were deemed negative (a cost) rather than positive (a benefit). As shown in Fig. 2 and Table 1, from this literature the average kWh of electricity produces a mean of 7.1 cents per kWh in unaccounted for externalities, or a median of 2.3 ¢/kWh. Using the mean, the energy systems with the greatest externalities are waste (14.6 ¢ per kWh), coal (14.5 ¢), and oil (7.6 ¢); those with the least externalities are geothermal (0.09 ¢), solar thermal (1.5 ¢), and hydroelectricity (1.7 ¢).

One striking aspect to these numbers is they approach the levelized costs of energy (LCOE)—the lifetime costs of an energy system divided by its energy production, often used to calculate the total cost of building and operating an energy system over its assumed lifetime—reported for some energy systems. Fig. 3 plots the most recent edition of Lazard's LCOE numbers for unsubsidized energy systems [51]. The LCOE of conventional coal is 6.6 to 15.2 ¢/kWh, yet its mean externalities are 14.5 ¢/kWh. The externalities for wind energy (2.98 ¢/kWh) are also close to its range of LCOE (2.8 to 5.4 ¢/kW), as are natural gas combined cycle turbines (externalities of 3.5¢, LCOE of 4.4 to 6.8 ¢/kWh). This illustrates the possible degree of market failure associated with energy systems—their social costs are almost as significant as their production costs.

Table 1
Summary of negative externalities associated with electricity supply (adjusted to US$2018, ¢/kWh). Note that "positive" externalities are reflected in this table with a minus symbol.

Source	# of obs.	min	median	mean	max	s.d.
Bio	34	−11.672	0.772	5.900	104.112	21.051
Coal	71	0.019	8.100	14.479	157.885	27.727
Fuel Cell	5	1.470	3.554	4.088	7.053	2.130
Gas	46	0.067	2.947	3.461	13.572	2.980
Geothermal	2	0.071	0.093	0.093	0.115	0.031
Hydro	26	−0.511	0.127	1.756	21.216	5.398
Nuclear	19	0.002	0.379	5.635	54.048	14.503
Oil	34	0.606	6.639	7.639	27.217	6.260
PV	16	0.085	0.666	5.338	74.496	18.449
Solar Thermal	6	0.088	0.232	1.502	7.964	3.166
Waste	5	7.819	10.034	14.615	31.764	9.976
Wind	24	0.007	0.199	2.976	42.099	9.486
Total	288	−11.672	2.328	7.152	157.885	17.578

When our overall externalities estimations are put into the context of global electricity supply, which amounts to roughly 14,000 million tons of oil equivalent each year (or 162,820 TWh/year), the results are striking. Using the mean number of 7.152 ¢/kWh, global electricity externalities would amount to $11.644 trillion; using the median number (2.328 ¢/kWh), they would amount to $3.79 trillion.

These estimations are similar to some in the existing literature. The International Monetary Fund projected the cost of externalities

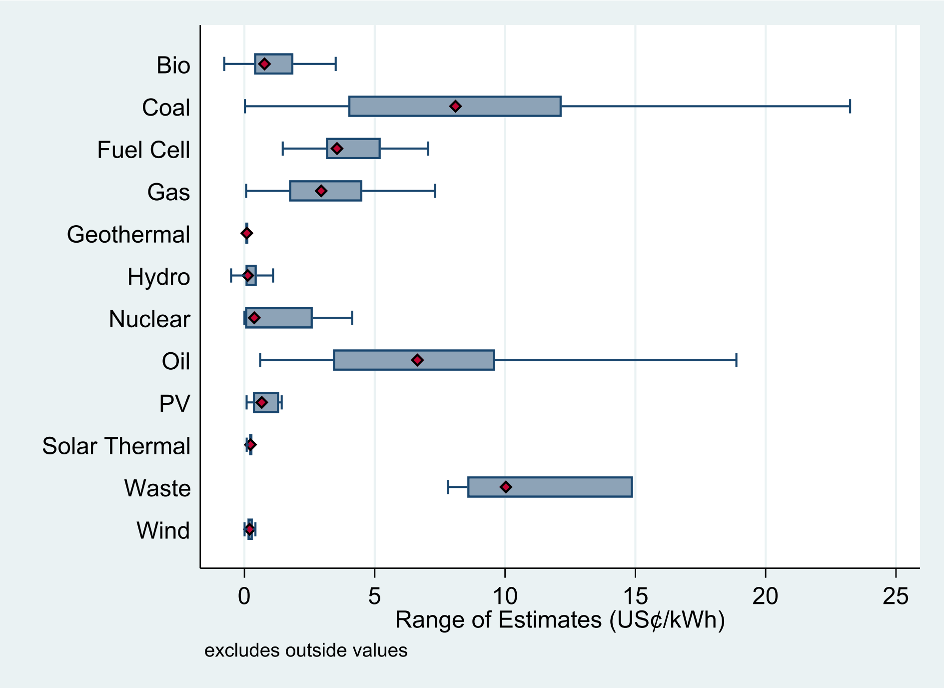

Fig. 2. The negative externalities associated with electricity supply (adjusted to US$2018, ¢/kWh). The estimates are for the externalities presented in Fig. 1, and air pollution and aesthetics (if estimated) are the most important in terms of cost. Low-carbon sources of electricity such as geothermal, solar thermal and solar PV, wind, hydro, and nuclear have the lowest negative externalities. The left end denotes minimum and the right end maximum in the box-and-whisker plots. The red dot means the median, and the left and right end of the box represent the first and third quartiles, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

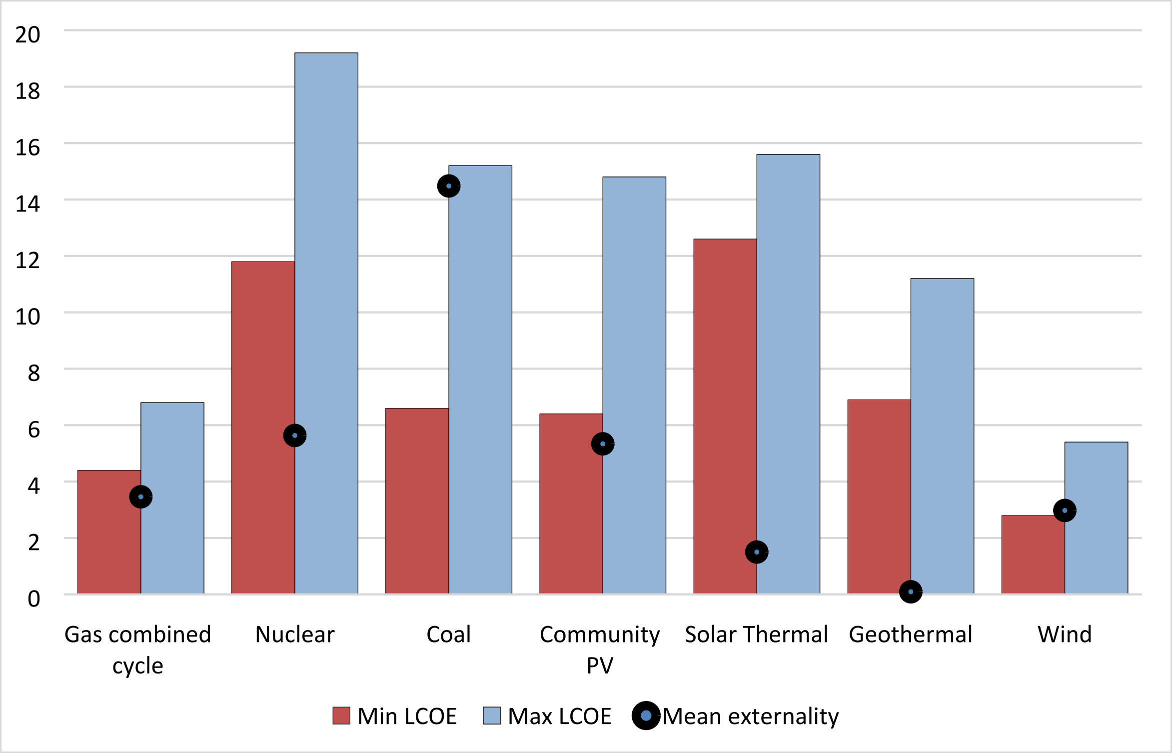

Fig. 3. Comparing the mean levelized cost of energy with mean externalities (in US$2018 cents/kWh). The figure shows the minimum Levelized Cost of Energy and Maximum Levelized Cost of Energy from Lazard's, a global database [51]. Mean externalities from our meta-analysis and research synthesis are plotted in the black bubble. The diagram shows how the externalities for coal are clearly far above its LCOE, those for gas, community solar, and wind nearly equal to their LCOE.

associated with global energy subsidies to be in the range of $5.2 trillion in 2017 (6.5% of global GDP that year) [52]. Hinkel et al. monetized just one externality from climate change (storm surges) in one area (coastal locations) and projected they could amount to $100 trillion by 2100, affecting up to 600 million people [53]. Internalizing the cost of mortality and asthma—just two externalities—into electricity prices would increase the price of electricity in Illinois, Massachusetts, and Washington by almost eight times [34]. Including the costs of coal mine dust, black lung disease, and acid deposition would double the price of coal if they were incorporated into its price [54]. Indeed, one recent

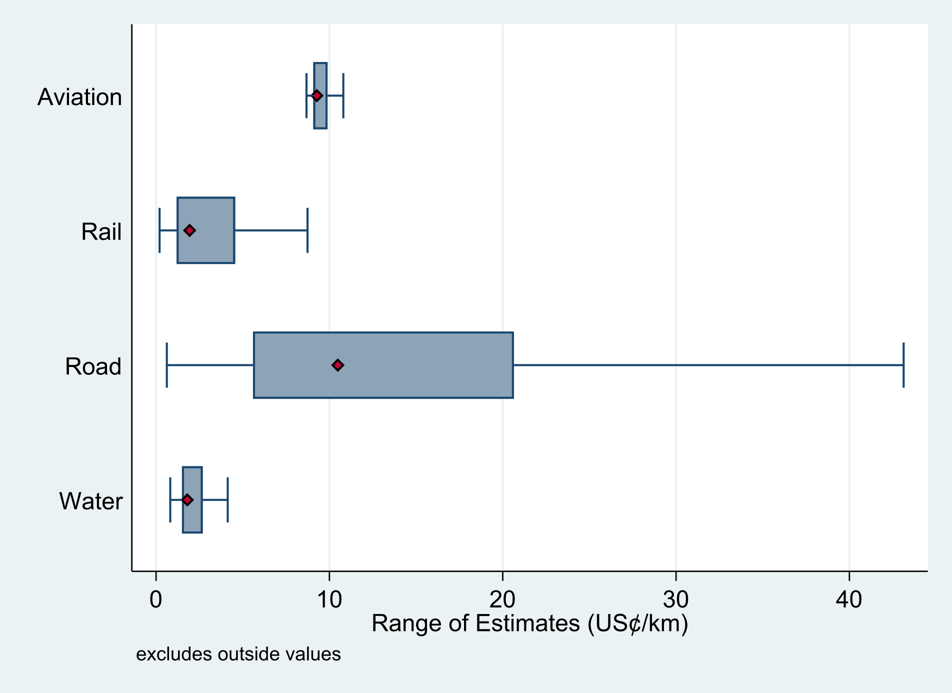

Fig. 4. The negative externalities associated with transport (adjusted to US$2018, ¢/kWh). The estimates are for the externalities presented in Fig. 1, and air pollution and congestion (if estimated) are the most important in terms of cost. Water and rail systems have the least negative externalities for transport. The left end denotes minimum and the right end maximum in the box-and-whisker plots. The red dot means the median, and the left and right end of the box represent the first and third quartiles, respectively.

study noted that “considering the external costs from local air pollution alone would increase the price of coal by a factor of two to three in most G20 countries, even without taking into account climate change impacts.”[55] Other older studies report that if the environmental costs of electricity generation were included in its price, they could very well be equivalent to one to two percent of the entire GDP for the EU [56,57].

3.2. *Transport*

Within the sample of 43 studies on transport we analyzed in depth, we collected 373 different estimations, of which 318 offered monetized estimations of those externalities. Similar to electricity (see Fig. 4 and Table 2), the bulk of these externalities were deemed negative (a cost) rather than positive (a benefit). The mean estimation of externalities was 17.8 cents per kilometer travelled across all sources of transport, although these did vary significantly with a mean of about 9 ¢/km for aviation but 11.9 ¢/km for rail and 22.6 ¢/km for road travel—a surprising finding that road travel has more externalities than air travel. Water based travel had by far the least externalities, with 2 ¢/km.

These externalities can be roughly correlated with actual travel patterns, and organized by mode of travel (see Appendix II for more details). Table 3 crosschecks our estimations of externalities with reported kilometers travelled or kilometer-tons travelled from the International Civil Aviation Organization (for aviation), International Union or Railways (for rail), International Road Federation (for passenger travel) and the International Transport Forum (for passenger travel, road/inland freight, and coastal shipping). Here, again, the numbers are staggering: transport externalities accumulate to $517.02 billion (min), $13.018 trillion (mean), or $99.926 trillion (max). If accurate, our estimations of global externalities are *greater* than public and private capital investment in transport around the world, which the World Resources Institute calculated to be between $1.4 and $2.1 trillion annually [58].

These numbers are similar to other estimations. Lovins estimated the external costs only with passenger automobiles—including congestion, accidents, pollution, climate change, and noise—in one country, the United States, and projected they were $820 billion in 2010$ [65]. Another study sought to estimate all external costs within the European Union associated with transport modes for road, rail, inland waterways, aviation, and maritime transport, and came up with an indicative estimate of €987 billion (or 6.6% of GDP) [66].

3.3. *Energy efficiency and demand response (DR)*

In the case of energy efficiency, we have an example of a net positive externality (more social benefits) rather than a negative one (more social costs). As just one example of this, Baskette estimate that avoided costs of California’s demand side management programs amounted to approximately $5/MWh [67]. Such positive externalities from energy efficiency improvements mainly come from energy savings and correlated features such as greenhouse gas emissions reduction, mitigating air pollution, enhancing energy security, industrial productivity improvements, and energy poverty alleviation (see Table 4).

Table 2
Summary descriptive statistics for negative externalities associated with transport (in cents per km in US$2018).

Source	# of obs.	min	median	mean	max	s.d.
Aviation	29	1.066	9.278	8.965	11.421	2.227
Rail	67	0.202	1.938	11.89	203.339	38.321
Road	201	0.621	10.487	22.564	239.174	35.48
Water	19	0.819	1.801	2.022	4.133	0.815
Total	316	0.202	7.769	17.818	239.174	33.934

Table 3
Summary of the negative externalities associated with transport (in billions of US$2018). Looking only at the mean numbers by transport mode, road travel accounts for the vast majority of these impacts (67.22%) followed by road freight (31.27%), water (0.96%), rail (0.39%), and aviation (less than 0.1%). More details are offered in Tables A1 and A2. Note that Rail has been deducted from the International Transport Forum data for “total inland freight” measurement to avoid double counting.

	min	mean	max	% total (mean)
Aviation (in US¢/p-km)	1.48	9.25	11.42	
Passenger billion km travelled/year[59]	84.46	84.46	84.46	
Cost/year (US$2018)	1.25	7.81	9.65	0.06%
Rail (in US¢/t-km)	0.20	1.70	8.41	
Billion kilometers travelled/ year[60]	2954	2954	2954	
Cost/year (US$2018)	5.97	50.22	248.46	0.39%
Road (passenger transport in US¢/p-km)	0.62	23.98	239.17	
Billion kilometers travelled/ year[61,62]	36,541	36,541	36,541	
Cost/year (US$2018)	226.92	8764.01	87396.73	67.32%
Road (inland freight in US ¢/t-km)	0.84	14.60	43.13	
Billion tons-km travelled/year [63]	27876.3	27876.3	27876.3	
Cost/year (US$2018)	233.60	4070.78	12023.05	31.27%
Water (coastal shipping in US¢/t-km)	0.82	2.08	4.13	
Billion tons-km travelled/year [64]	6016.5	6016.5	6016.5	
Cost/year (US$2018)	49.28	125.20	248.66	0.96%
Total	**517.02**	**13018.02**	**99926.55**	

Given that avoided negative externalities could be actively monetized into positive externalities, then the social value of demand-response can be obtained from the following calculation:

(Avoided electricity generation (negawatt) by DR) × (*weighted average of negative externalities from electricity)*

Given we already calculated the negative externalities with electricity, it is possible to convert this into a more rigorous unit (see Table 5). Assuming the avoided electricity generation by global DR affects the world power mix equally, then we can get the positive externality of DR. This is a sort of conservative estimate because DR would reduce the power generation from fossil fuels. Countries introducing DR in the electricity market are inclined to choose environmental dispatch rather than an economic one. Based on this logic, the average positive value of energy efficiency or demand response is 7.804¢/kWh. We calculate from this that global DR efforts produce about $312 billion in positive externalities.

Again, our ballpark estimates for efficiency are congruent with other estimations. One assessment noted (using 2012 data) that new efficiency standards alone (one type of efficiency) were estimated to lead to energy efficiency investments of $80 billion a year up to 2020 which would save between $40 billion and $190 billion in fuel costs (only one type of positive externality) [78]. Between 2015 and 2018, IEA member countries (not all countries) saw more than $100 billion in lower fuel costs (just one type of positive externality) thanks to efficiency gains, with cumulative avoided expenditure since 2000 reaching $600 billion [79]. The IEA also estimated that annual investments in global efficiency across buildings, transport and industry were about $240 billion [78]—a number lower than the positive externalities we calculate. This all affirms the positive cost-benefit ratio of energy efficiency efforts: the positive externality of efficiency investment appears greater than the direct efficiency gains.

3.4. *Severity and types of externalities*

Qualitatively, the externalities associated with energy or mobility differ substantially by type, with the literature suggesting at least nine

Table 4

Summary of the externality studies focusing on energy efficiency, demand management and demand-response. The benefits of efficiency do differ by type of technology or program. Air conditioning efforts tend to have the greatest positive externalities (or net avoided costs) followed by refrigeration and lighting. These efforts do also vary based on new vs. existing technologies and their externalities are distributed across not only energy supply but also transmission and delivery and the environment.

Study	Program	Country	Externalities	Method	Estimate(s)
Baskette *et al.* [67]	Air conditioning, Outdoor lighting, Refrigeration	USA	Air pollution, CO_2	Avoided cost	With the avoided cost of electricity, transmission and distribution, ancillary services) $138/MWh for air conditioning, $78/MWh for outdoor lighting, and approximately $80/MWh for refrigeration.
Alnatheer [68]	Demand-side management	SAU	Air pollution, CO_2, Water, Land	Damage cost (*meta*-analysis)	Mid-range values of externalities is 796 billion 1999 SR without DSM, 741 with moderate DSM, and 717 with aggressive DSM.
Jakob [69]	Thermal insulation	CHE	Air pollution, CO_2, noise, indoor air quality, comfort	Marginal cost estimation	Conventional air pollutants: 0.008–0.034 CHF/kWh. Greenhouse gas emissions: 0.045–0.08 CHF/kWh. Avoidable external costs of energy use due to improved thermal insulation: a few cents of CHF/kWh. Cannot be acquired: avoided costs caused by illness or by loss of earnings. Only in figure: noise reduction, room air quality, comfort
Xiao *et al.* [70]	Various energy efficiency technologies	CHN	CO_2	Own bottom-up model (marginal abatement cost)	Average carbon abatement cost of the China's building sector by various energy efficiency technologies is 19.5$/t-$CO_2$.
Smith and Brown[71]	Demand response	USA	CO_2	GT-NEMS simulation and regression	DR is likely to have little impact on CO_2 emissions from the U.S. electricity sector under a variety of scenarios and ways that DR might operate.
Callaway *et al.* [72]	Lighting	USA	CO_2	Marginal cost estimation	Avoided emissions values are 18.23–36.85 $/MWh for commercial lighting efficiency, 18.05–37.66 $/MWh for residential lighting efficiency.
Jones[73]	Lighting (LED streetlights)	USA	Well-being	Difference-in-difference	$477 (6.9%) increase in per capita monthly household income.
Royo *et al.* [74]	Retrofitting of industrial furnaces	GRC, ITA, ESP, FRA	Air pollution, CO_2, Water	LCA	The innovative DC induction system in the three scenarios are ranged from 0.85 to 0.91 Euros per aluminum billet as the European average. The decrease was mainly attributed to the GHG reduction caused by the energy efficiency enhancement of retrofitting technology.
Yang and Lam[75]	Energy efficiency management system using ICT	HKG	Non-market benefits (happiness, health, etc.)	CV	EWTP equals HK$161.04/person, the expected non-market benefits would be HK$526.66 million (about 2018 US$67.52 million).

Table 5

Summary of positive externalities associated with energy efficiency (adjusted to US$2018, ¢/kWh). The IEA notes that this estimation of 4000 TWh assumes the New Policies Scenario. The amount represents the sum of flexible loads at each hour of the year, excluding EVs at times when they are expected to be in motion. The size of this potential demand-side response offers considerable scope to reduce peak loads. We can again take this number and correlate it with global efficiency and DR efforts. The IEA reports that annual demand-side response provided 4000 TWh of energy savings in 2018, or about 15% of global total electricity demand [76]. Granted, these positive externalities or savings would not be distributed equally. The IEA also notes that while DR efforts have been historically limited to large-scale industrial consumers, most future DR potential (more than 75%) lies in DR for buildings, with space heating, water heating and air conditioning loads contributing the greatest [77]. They also project an increase in DR to 7,000 TWh by 2040, an amount which would correspond to $546.3 billion in positive externalities (following our earlier calculation).

	Generation in 2018(TWh)	percentage	Min (¢/kWh)	Median (¢/kWh)	Mean (¢/kWh)	Max (¢/kWh)
Coal	10,123	38.11%	0.019	8.100	14.479	157.885
Natural Gas	6118	23.03%	0.067	2.947	3.461	13.572
Oil	808	3.04%	0.606	6.639	7.639	27.217
Nuclear	2718	10.23%	0.002	0.379	5.635	54.048
Hydro	4203	15.82%	−0.511	0.127	1.756	21.216
Bioenergy	636	2.39%	−11.672	0.772	5.900	104.112
Wind	1265	4.76%	0.007	0.199	2.976	42.099
PV	592	2.23%	0.085	0.666	5.338	74.496
Geothermal	90	0.34%	0.071	0.093	0.093	0.115
CSP	12	0.05%	0.088	0.232	1.502	7.964
Marine	1	0.00%				
Weighted Average			−0.316	4.069	7.804	79.163

Source: Authors, with data from World Energy Outlook 2019 (IEA, 2019)

distinct categories [80–85]. *Air pollution* includes acid rain and its disruption or degradation of fisheries, forests, and crops, as well as atmospheric damage to buildings, automobiles, and materials by corrosion and the increased maintenance it requires. *Climate change* includes global warming and all of the associated impacts of sea level rise or temperature changes. *Chronic accidents* include leaks, minor spills, and safety incidents. The risk of *catastrophic accidents* includes nuclear meltdowns, oil spills, coal mine collapses, natural gas wellhead explosions, and dam breaches. *Aesthetic issues* include the incidence of noise and reduced amenity or visibility. *Direct land use* impacts include deforestation, sedimentation, desertification, acid drainage, and subsidence. Traffic and transport infrastructure negatively affects land and deforestation. It includes damage to vegetation, soil pollution by infrastructure and heavy metals, and the land used for associated roads, rails, and ports. *Water use* includes water consumption and withdrawals and consequent impacts on agriculture and ecosystems where water is scarce. *Species loss and habitat destruction* include the disruption of ecosystem services provided by wetlands, waterways, different types of forests, grasslands, deserts, tundra, coastal and ocean habitat. *Occupational exposure* includes the threat posed by hazardous substances and public health issues and diseases resulting from pollution or harmful exposure to fuels or technologies, including premature deaths and injuries.

These nine categories show up frequently within our research synthesis, as Table 6 summarizes, alongside a more diffuse category of "other" externalities including the increased likelihood of wars due to natural resource extraction, the "resource curse," or the securing of energy supply; degradation of cultural icons such as national parks, recreational opportunities, or activities such as fishing or swimming; the perhaps perpetual and extremely long-lived maintenance of caches of spent nuclear fuel; and changes to the local and regional economic structure through the loss of labor and jobs and transfer of wealth and reductions in GDP. Fig. 5 (Panel A) shows that after climate change, the most costly monetized externality with electricity is air pollution followed by land degradation. For transport (Panel B), the largest externality is congestion (by far) followed by traffic accidents, air pollution, and climate change, with noise only coming fifth. The external cost of traffic congestion includes opportunities foregone due to travel delay, but also energy use, accident possibility, vehicle wear and tear by the congestion, the discomfort of crowding, and time uncertainty of travel [86]. Thus, it is logical that the cost of traffic congestion has a higher value than other externalities.

More details are offered in Tables A3 and A4.

Table 6

Summary of negative externalities by type associated with electricity supply and transport (adjusted to US$2018).

a. Electricity supply (¢/kWh)

Externality	# of obs.	min	median	mean	max	s.d.
Air Pollution	189	−0.429	0.625	3.574	114.906	11.643
Climate Change	152	−0.701	1.279	2.297	17.277	2.962
Chronic Accidents	1	0.002		0.002	0.002	
Catastrophic Accidents	23	0.000	0.047	0.414	4.257	1.007
Noise	10	0.000	0.002	0.068	0.532	0.168
Aesthetics	8	0.007	0.148	5.446	42.099	14.813
Land/ Deforestation	23	0.000	0.380	2.217	20.220	4.895
Water	19	0.000	0.000	0.232	3.345	0.759
Species/Bio Diversity Loss	40	0.000	0.059	0.101	0.477	0.123
Occupational Health	33	0.003	0.050	0.088	0.386	0.105
Other	122	−0.517	0.033	1.678	66.515	7.719

b. Transport (¢/km)

Externality	# of obs.	min	median	mean	max	s.d.
Air Pollution	69	0.000	1.523	8.233	105.961	19.946
Climate Change	52	0.019	0.838	1.269	16.064	2.326
Chronic Accidents	68	0.000	2.048	6.535	107.785	15.827
Catastrophic Accidents	0					
Noise	70	0.000	0.600	2.825	71.666	9.446
Aesthetics	9	0.000	0.086	0.080	0.154	0.047
Land/ Deforestation	3	0.016	0.157	2.439	7.144	4.076
Water	12	0.000	0.060	0.123	0.576	0.167
Species/Bio Diversity Loss	9	0.000	0.034	0.046	0.103	0.040
Occupational Health	0					
Congestion	46	0.000	4.438	13.482	81.379	21.156
Other	26	0.000	0.400	0.828	6.094	1.389

Note that "positive" externalities are reflected in this table with a minus symbol.

4. Common approaches and the technological and geographic distribution of externalities

Although monetizing positive and negative externalities is useful, it obscures some of the assumptions put into generating discrete estimates, as well as the potential technological and geographic distribution of those externalities.

4.1. Methodological assumptions and approaches

The literature uses varying methodologies and approaches, with no agreed upon or unified approach. Assessing the monetary value of the externalities has the same way of appraising environmental and health damages by pollutants. Thus, monetization methodologies for externalities are diverse and have a long history. We classify them into seven groups, with Table 7 and Fig. 6 offering an overview of their frequency of use within our research synthesis for electricity (Panel A) and transport (Panel B).

4.2. Distribution of externalities by nation and fuel-source

The grand figures presented in Section 3 tell us little about the distribution of externalities by country or region or technology and fuel source. As a thought experiment, we correlated our externalities numbers with data from BP's most recent Statistical Review of World Energy [101]. We chose this source because it:

- Breaks down energy demand by fuel source;
- Disaggregates energy demand by geographic region;
- Offers macroeconomic estimations that include energy demand as a whole (across buildings, industry, agriculture, etc.);
- Projects future energy demand outward to 2040.

The results illustrate a range of externality impacts across China, India, the United States and the European Union. Our analysis buttresses the point that many externalities are location dependent, the exception perhaps being greenhouse gas emissions and global climate.

Nonetheless, consider the national level externalities of just one of these countries. Taking the extra cost associated with scrubbed coal—a mean of 14.48 ¢/kWh—and multiplying it by coal's projected total supply for one year (2020) in the United States (3570.41 TWh, for all sectors including electricity and industry), the amount is $516.96 billion. In other words, coal generation created $517 billion of additional costs that neither coal producers nor consumers had to pay for, costs that were instead shifted to society at large. For oil, the number is $787.8 billion (7.639 ¢ and about 9920.39 TWh). For natural gas, the number is $265.6 billion (3.46 ¢/kWh and about 7675.8 TWh). For nuclear, it is $87 billion (5.635 ¢/kWh and about 2093.4 TWh). Sticking with the mean numbers from our sample, it's another $13.68 billion for hydropower; for all other renewables about $73.4 billion. Adding all of these together, one gets more than $1.745 *trillion*, far, far more than the entire revenues the electricity industry reported for 2019 ($390 billion [102]), or those from the upstream oil and gas industry ($181 billion [103]).

When looking at the expected 2020 data by fuel sources and all four geographic regions, Fig. 7 reveals that coal accounts for by far the largest share of externalities ($4.78 trillion, or 59%) followed by oil (more than $2 trillion, 26%) and gas ($552 billion, or 7%). The minimum range does become net positive in some situations, a gain of $10 billion in positive externalities for the United States in 2040, and gains of $9 billion for India in 2030 and $24 billion in 2040. Less carbon intensive fuel mixes have fewer externalities, so as you decarbonize more social benefits can be gained. But these are the exceptions and only the minimum estimates. Even the minimum estimates (that would be the most conservative, and presume the best operating technologies) collectively suggest major damages across these four locations: $110 billion. The

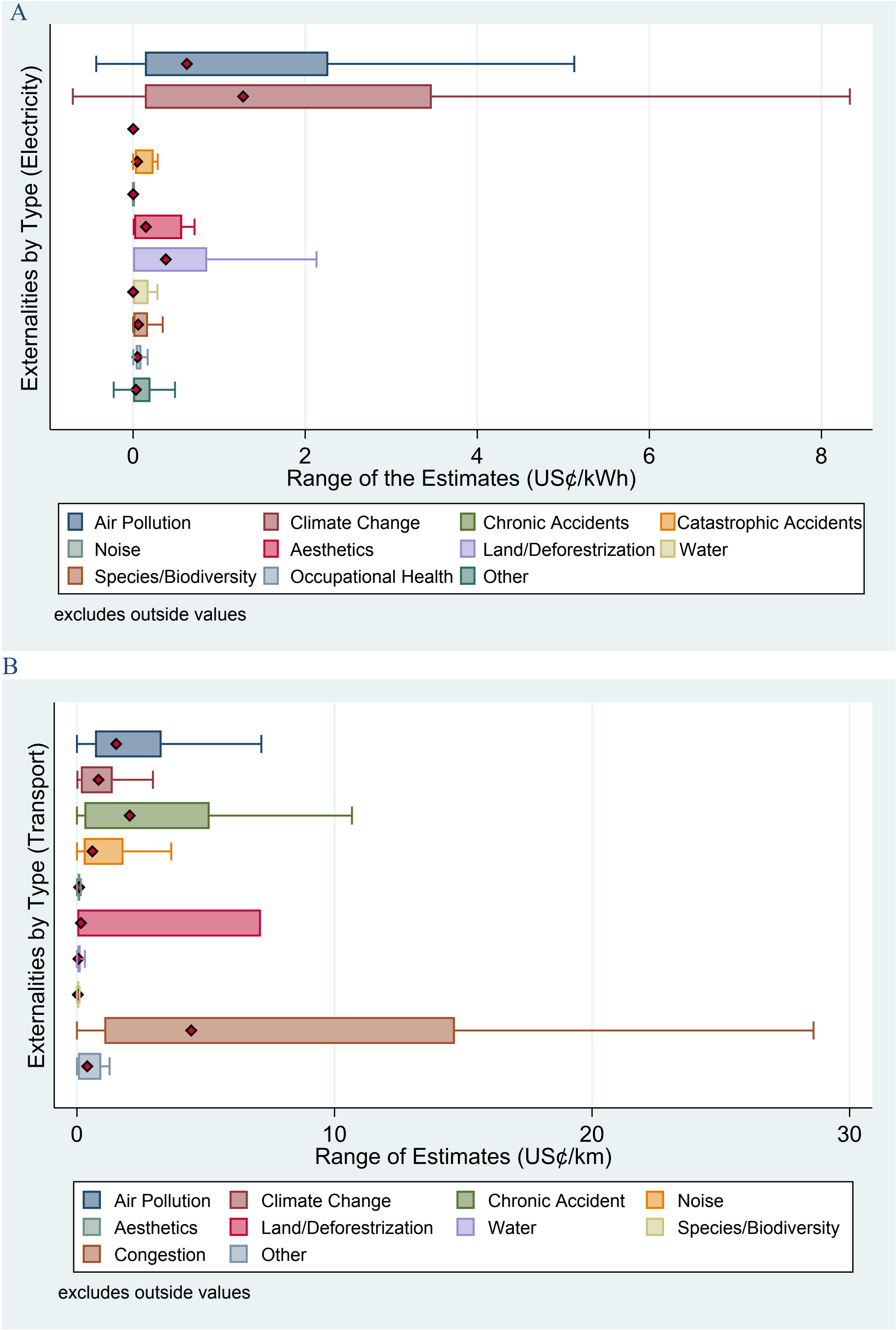

Fig. 5. The negative externalities by type associated with electricity supply (top panel) and transport (bottom panel) adjusted to US$2018, ¢/kWh and ¢/km. The range of the monetized estimates is broad. Because of the large standard deviation of aesthetics, air pollution, and congestion, the severity of externalities is changed if we apply mean values instead of the median. In terms of mean, the most severe externality with electricity is aesthetics, followed by air pollution, climate change, and degradation. For transport, the mean value indicates congestion as the most costly externality like the median, but air pollution takes second place, followed by accidents, noise, and land degradation. Note: The left end denotes minimum and the right end maximum in the box-and-whisker plots. The red dot means the median, and the left and right end of the box represent the first and third quartiles, respectively.

Table 7
Methodological approaches of selected externality studies.

Methods	Symbol	Description	Examples
Contingent Valuation/ Choice Experiment	CV/CE	Contingent valuation and choice experiment capture a consumer's stated preference. Through well-designed surveys and econometric models, they can monetize negative or positive externalities associated with electricity supply and transport.	[87,88]
Hedonic	Hedonic	The hedonic approach is powerful when the externality directly (or even indirectly) affects any property value. For example, we could apply the hedonic method if there are aesthetic changes by installing a wind farm nearby residential area.	[89,90]
Impact Pathway Approach	IPA	The IPA is the method introduced in the ExternE project. The IPA quantifies various externalities through preferences of individuals affected (willingness to pay), market prices, replacement cost, averting cost, and hedonic approaches [91].	[92,93]
Life Cycle Assessment	LCA	LCA approaches seek to capture the externalities associated with all stages of an energy system, so-called "from the cradle to the grave." Sometimes multiples monetization methods, such as contingent valuation and input–output analysis, are applied by stages.	[94,95]
Meta-analysis	Meta	Because of the diversity of the externality types and estimates, a *meta*-analysis could be a reasonable alternative to infer their monetary value. Statistical approaches or econometric methods used to be applied for the data from previous literature in a *meta*-analysis. Although it is time-consuming work, a well-organized *meta*-analysis can present a reliable range of the estimates.	[96,97]
Multiple methods	Multi	There exist studies that apply multiple methods for the monetization, which we classified them into the "Multi" group. The IPA and LCA also use multiple methods, but we classify them separately because it is worthwhile to see them individually.	[98,81]
Others	Others	The "Others" group consists of unpopular methods for monetization and ambiguous studies to classify. Besides the above popular monetization methods, some studies utilized a well-known technique in another field. The Input-Output analysis method for the macroeconomic impact of an externality is one example.	[99,100]

mean numbers are far more substantial at $8.065 trillion, and the maximum range of $69.504 trillion is approaching the entire world's GDP (about $86 trillion without adjusting for purchasing power parity). Worryingly, the numbers would not shift that significantly by 2040: with a collective minimum of −2$ billion (a net gain of $2 billion), a mean of $8.372 trillion, and a maximum of $73.5 trillion. See Table 8 for more details.

4.3. Distribution by vulnerable or exposed population

Although we present these findings at the national level, they would likely have strong repercussions at smaller scales. Research in energy, climate, and environmental justice suggests that the trend in many of these sobering impacts is that the most affected parties – often the poor or disenfranchised – are under-represented in the marketplace, and have external costs imposed upon them [104], particularly air pollution and toxics [105]. So the externalities we identify in this study would not be necessarily distributed equally or fairly.

For example, the externalities literature discusses how air pollution most affects minority communities with asthma and respiratory problems [106,107]. Climate change, by contrast, most seriously threatens those residing in low lying island states such as the Maldives or Vanuatu [108,109]. Chronic accidents at energy facilities affect those living adjacent to energy infrastructure, especially energy boomtown communities [110,111]. Catastrophic accidents such as damn failures or nuclear meltdowns can affect the entire public and impact the lives of millions of households at once [112,113]. Aesthetic issues such as harming viewscapes or mountainsheds tend to affect recreationists, pastoralists, tourists (especially on beaches) and other users of nature [114,115]. Direct land use can affect the livelihoods of farmers or ranchers [116,117]. Water use can affect fishers and river navigation or in transboundary river basins lead to geopolitical tensions [118]. Habitat destruction can affect non-human species ranging from the health and vitality of forests [119] and tropical rainforests [120] to coral reefs [121] and even deserts [122]. Occupational exposure can threaten coal miners [123], uranium miners [124], oil and gas workers [125], or even those extracting cobalt, copper, and lithium as material inputs for energy systems [126]. These diffuse examples all reveal how the burdens of energy systems are not disseminated justly, but among very specific groups and subpopulations, some of them not even human.

5. Implications for research and policy

Our research synthesis has direct implications for policy and research.

5.1. Policy implications

For policymakers, our study clearly reveals a more systematic and updated assessment of the hidden costs with some energy systems, notably oil, coal, and waste in electricity portfolios—which generate far more externalities than alternative sources of supply. Taking the mean from our research synthesis, coal has about three times as many negative externalities as solar PV, five times as many as wind, and 155 times as many as geothermal (See Fig. 8). Including these social costs would dramatically change least-cost planning processes and integrated resource portfolios.

Moreover, although our findings suggest that utilizing LCOE gives only a partial picture to an energy system's impact on society, we also offer an antidote. Fig. 9 modifies LCOE figures with mean externalities, and in doing so shows that wind, natural gas, geothermal and solar thermal would be the most socially cost effective sources of electricity. Conversely, coal and nuclear would be more expensive. It is not that these costs are never paid by society, they are just not reflected in the costs of energy. Same with trying to minimize road transport in favour of other more less externally costly travel modes such as water travel, rail or aviation. Society still "pays," just in the form of health care burdens, aggravated morbidity and mortality, blighted landscapes, car crashes, traffic jams, higher insurance premiums, and a variety of other compensatory mechanisms that further hide the social cost of energy or mobility.

Lastly, our findings are timely insofar as they can help inform the design of ongoing "Green New Deals" [127,128] or post-pandemic Covid-19 recovery packages [129] within these countries, and beyond. Some of the most important commonalities of many stimulus packages have been bailouts for the fossil fuel, automotive and aeronautic industries. Several countries also implemented electricity price freezes. Any global or national recovery may not be sustainable if treating externalities are not better included or accounted for in the design of Green Deals or stimulus measures, which could merely entrench or even worsen existing externalities or their patterns of distribution. It is well worth noting that although investment into energy efficiency measures has started stagnating in recent years, their ability to offer net positive

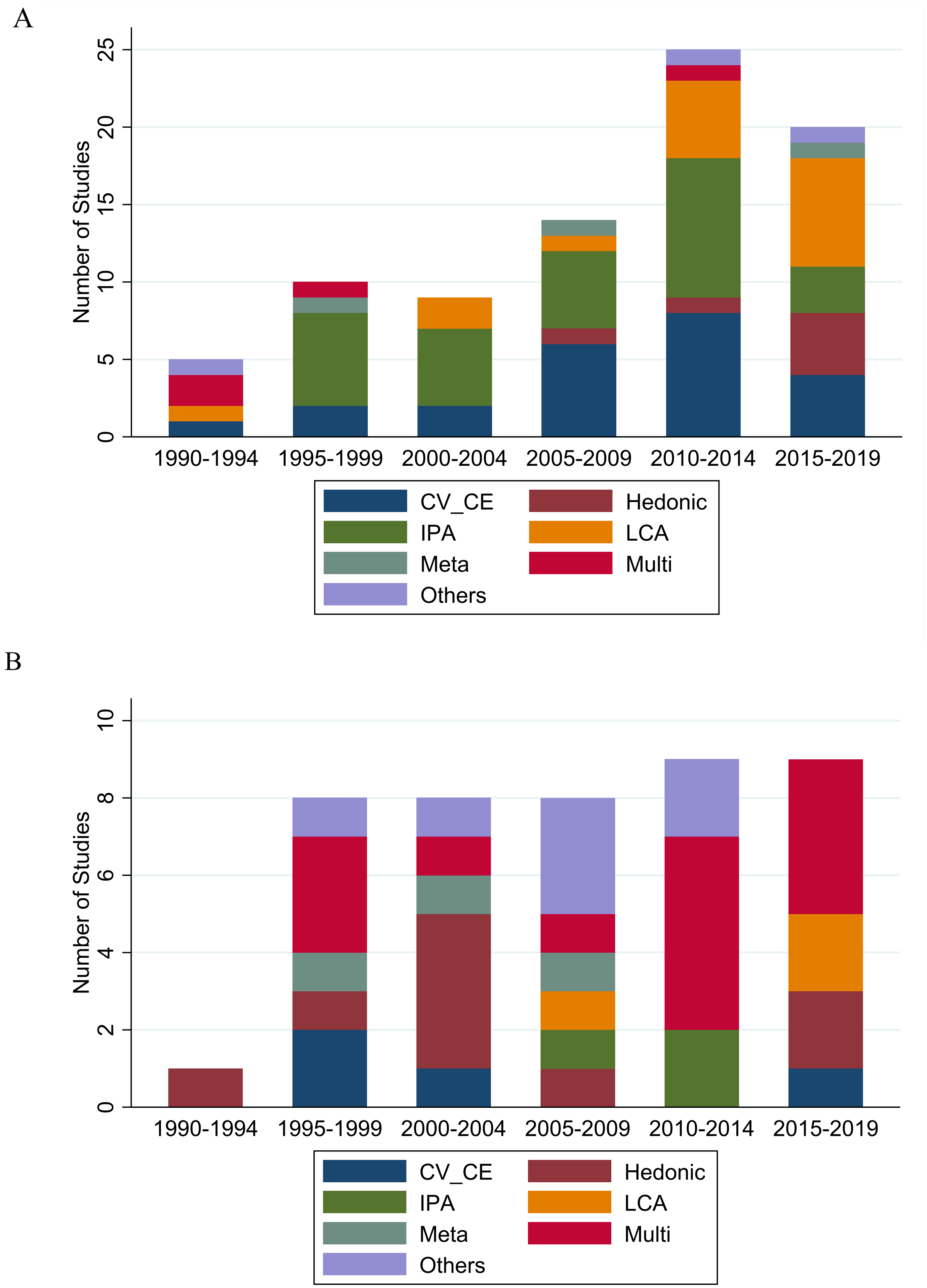

Fig. 6. Trends of methodological approaches of selected externality studies (n = 83) for electricity and transport (n = 43). Ten different methods are utilized frequently within the externalities literature. Note: CV = contingent valuation. CE = Choice experiment. IPA = Impact Pathway Approach. LCA = Life-cycle Assessment.

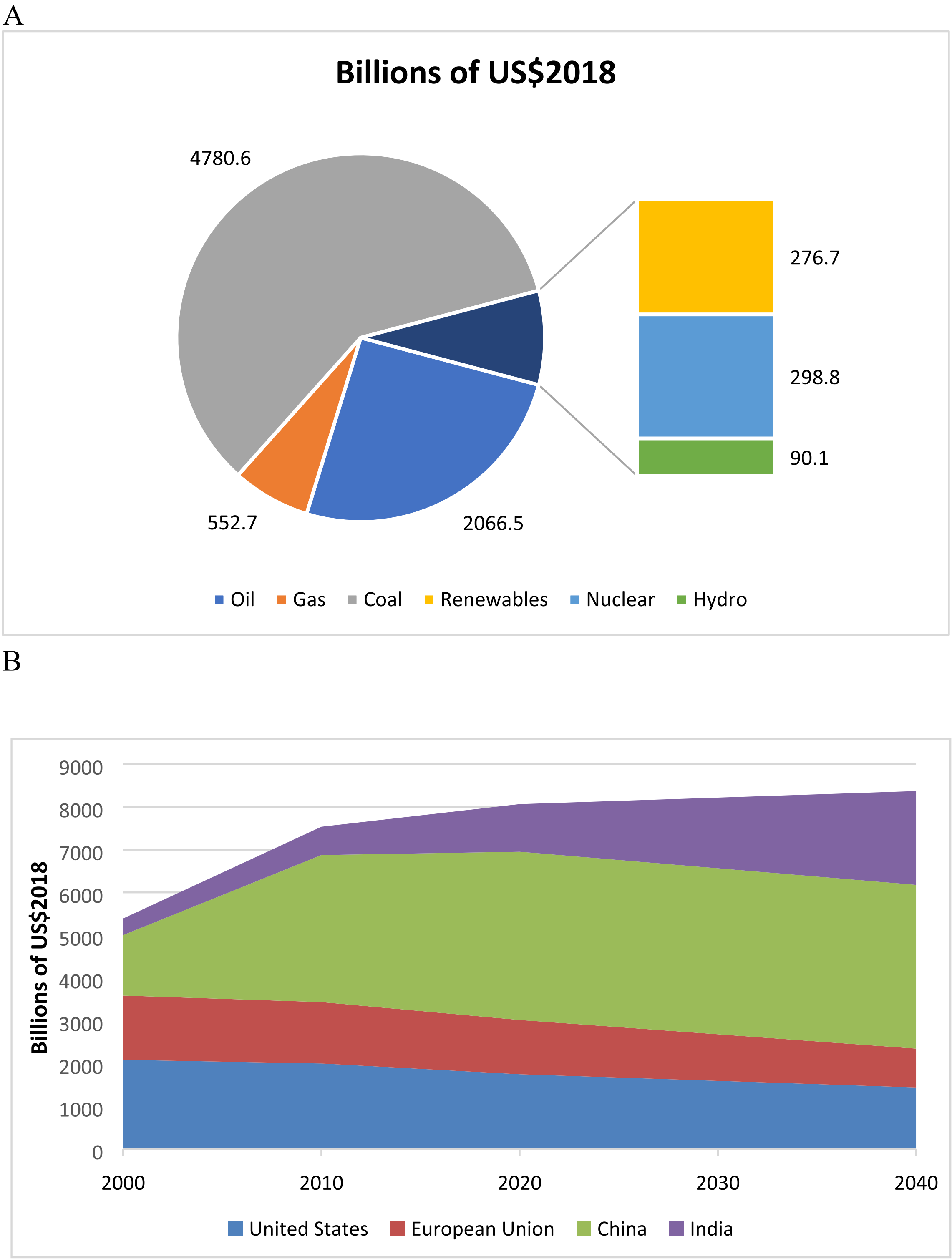

Fig. 7. Global energy externalities for the United States, European Union, China, and India by fuel source and country (Billions of US$2018). Panel A shows by fuel source in 2040, Panel B by geographic location from 2000 to 2040. Lower carbon sources of energy are less than 8% of the total: non-hydro renewables at $276.7 billion (3%), nuclear at $298.8 billion (4%), and hydro at $90.1 billion (1%). By country, it is China generating by far more externalities than any of the other four regions. When one projects out 2040, China would have 45.7% of these external costs compared with just 17.1% for the United States, 10.8% for the European Union and 26.2% for India. This clearly implies a shift in externalities from North America and Europe to Asia as those economies continue to develop.

Table 8

Estimated costs of externalities by country (top panel) and fuel source (bottom panel) in in billions of US$2018. BP numbers have been converted from billion tons of oil equivalent into TWh. We have also used a slightly modified version of our externality estimations as the category of non-hydro “renewables” includes bioenergy, geothermal, solar PV, solar thermal, wind energy and waste. We varied the renewables estimations for each of the four countries, based on data from the U. S. Energy Information Administration (for the United States), Eurostat (EU), International Energy Agency (China), and Central Electricity Authority (India).

a. By country

		2000	2010	2020	2030	2040
United States	Min	63	52	36	13	−10
	Mean	2083	1998	1745	1591	1437
	Max	15,100	14,534	11,700	10,486	9285
European Union	Min	50	47	42	35	28
	Mean	1504	1437	1270	1090	909
	Max	10,437	9960	8917	7794	6657
China	Min	15	26	25	14	4
	Mean	1414	3438	3936	3883	3831
	Max	13,877	34,320	38,449	37,474	36,500
India	Min	7	9	7	−9	−24
	Mean	388	662	1114	1653	2195
	Max	3465	6059	10,438	15,755	21,098

b. By fuel source

United States	*Min*	*Mean*	*Max*
Oil	60.1	757.8	2700.0
Gas	5.1	265.7	1041.8
Coal	0.7	517.0	5637.1
Renewables	−25.7	73.4	1024.3
Nuclear	0.0	118.0	1131.4
Hydro	−4.0	13.7	165.3
Total	36.3	1745.5	11700.0
European Union			
	Min	*Mean*	*Max*
Oil	42.4	533.9	1902.4
Gas	3.1	161.0	631.4
Coal	0.5	360.4	3929.5
Renewables	0.5	85.0	1173.2
Nuclear	0.0	116.0	1112.6
Hydro	−4.0	13.9	167.8
Total	42.4	1270.2	8916.8
China			
	Min	*Mean*	*Max*
Oil	43.8	551.7	1965.7
Gas	2.0	101.4	397.8
Coal	4.0	3081.6	33602.5
Renewables	−9.0	89.4	1271.6
Nuclear	0.0	56.4	540.6
Hydro	−16.2	55.5	671.1
Total	24.7	3936.0	38449.3
India			
	Min	*Mean*	*Max*
Oil	17.7	223.0	794.5
Gas	0.5	24.6	96.3
Coal	1.1	821.7	8960.7
Renewables	−10.7	28.9	421.4
Nuclear	0.0	8.5	81.7
Hydro	−2.0	6.9	83.9
Total	6.6	1113.6	10438.5

externalities (see Section 3.3) suggests that they may deserve a more prominent role in ongoing policies and stimulus packages.

5.2. *Future research directions*

For research, it points towards commonly examined technologies, but also under-covered ones. Coal, gas, wind, oil, biomass power, hydroelectricity, nuclear, and solar PV accounted for 90.8% of the estimates (see Table 9); others such as all power generation, CSP, coal-nuclear hybrids, tidal, biogas, and geothermal were understudied. There is more diversity in the transport literature, although research is still dominated by road and rail systems; with less work on aviation, and hardly any work on water transport or multi-modal transport. This implies strongly the need for more research in those areas.

One shortcoming within the literature was the lack of comparative work or multi-technology work. No study for instance modelled global externalities for energy *and* transport, a gap that justified our research synthesis. Now that we know this gap exists, we urge future modelers to take up the task, especially more nuanced and granular work at the level of cities, regions and stages, which can clearly assist energy and transport policy. Also, as we discussed in Section 4.3, identifying the discriminative impact of externalities at smaller scales—on vulnerable groups such as the poor or disenfranchised, for example—remains for further research. The identification could be made using micro-level data, including socio-demographic variables. Moreover, most of the articles estimating these externalities have studied developed or developing countries as the unit of analysis. Thus, the influence of negative externalities by income group, and across a broader set of geographic regions, will also be valuable topics to investigate.

Furthermore, most studies examine only an individual power plant or location rather than a fleet of power plants or an integrated portfolio of technologies. This means they may miss the combined or cumulative

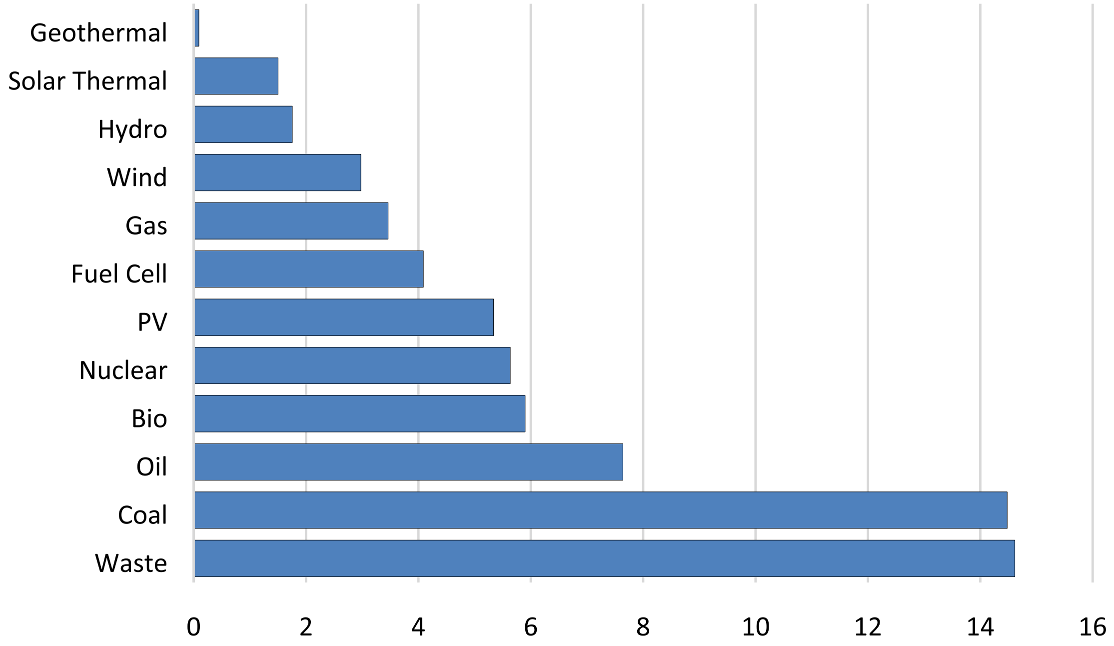

Fig. 8. Plotting mean externalities for electricity supply from highest to lowest (in US$2018 cents per kWh). When looking purely at externalities, and not LCOE or the costs of producing or generating electricity, geothermal, solar thermal, hydro, and wind energy have the total lowest external social costs. Waste to energy, coal, and oil have the highest external social costs. Source: Authors.

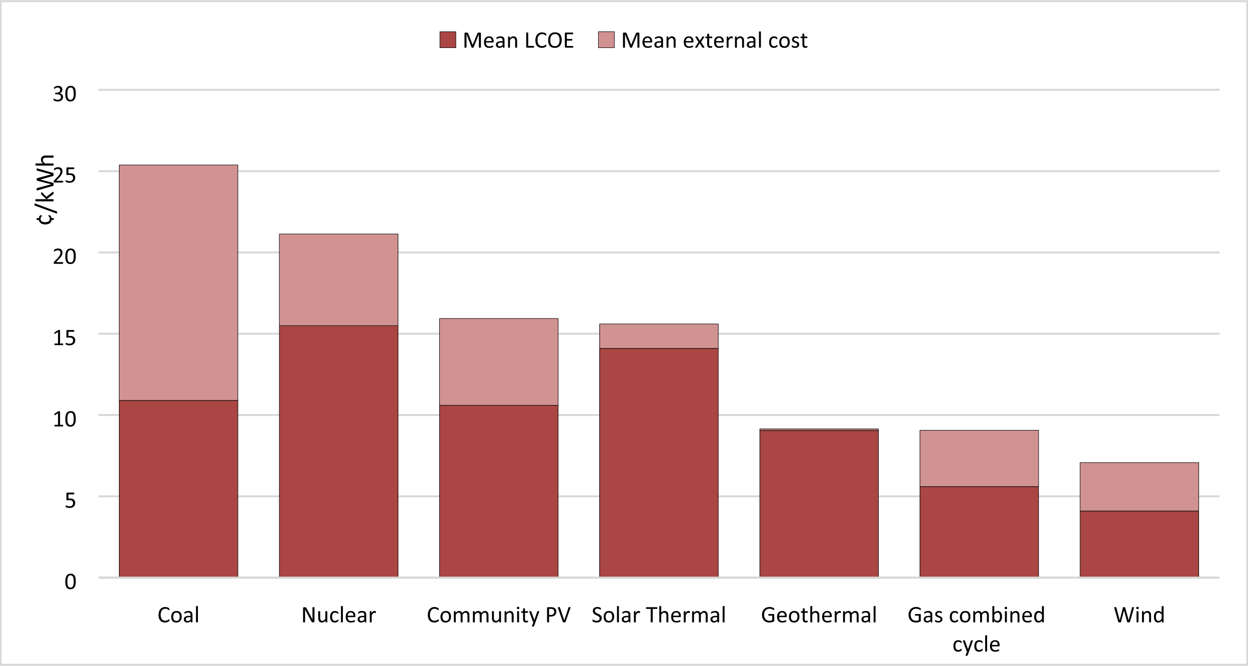

Fig. 9. Estimating the total social cost of electricity systems (LCOE + mean externality cost in US$2018 cents per kWh). From a purely LCOE standpoint, using mean average numbers from Lazard's, then the lowest merit order for energy systems is wind (7.1 ¢/kWh), gas (9 ¢/kWh), and geothermal (9.1 ¢/kWh). Solar PV and thermal falls in the middle around 15 ¢/kWh, Coal (25.4 ¢/kWh) and nuclear (21.1 ¢/kWh) become uneconomical and the two most expensive forms of energy on the market. Including their social costs rules them practically out of the portfolio. Note that some sources of electricity, such as hydropower, bioenergy or waste, are not included in Lazard's estimations and are therefore not represented in the diagram.

damages from a fleet of power plants or an entire utility or interstate highway system. Moreover, many studies assume as a reference state of the art technology, but not actual older technology with lower capacity factors or more problems of aging equipment. In the United States, for example, about 20% of the county's power plants are more than 50 years old [130]. The average age of a car or truck in the United States is also 11.8 years [131].

We introduce an unweighted assessment of externalities and publish our full dataset and accompanying data tables. Appraising the weighted externalities is thus another future research topic. To estimate the

Table 9

Commonly studied and uncommonly examined technologies for electricity (top panel) and transport (bottom panel). Note that CSP refers to concentrated solar power, PV photovoltaics.

a. Electricity (n = 318)

Technology	Number of studies	Percent of all studies
All power generation	1	0.3%
CSP	1	0.3%
Coal and Nuclear	1	0.3%
Fossil Fuels	1	0.3%
Solar	1	0.3%
Tidal	1	0.3%
Biogas Power	2	0.6%
Geothermal	2	0.6%
Lignite	2	0.6%
Peat	2	0.6%
Fuel Cell	5	1.6%
Solar Thermal	5	1.6%
Waste Incineration	5	1.6%
PV	16	5.0%
Nuclear	20	6.3%
Hydro	31	9.7%
Biomass Power	34	10.7%
Oil	34	10.7%
Wind	41	12.9%
Gas	46	14.5%
Coal	67	21.1%

b. Transport (n=373)

Technology	Number of studies	Percent of all studies
All/multi-modal	3	0.8%
Aviation	50	13.4%
Rail	87	23.3%
Road	210	56.3%
Water	23	6.2%

weighted values, a researcher may narrow the scope into a specific monetization method, power sources, or transport mode. The monetization method is highly context-specific, so it hinders the consistent weighting of the various externalities. Our results and accompanying data tables could be a starting point. With additional datasets such as population, technological progress, and income level, one could assess weighted externalities for a particular field, such as road transport. A final limitation within studies is that many do not look at the full lifecycle or "whole system" of a technology, thereby missing "embodied injustices" or externalities across things like extraction, processing, or waste [132,126]. For example, many studies looking at the externalities of nuclear power may focus on construction of a power plant or generation of electricity, but neglect upstream uranium mining and fuel processing, or downstream waste storage or decommissioning [133]. Similarly, nearly all externality studies of natural gas or shale gas do not take into account methane emissions upstream since they were barely quantified or appropriately measured [134–137]. Future work should try to better capture externalities across all of these stages or scales of a given energy fuel or mode of transport.

6. Conclusion

Using the mean numbers from our meta-analysis and research synthesis, the external costs associated with the global energy system could be $11.644 trillion and the global externalities associated with transport could amount to another $13.018 trillion. If this extra $24.662 trillion (or 28.7% of global GDP)[138] were included in the price of energy or mobility, it would become clear not only that we need to fundamentally change our systems and markets, but that it would actually be profitable to do so. If the maximum estimates of $169.43 trillion are taken into consideration, they *surpass* the entire annual GDP of the world (estimated at about $85.931 trillion in 2018).

And let us not forget exactly *who* it is paying these external costs. Under the present energy and mobility system, it is paid by those who can least afford it: islanders in Kiribati and Tuvalu faced with losing their homes under the sea; farmers in Africa struggling with drought and salinization; miners dying of lung cancer; children struggling to breathe; communities forced to relocate because their soil and water is contaminated; taxpayers responsible for a stretched health care system that has to cope with the health impacts of polluted air and water; and government agencies (and taxpayers again) charged with cleaning up oil spills, mine tailings, fly ash spills, and nuclear meltdowns.

However, our findings are not all negative. Energy efficiency and DR efforts induce positive externalities—avoided costs, emissions, and other impacts—as they are implemented, helping "undo" some of the negative damage. By our assessment, these programs have a mean collective net positive externality of 7.8 ¢/kWh. When put into the context of global demand efforts, this approaches an annual positive value of $312 billion, an amount *greater* than global investments in efficiency, a sign once again such efforts tend to more than pay for themselves.

The challenge is to convince policymakers, regulators, and planners to get electricity and transport markets to function as they should in theory—to accurately price the potential $20.37 trillion in mean external costs our energy and mobility industries, and patterns of consumption, shift surreptitiously to society. Although the services provided by energy and transport systems generate unprecedented opportunities for those who have access to them, the externalities that result from these same systems limit opportunities for many others, frequently to the extent of making it difficult to live a meaningful and healthy human life, and sometimes to the extent of making it impossible to live.

In this view, progressive energy, climate, and mobility policy is an attempt to promote fairness by correcting a massive market failure as much as it is about promoting jobs or protecting the environment. A fundamental question is whether we want energy and transport policies (such as subsidies) that manipulate the presence of externalities to their advantage, or those that attempt to fully internalize them and hold producers (and consumers) accountable.

7. Data availability statement

All data generated or analyzed during this study are included in this published article (and its Appendices and supplementary information files).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2020.101885.

Appendix B. Supplementary Data Tables

Table B1
Summary of negative externalities by transport type (adjusted to US$2018, ¢/km).

	Source	# of obs.	min	median	mean	max	s.d.
Total	Aviation	29	1.066	9.278	8.965	11.421	2.227
	Rail	67	0.202	1.938	11.89	203.339	38.321
	Road	201	0.621	10.487	22.564	239.174	35.48
	Water	19	0.819	1.801	2.022	4.133	0.815
	Total	316	0.202	7.769	17.818	239.174	33.934
Passenger (all unit)	Aviation	28	1.481	9.286	9.247	11.421	1.658
	Rail	35	0.320	3.687	21.206	203.339	51.586
	Road	108	0.621	11.018	27.925	239.174	43.760
	Water	1	0.967	0.967	0.967	0.967	
	Total	172	0.320	9.269	23.361	239.174	42.160
Freight (all unit)	Aviation	1	1.066	1.066	1.066	1.066	
	Rail	32	0.202	1.244	1.700	8.411	1.601
	Road	63	0.838	9.024	17.980	150.832	23.133
	Water	18	0.819	1.938	2.081	4.133	0.796
	Total	114	0.202	4.124	10.751	150.832	18.962
in p-km	Aviation	28	1.481	9.286	9.247	11.421	1.658
	Rail	33	0.320	3.293	13.786	179.581	40.139
	Road	91	0.621	10.735	23.984	239.174	40.556
	Water	1	0.967	0.967	0.967	0.967	
	Total	153	0.320	9.141	18.937	239.174	36.797
in t-km	Aviation	1	1.066	1.066	1.066	1.066	
	Rail	32	0.202	1.244	1.700	8.411	1.601
	Road	60	0.838	8.773	14.603	43.130	11.555
	Water	18	0.819	1.938	2.081	4.133	0.796
	Total	111	0.202	4.099	8.731	43.130	10.649
in v-km	Rail	2	83.931	143.635	143.635	203.339	84.435
	Road	37	1.537	11.671	31.544	201.380	45.512
	Total	39	1.537	12.411	37.292	203.339	52.700

Table B2
Summary of negative externalities by transport type and unit (adjusted to US$2018, ¢/km).

	Source	# of obs.	min	median	mean	max	s.d.
Passenger in US¢/p-km	Aviation	28	1.481	9.286	9.247	11.421	1.658
	Rail	33	0.32	3.293	13.786	179.581	40.139
	Road	91	0.621	10.735	23.984	239.174	40.556
	Water	1	0.967	0.967	0.967	0.967	
	Total	153	0.32	9.141	18.937	239.174	36.797
Freight in US¢/t-km	Aviation	1	1.066	1.066	1.066	1.066	
	Rail	32	0.202	1.244	1.7	8.411	1.601
	Road	60	0.838	8.773	14.603	43.13	11.555
	Water	18	0.819	1.938	2.081	4.133	0.796
	Total	111	0.202	4.099	8.731	43.13	10.649

Table B3
Number of studies by externality for electricity.

Externalities	Number	Applied Methods
Air Pollution	53	CE/CV, Control, IPA, LCA, Meta, Multi
Climate Change	36	CE/CV, Control, IPA, LCA, Meta, Multi
Chronic Accident	3	IPA
Catastrophic Accident	9	CE/CV, IPA, LCA, Multi, ND
Noise	6	CV, Hedonic, IPA, LCA
Aesthetics	23	CE/CV, Hedonic, IPA, LCA
Land/Deforestation	9	CE/CV, IPA, LCA, ND
Water	8	CV, IPA, LCA
Species/Biodiversity	13	CE/CV, IPA, LCA
Health	4	IPA, LCA
Other	20	CE/CV, Hedonic, IPA, LCA, Multi, ND

Note: CE: Choice Experiment, CV: Contingent Valuation, Control: Control cost valuation, Hedonic: Hedonic approach, IPA: Impact Pathway Approach, LCA: Life Cycle Assessment, Meta: Meta-analysis, Multi: studies that apply multiple methods, ND: Not Decisive.

Table B4
Number of studies by externality for transport.

Externalities	Number	Applied Methods
Air Pollution	32	CE/CV, Hedonic, IPA, LCA, Meta, Multi, ND
Climate Change	22	CE, IPA, LCA, Meta, Multi, ND
Chronic Accident	22	LCA, Meta, Multi, ND
Catastrophic Accident	0	–
Noise	32	CV/CE, Hedonic, IPA, LCA, Meta, Multi, ND
Aesthetics	2	Hedonic, Multi
Land/Deforestation	8	Hedonic, LCA, Meta, Multi
Water	5	LCA, Multi
Species/Biodiversity	2	LCA, Multi
Health	0	–
Congestion	15	LCA, Meta, Multi, ND
Other	12	Hedonic, LCA, Multi, ND

Note: CE: Choice Experiment, CV: Contingent Valuation, Control: Control cost valuation, Hedonic: Hedonic approach, IPA: Impact Pathway Approach, LCA: Life Cycle Assessment, Meta: Meta-analysis, Multi: studies that apply multiple methods, ND: Not Decisive.

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Corrigendum

Corrigendum to “The hidden costs of energy and mobility: A global meta-analysis and research synthesis of electricity and transport externalities” [Energy Res. Social Sci. 72 (2021) 101885]

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A thoughtful reader has detected an important error in the hypothetical part of the article calculating the global external costs for electricity and energy in this article, a mistake that escaped both the authors and peer reviewers. In section 3.1, the article presented numbers for global electricity supply when in fact these were for global energy supply.

To clarify, global electricity supply in 2018 was 26,566 TWh according to Table 5, which is referred to the World Energy Outlook 2019 from International Energy Agency. However, we stated that global electricity supply was “roughly 14,000 million tons of oil equivalent each year (or 162,820 TWh/year),” a number that reflects total global energy supply, not just electricity. Thus, the corrected expression should appear as:

“When our overall externalities estimations are put into the context of global energy supply, which amounts to roughly 14,000 million tons of oil equivalent each year (or 162,820 TWh/year), the results are striking. Using the mean number of 7.152 ¢/kWh, global energy externalities would amount to $11.644 trillion; using the median number (2.328 ¢/kWh), they would amount to $3.79 trillion.”

The external costs of “$11.644 trillion” also appear in the abstract and conclusion, where it should be clarified that they refer to global energy supply rather than global electricity supply.

When one looks at electricity only—a subset of global energy supply, at only 26,566 TWh/year—the externalities would be a mean of $1.90 trillion; using the median number (2.328 ¢/kWh), they would amount to $0.62 trillion.

Interestingly, this would suggest that the externalities from the electricity sector as a whole ($1.90 trillion) are far less than those from transport ($13.018 trillion), almost seven times less. But those from the entire energy system are almost equivalent at $11.644 trillion.

No other findings or calculations are affected.

The authors would like to apologize for any inconvenience caused.

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