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External Costs of Electricity: A Review

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Abstract

The quality of the environment is a pure public good.Externality is the root of environmental problem.This paper reviewed the literatures studying environmental externalities, especially theexternal costs of electricity consumption. Then international studies on the cost of externalities using impact-pathway-approach and other approaches are investigated.External costs of electricity differ widelydepending on electricity generation technologies and the different impact categories.

Key Words: External Costs, Electricity Consumption, Environmental Externality, Impact-pathway-approach

1. Introduction

The protection of the environment is a major public concern today. The root of environmental problem is an externality: production or consumption activities affect the environment, but these effects are not included in private costs or benefits; the quality of the environment is a pure public good (Tulkens, 2006). The cross-borders nature of the environmental externalities makes the problem more complicated.

In economics, an externality is a cost or benefit that is not included in the current pricing systemand is incurred by a party who was not involved as either a buyer or seller of the goods or services causing the cost or benefit (Griffin and Steele, 1986; Papandreou, 1994; European Commission, 2003; Owen, 2004; Weinzettela et al., 2012). The cost of an externality is a negative externality, or external/social cost, while the benefit of an externality is a positive externality, or external benefit. Due toexternal cost (or in some literature, social cost), private costs of production tend to be lower than its actual cost. Hence, the standard market mechanism fails to maximize social welfare (Weinzettela et al., 2012).

In this paper we will first review literatures studying environmental externalities, especially external costs of electricity consumption.Then international studies on the cost of externalities fromdifferent electricity generation technologies of different countriesare investigated in Section 4. Finally, a summary of this study is presented in Section 5.

2. Environmental Externalities

According to Owen (2004), environmental externalities “refer to uncompensated environmental effects that affect consumer utility and enterprise cost outside the market mechanism”.Pollution is an external cost because damages caused by it are borne by the whole community and are not reflected in market transactions (Koomey and Krause, 1997). One example of negative environmental externalities is pollution emitted by road vehicles.

The impact on those who suffer damage to their health from this kind of air pollution is not taken into account by the pollution generator. The environmental costs are “external” because the owner of the road vehicles is not taking real costs into account when making decisions.

2.1Game theoretical model to identifyEnvironmental Externalities

Game models have been developed to examine environmental externalities. For example, Cian and Tavoni (2012) examined international emission trading by studying how a cap to the trade of carbon offsets influences innovation, technological change, and welfare.They investigated the main mechanisms that shape these relationshipsand also assessed environmental and technology externalities. Factors they took into consideration included volume, the timing, and the regional allocation of carbon offsets, and the incentive to invest in innovation and low carbon technologies. The results of the paper indicated that, for moderate caps on the amount tradable emissions permits and sufficiently high technology spillovers, global innovation and technical change would increase and that this additional innovative effort could lead to economic efficiency gains.

Do et al. (2012) introduced a special class of games with externalities and issue linkage to promote cooperation on transboundary water resources. They analyzed whether issue linkages could be used as a form of negotiations on sharing benefits and mitigating conflicts. They showed that whenever opportunities for linkages exist, countries might indeed contribute towards cooperation. Millock et al. (2012) analyzed a dynamic model of stock pollution when the regulator had incomplete information on emissions generated by heterogeneous agents. They studied a decentralized policy for adoption of monitoring equipment over time and determined the second-best tax rates, the pattern of monitoring technology adoption, and identified conditions for the voluntary diffusion of monitoring technologies over time. Other studies can be found in Chander and Tulkens (1995 and 1997).

2.2 Internalize the Environmental Externalities

European Commission (2003) identified several ways of taking into account the external cost to the environment and health: one way would be via eco-taxes or pollution tax, i.e. by taxing damaging fuels and technologies according to the external costs caused. Taxes provide effective incentives to reduce emissions and improve the environmental conditions, minimize the total abatement costs, internalize the environmental costs, and provide a source of revenue (see Barde, 2000; Arnold, 1995; Goulder, 1995; Toman and Withagen, 2000; Eskeland and Kong, 1998; Kahn, 1998).For instance, Antoci et al. (2012) proposed a taxonomy of different structural changes on the basis of distributive, environmental and economic outcomes and they studied a two-sector model with environmental externalities to identify under which conditions each structural change could occur.

Another possibility would be to encourage or subsidize cleaner technologies thus avoiding socio-environmental costs, e.g. Yeung and Petrosyan (2016) constructed a cooperative dynamic environmental games with clean technology development, which brought about cost savings and improved effectiveness.

Another application is the use of external-cost estimates in cost-benefit-analysis. In such an analysis the costs to establish measures to reduce a certain environmental burden are compared with the benefits, i.e. the damage avoided due to this reduction.

Other application of internalizing the environmental externalities includes the willingness-to-pay by users. An example of willingness-to-pay to reduce noise and air pollution was examined by Lera-López et al. (2012).Several models were used for estimation based on contingent valuation, noting that those living near roads, younger people, the better educated, and the more environmentally aware individuals were willing to pay more to reduce those externalities of air and noise pollution.

3.Electricity Externalities: External Costs of Electricity Consumption

Electricity constitutes a critical input in sustaining a nation’s economic growth and development. Power production is a centralized source of pollution. As one of the major sources of pollution, power system operation and planning are gaining more attention than before (Vrhovcak et al., 2005).According to the latest study in a UN report, coal-fired power was the highest environmental impact sectors in eastern Asia (TEEB, 2013).Many research projects have focused on the determination of economic value of the environmental impacts from electricity and their results help policy makers to make decisions (Weinzettela et al., 2012).

Externalities of electricity are environmental and social costs that are not accounted for in the market price of electricity (European Commission, 1999; Ding et al., 2006; ATSE, 2009). The external costs of power sector represent an important part of social welfare.

Electricity is so important that it attracts many efforts of the studies of externalities. Freeman (1996) took a surveyto investigate environmental costing issues and those questions raised by calculating the environmental costs of electricity. The paper compared different external cost studies and identified the methodology questions for quantitating environmental externalities.Eyre (1997) outlined some provisional implications for energy policy and found that external costs were technology dependent and for some older power plants were large compared to electricity prices; global warming and nuclear accidents had very uncertain external costs and pose threats to sustainability; well-located renewable energy sources had low external costs and provide sustainable options. Kim (2007) focused on three dimensions: theoretical and methodological backgrounds; critical review of specific studies: methodologies, results, and limitations; and discussing their results and implications for environmental policy and further research. Neoclassical and institutional approaches led to a common conclusion that fossil fuels and nuclear power show the highest environmental impact. External cost estimation and recommendations to regulator would also be affected by new scientific insights and changing background assumptions over time Krewitt (2002).

Specific emission factors for the different power generation technologies were identified from Winkler (2007) and Bauer et al. (2008). Sabour (2005) developed an option-pricing model to quantify the external cost of oil consuming, assuming that the external cost of consuming a barrel of oil equaled the value of the option to get a barrel of oil in the future at the same current cost. Then the total cost of consuming a barrel of oil at that time would be the summation of the oil price and the external cost. Fouquet (2011) considered how external costs change through time.

In the 1990s, some major studies have been completed and provide estimates of external environmental costs of electric generating system. The studies included: the California Energy Commission Study (Thayer, 1991); the ExternE Project by European Commission (1994), which studied externalities of fuel cycles; a research to estimate externalities of electric fuel cycles by Lee et al. (1994) from the US Department of Energy Fuel Cycles Study; The New York State Environmental Externalities Cost Study (Rowe et al., 1995); and a study assessing environmental externality costs for electricity generation from the Northern States Power Company (Minnesota) Study (Desvousges et al., 1995).

Some studies calculated electricity externalities of their own countries. Dalianis et al. (1997) presented calculations of the social cost of electricity generation from fossil fuels in Greece. They authors compared the actual price of electricity and the electricity produced by renewable energy sources, mainly wind and photovoltaic. The estimated social cost of energy was found to be in the range of 7.3-5.4 GRD/kWh. Faaij et al. (1998) investigated and compared externalities of electricity production from biomass and coal in Netherlands.

Aravena et al. (2012) investigated the preferences of households for different sources of electricity generation, i.e. fossil fuels, large hydropower in Chilean Patagonia and other renewable energy sources. The results of their study suggested a strong preference for renewable energy sources with higher environmental prices imposed by consumers on electricity generated from fossil fuels than from large dams in Chilean Patagonia, and the possibility of introducing incentives for renewable energy developments that would be supported by consumers through green tariffs or environmental premiums. Many studies have tried to determine the economic value electricityexternality and some regulators also attempted to internationalize the external costs at the investment stage (Cohen et al. 1990; Hashem and Haites 1993).

Barla and Proost (2012) explored energy efficiency policies in the presence of a global environmental problem and international cost interdependency associated with R&D activities. They developed a simple model with two regions where the cost of an appliance in one region depended upon the level of energy efficiency in that region and the level of R&D activities by the appliance industry. In their model, the cooperative outcome could be decentralized by imposing a tax. However, the authors showed that when regions did not cooperate, they had an incentive to adopt additional instruments to increase energy efficiency. The lack of cooperation led to under-taxation of the environmental externality which in turn created an incentive to try to reduce emissions produced abroad. Owen (2004) reviewed life cycle analyses of alternative technologies in terms of both their private and societal costs (that was, inclusive of externalities and net of taxes and subsidies).

The author found that the removal of subsidies to fossil fuel-based technologies and the appropriate pricing of these fuels to reflect the environmental damage (local, regional, and global) created by their combustion were essential policy strategies for stimulating the development of renewable technologies in the stationary power sector. The life-cycle analysis approach was also used by Mahapatra et al. (2012) to monetize externalities from coal power generating systems.

4. International Studies on External Cost of Electricity

Economic value of external cost has been gaininginternational concerns. During the last two decades, a series of valuation studies have made attempts to estimate the external environmental costs of various power generation sources within the European Union and the United States (Ding et al., 2006).

External Costs of Energy or ExternEwas a series of projects studying external cost of electricity starting from early 90s till 2005."ExternE-Methodology" is an approach of calculating environmental external costs as it was developed during the "ExternEproject-series" -- called Impact-Pathway-Approach. In this section, implementations of ExternE projects both in some European countriesand in countries outside Europe arescrutinized.Moreover, studies of externalities in USA and Chinaare explored. Finally, studies of electricity externalities on a global scale are presented.

4.1 ExternE Project: A Major Research Program to Quantify Externalities

The ExternEproject was a major research program launched by the European Commission at the beginning of the 1990s. Such a project was designed to form a scientific basis to calibratethe economic values of electricity externalities and to give recommendations to regulators when designing internalization measures. With the contributions of researchers, the ExternE label became a well-recognized standard source for external cost data (Krewitt, 2002). The European Commission's ExternE Project has made major advances in the quantification of external costs (Eyre, 1997).

Pollution represents an external cost because damages associated developed within the ExternE project series and represents its core. Impact pathway assessment is a bottom-up-approach (otherwise known as the damage function) and uses technology specific emissions data for individual locations (Eyre, 1997). The approach traces pollutants from source emissions via quality changes of air, soil and water to physical impacts, and then expresses in monetary benefits and costs (European Commission, 1991). The impact pathway approach generally has four steps: 1) determine the emissions associated to the source being evaluated; 2) calculate pollutant concentration for all affected regions using an atmospheric dispersion model; 3) determine the impact caused by being exposed to pollutant using dose-response functions and 4) evaluate the economic impacts leading to degradation costs (European Commission, 2003; Alves and Uturbey, 2010). The impact pathway approach can be considered as a specific application of life cycle analyses (Owen, 2004). The method has already been extensively used to help decisions concerning environmental issues like the European Commission draft ozone directive, the national emissions ceiling directive, the draft directive on non-hazardous waste incineration, air quality guidelines on CO and benzene, the UN/ECE multi-pollutant, multi-effect protocol and a number of national activities. However, stochastic elements exist and certain assumptions have to be made, nevertheless the method gives valuable support for decision making and a range of results. The methodology is constantly modified and developed.

ExternE projects have both been implemented in some countries in Europe and in other countries outside Europe:

(1)ExternE in Europe

The ExternE project series covered a wide range of fuels, different technologies and countries in Europe. Krewitt et al. (1999) applied an extended impact pathway model and attempted to quantify external coastsfrom fossil-fuelpowerplants, i.e.average health and environmental damage costs, in Germany and Europe. The average damage costs resulted from the operation of fossil power plants in Germany, taking into account the spatial distribution of emission sources, and the respective fuel mix in the different parts of Germany and Europe. While external costs from fossil fired power plants in the former Federal Territory of Germany were below the European average, the external costs from power plants in the former German Democratic Republic in 1990 amount to 0.23 USD/kwh. The external costs of both former Federal Territory of Germany and the former German Democratic Republic were reduced significantly until 1996.

A comparative evaluation of fossil, nuclear and renewable fuel cycles waspresented in European Commission (2003). This study illustrated that the external costs of electricity generation differ greatly, depending on fuel choice, technology and location among the 15 countries in EU. Sub-total of quantifiable externalities included those have impact on global warming, public health, occupational health and material damage.

The study of Weinzettel et al. (2012) showed that there were significant differences in the external costs of electricity generation and consumption in some EU countries due to the international trade in electricity. They compared external costs from electricity generation and consumption per unit of electricity for 20 European Countries in 2005. The composition of the external costs of electricity was identified according to four impact categories. The category of 'human health' included premature mortality and increased incidence of morbidity; 'climate change' included impacts caused by climatic effects all over the world; 'biodiversity loss' included damages due to acidification and eutrophication; and 'crops' denoted the effects from tropospheric ozone creation, acidification and fertilization.Acidifying substances, airborne particles and greenhouse gas emissions were the main reasons for external costs of electricity generation in this study; while heavy metals and VOCs contributed little to the external costs. Electricity was generated with the highest external costs per unitof electricity in Greece due to the high ratio of coalpower plants in the electricity generation mix. The lowest externalcost was found in Norway, where high share of renewable and nuclear power plants (more than 98%of the electricity generation mix in Norway was hydropower).

A report by European Environment Agency (2008) indicated that the average external costs of electricity production in 27 EU Member States were between 0.02178–0.07139$/kwh in 2005 (depending on whether high or low estimates for external costs are used).

Georgakellos (2010) applies the EcoSenseLE (EcoSense Look-up Edition, which was used for approximate but quick estimates of damage costs based on the impact pathway approach) online tool and quantified the external cost of greenhouse gases (specifically CO_2) generated during electricity production in the thermal power plants in Greece. They found that compared to the production cost in lignite-fired power plants, external cost was remarkably high.

In Poland, Czarnowska and Frangopoulos (2012) used the EcoSenseWeb software, which was based on the results of the ExternE project, to assess the external environmental cost (externalities) of pollution generated from Energy conversion systems. Another study examined the external costs of environmental impact in the generation of electricity was conducted by Cel et al. (2018). They demonstrated the viability of support through a system of certification for renewable energy sources and presented the external costs dependent on the type of fuel. Data were presented in Table 1.

Istrate et al. (2019) examined the role of a national power plant and estimated the external costs of power production through a combined Life Cycle Assessment and Energy Systems Modelling approach (showed in Table 1).

Table 1: Overview of Studies on External cost of Electricity in EU

Studies	Location	Impact Considered	Power-Plant Type	Low (USD/kWh)	High (USD/kWh)
Krewitt et al. (1999)	Germany	HI, environmental damage costs	FF	0.015	0.23
Krewitt et al. (1999)	Germany	HI, and environmental damage costs	FF	0.009	0.077
European Commission (2003)	EU-15	CC, HI, occupational health, M	FF, N, Re	0.00036	0.1815
European Environment Agency (2008)	EU-27	CC, AP, SOC	FF, O, H, N, Geo, CHP Gas, PV, W, NG-CCGT, CHP D	0.02178	0.07139

Georgakellos (2010)	Greece	AP; CO_2 costs	L, O, NG	0.01136	0.02826
Weinzettel et al. (2012)	EU-21	HI, CC, BioL, Agr	FF, N, Re	0.00038	0.07018
Czarnowska and Frangopoulos (2012)	Poland	CC, AP, SOC	C	0.029	0.25
Cel et al. (2018)	Poland	CC, AP	C, L	0.41(C)	0.082(L)
Istrate et al. (2019)	Spain	CC, AP	WTE	0.99	0.99

(Note: 1 EUR=1.21 USD; See Appendix for Acronyms and Abbreviations)

Similar approach that appliedin different case studies issummarized in Table 1.

(2)The Impact Pathway Approach applied in Other CountriesoutsideEurope
The method developed within the ExternE project to calculate external cost, especially the impact pathway approach, has been applied not just in Europe, but also in a variety of emissions from electricity generators outside Europe. The following paragraphs reviews selected studies in different countries based on ExternE method in chronological order.

In South Africa, Eskom owned and operated 92% of electricity generation capacity, while municipalities and private generators owned 6% and 2%, respectively. Spalding-Fecher and Matibe (2003) adopted the impact pathway approach and presented a quantitative analysis of air pollution impacts on human health, damages from greenhouse gas emissions, and the avoided health costs from electrification. The central estimates of external costs for coal-fired power generated and electricity transmission were 0.0044 USD/kwh and 0.0043 USD/kwh, respectively. Low and high estimates of external costs for coal-fired power generated are presented in Table 2.

Table 2. Overview of Studies on External Cost of Electricity outside EU

Studies	**Location**	**Impact Considered**	**Power-Plant Type**	**Low (USD/kWh)**	**High (USD/kWh)**
Spalding-Fecher and Matibe(2003)	South Africa	AP, CC, HI	C	0.014	0.093
Vrhovcak et al. (2005)	Croatia	AP	C, NG, O	0.001 (NG)	0.007 (NG, O)
Carbonell et al. (2007)	Cuba	AP	O	0.008	0.013
ATSE (2009)	Australia	CC, HI	C, NG	0.01444	0.03952
Streimikiene et al. (2009)	Baltic States	HI, BioL, Agr, M	C, O, NG	0.00242	0.0242
Alves and Uturbey (2010)	Brazil	CC, HI	H, C, NG, O	0.02326	210.69
Hainoun et al. (2010)	Syrian	HI	O, NG	0.0007	0.025
Sakulniyomporn et al. (2011)	Thailand	HI	C, Li, O, D, NG	0.000298	0.077877
Mahapatra et al. (2012)	India	HI, M, CC, Agr	C	0.00073	0.0314
Edkins et al. (2010)	South Africa	CC, HI	C, N, Gas-CCGT; D-OCGT; Bio; H; W; CSP; PV	0.000134	0.03306

Dimitrijevic et al. (2011)	Bosnia and Herzegovina	AP	C	0.115	0.225
Buke and Kone (2011)	Turkey	AP, HI	Li	0.002	0.035
Streimikiene and Alisauskaite-Seskiene (2014)	Lithuania	CC, AP, R	Bio, C, Li, N, NGCC, O, S, W	0.001(H)	0.078(Bio)
Karimzadegan et al. (2015)	Iran	AP, HI	C, NG, steam , CCP	0.019 (C)	0.089 (C)

(Note: 1AUD=0.76USD; 1 EUR=1.21USD; See Appendix for Acronyms and Abbreviations)

ATSE (2009) adopted the environmental cost of CO_2 emissions (equivalent to 31AUD/tonne CO_2) in ExternE project to calculate the external cost in Australia. Greenhouse gas damage costs for their currently deployed fossil fuel technologies in Australia range from 0.018AUD/kwh for natural gas to 0.039AUD/kwh for brown coal. The study in ATSE assumed that Australian health damage costs per unit of emission were about 7-20% of costs in Europe concerning the same health impacts. Based on that assumption, the total health damage cost of Australia's three coal-fired power station emissions was about 0.013AUD/kwh, equivalent to an aggregated national health burden of around 2.6AUD billion per annum. Combining greenhouse and health damage costs, Australia's total external costs were about 0.019AUD/kwh for natural gas, 0.042AUD/kwh for black coal and 0.052AUD/kwh for brown coal. The average wholesale price of electricity in Australia was 0.40 AUD/kWh, so the average external costs were 9.42% of electricity price. Their research found that a greater focus on externalities, preferably quantified in monetary terms, would help Australia to gain maximum social and environmental benefit from the portfolio of electricity generating technologies it would use for meeting emission reduction targets.

Streimikiene et al. (2009) calculated external costs of electricity generation in the main power plants burning fossil fuel in Baltic States (Lithuania, Latvia and Estonia) in 2005 based on ExternE methodology (impact pathway approach). The average cost of electricity generation in Lithuania estimated per kwh amounted to 0.004 EUR/kwh; the average external cost of electricity generation in Latvia makes about 0.02 EUR/kwh; and the average external cost of electricity generation in Estonia is 0.002 EUR/kwh.

In Streimikiene and Alisauskaite-Seskiene (2014), external costs of electricity generation were calculated based on ExternE methodology and were analysed in terms of external costs categories, electricity generation technologies life cycle stages and time frame 2010–2030 for Lithuania.

Alves and Uturbey (2010) applied the impact pathway approach and investigated environmental external costs associated to both hydro-power and thermal-power electricity generation in Brazil. The study reinforced the discussion about monetary valuation of environmental damages, i.e. human health and climate change, due to electricity generation during planning stages. For medium density populations, human health damage costs ranged from 23.31 USD/kWh with imported high-quality coal to 210.69 USD/kWh with Brazilian low-quality coal. The monetary value of Climate change impacts was equal to 0.02326 USD/kWh, when high quality coal was used; and 0.02440 USD/kWh when low quality coal was used.

Hainounet al. (2010)investigated the Syrian electricity production system and assessed the environmental impacts caused by airborne pollutant through a simplified impact pathway approach.They evaluated the external damage costs to human health and indicated that the environmental impacts could add considerable external cost to the typical generation cost. They estimated that external damage costs to human health vary between 0.0007 - 0.025 USD/kwh for heavy fuel oil and natural gas fired power plants respectively. The external cost was estimated to be about 25% of the production costs of fuel oil fired power plants.

Sakulniyomporn et al. (2011) investigated thefossil-fuelpower plant in Thai and estimated its impacts on human health degradation. They adopted the impact pathway approach and CALMET/CALPUFF modeling system to simulate advections of the criteria pollutants (SO_2, NO_X, and PM_{10}) including secondary particulates; and used the exposure-response functions to quantify the marginal damage to public health. The external cost per kwh was highly site-specific. A number of large capacity power plants were located in the central area which was the most densely populated region of Thailand.

In India, Mahapatra et al. (2012) estimated that cost of externalities of power generation on human health, building material, agriculture crops and global warming were 39.7paisa/kwh, 4.1paisa/kwh, 3.3paisa/kwh and 141.3paisa/kwh. With 1 USD=45 Indian rupees, the final external cost for generating 1kwh of electricity from coal fuel cycle was found to be 0.046USD. While the average electricity price in India was 5-7 rupees/kwh (HKTDC Research, 2012), the final external cost from Coal fuel cycle was 29.6%-41.4% of electricity price.

Edkins et al. (2010) reviewed the local and international literatures on the external cost from different electricity generation technologies in South Africa. The major external costs from power generation in South Africa are climate impacts from GHGs emission and health impacts from NO_X, SO_2 and particulates.

Vrhovcak et al. (2005) presented the damages to human health resulting from Croatian thermal power plants annual operationand used data on relations between human health degradation and ground concentrations of the analyzed pollutants. External costs werethen calculated.

Carbonell et al. (2007) assessed the external costs of threefossil-fuel power plants in Cuban power with high sulfur content. The external cost assessed for the three plants was 0.0106USD/kWh. The authors indicated that costs derived from sulfur species (SO_2 and sulfate aerosol) stood for 93% of the total costs.

Dimitrijevic et al. (2011) reported that Bosnia and Herzegovina adopted ExternE methodology help make decisions about restricting emissions from major combustion sources. They examined electricity generation at a fossil fuel power plant and found that the difference for two scenarios between benefits and costs were not large. Results of their study are summarized in Table 2.

Buke and Kone (2011)used the impact pathway approach to quantitatively estimate the level of the health effects caused by sulphur species emission from coal-fired power plant in Turkey. They compared the estimated health impacts with and without the flue-gas desulphurisation equipment. External costs in monetary terms were presented in Table 2.

Karimzadegan et al. (2015) analyzed and evaluated the internalization of health effects and other environmental damages of power plants in Iran. According to their study, marginal external costs in Iran were roughly 0.019-0.0899 USD/kWh for fossil-based electricity generation plants; 0.0687-0.1125 USD/kWh for steam power plants;0.0737-0.1275 USD/kWh for natural gas power plants; and 0.0503-0.0782 USD/kWh for combined cycle power plants.

Table 2 provides a summary of the above studies, which are based in the Impact Pathway Model outside EU.

4.2 Studies of Electricity Externalitiesin USA

The study by Pace University Center for Environmental Legal Studies (Ottinger et al., 1990) is one of the best known and most frequently cited studies of environmental costs in USA. Another study by Tellus Institute was reported in 1990 (Bernow et al., 1990); and results were published in 1991 (Bernow et al., 1991). The estimations on environmental costs of electricity by Pace and Tellus are based on two sets of electricity production modes which are not identical. The Tellus study estimated the costs of airborne pollutants only. Quantitative results of environmental costs from electricity production in the USA extracted from the Pace and Tellus studies are summarized inTable 3.

Table 3. Overview of Studies on External Costof Electricity in USA

Studies	Impact Considered	Power-Plant Type	Low (USD/kWh)	High (USD/kWh)
Ottinger et al. (1990)	AP, WP, CC, AR, LU	C, O, NG, N, S, W, Bio, WTE, DSM	0.0001 (W)	0.079 (O)
Bernow et al. (1990 and 1991)	AP	C,O, NG	0.0168 (NG)	0.0997 (C)
Parfomak (1997)	Con	C, NG	0.0003	0.68
Machol and Rizk (2013)	HI	C, NG, O	0.02 (NG)	0.45 (C)
Keske et al. (2012)	AP	H, Geo, C, NG, S, ASC	0.0018 (Geo)	0.1709 (C)

(Note: See Appendix for Acronyms and Abbreviations)

Parfomak (1997) summarized externality costs based on six widely cited studies of electric generation plant emissions in the 1990s. Per-unit externality costs for common thermal power plants were estimated and summarized in in 1994 constant dollars. The external costs ranged from a low of 0.0003USD/kWh for a steam gas plant to a high of almost 0.68USD/kWh for an uncontrolled coal plant.

Machol and Rizk (2013) quantified the economic value of health impacts associated with PM2.5 and PM2.5 precursors (NO_x and SO_2) on a per kilowatt hour basis, using national average benefit per ton figures provided in Fann et al. (2009). When studying the economic value which was used to improve human health, they found that California beardthe lowest cost (0.005USD/kwh – 0.013USD/kwh) to avoid emissions from fossil fuel electricity, while Maryland bear the most (0.41USD/kwh – 1.01USD/kwh).Theypresented the national average economic value of health impacts for fossil fuels by fuel type: SO_2 and PM2.5 emissions had a much greater impact on the total economic value of health impacts than NO_x.

Keske et al. (2012) presented a total cost electricity pricing model in which environmental costs of electricity generation were also calculated. They used the state of Colorado as an example and determined shadow prices for the external costs of electricity generation in a marginal damage function, which were mercury, CO_2, NO_x, SO_2, and fine particulate matter PM2.5 levels, as well as water consumption and quality. They presented the environmental cost of several air pollutants for each technology.

Table 3 provides a summary of the above studies on external cost of electricity in USA.

4.3Electricity Externalities in China

From China Energy Statistical Yearbook, the gross production of electricity in China in 2011 is more than 15 times of 1980. Even though the proportions of thermal power differ among regions, thermal power generation has been the major production source of electricity in China (Bai et al, 2014), accounting around 80% from 1980 to 2011(China Energy Statistical Yearbook, 2012). In 2011, the total production of electricity from nuclear power and wind power is merely 3%.According to International Energy Agency, 78.9% of electricity production was from coal and peat power plants in 2009.

In China, coal has been the major resources of energy for the last 30 years, accounting from 71.5% to79.5%, and is followed by petroleum andnatural gas. New energy resources, such as hydro power, nuclear power and solar power, take up only 4% at most (China Energy Statistical Yearbook, 2012).

Even though plenty of studies on electricity externalitieshave been conducted internationally, only a few have been made in China.

Using economic theories, pollutants calculation methods and pollutants' environmental costs, Ding et al. (2006) developed a model named "the external cost of electricity generation model in China". Their model calculated environmental costs of electricity generation with available data of power plants and provided a detailed external cost analysis for the Guiyang power plant with coal combustion. They presented environmental costs of power plants in different areas of China. Their study even estimated environmental costs of new energy power plants in East China by comparing electricity generation based on traditional power plants of China with Europe's. The external cost ofcoalbasedpower plant is 0.0266 USD/kwh; while the external costs of oil based and gas based power plant are 0.0222 USD/kwh and 0.0101 USD/kwh, respectively. Their results showed that the external costs from new energy power generation such as wind, photovoltaic (PV), hydro, nuclear, biomass were much lower than those of electricity generation based on coal, oil, and gas. The study ofDing et al. (2006) onestimation of environmental costs are showed in Table 4.

Table 4. Overview of Studies on External Costof Electricity in China

Studies	**Impact Considered**	**Power-Plant Type**	**Low (USD/kWh)**	**High (USD/kWh)**
Ding et al. (2006)	AP	C, O, NG, N, Bio, H, PV, W, WTE	0.0009 (W)	0.0266 (C)
Zhang et al. (2007)	AP	N, Bio, H, W, WTE	0.0007 (H)	0.1156 (WTE)
Jiang et al. (2008)	HI, Agr, F, Eco, M, Cle, RHI, CC, CMA	C	0.0492	0.0492

Jiang (2010)	HI, Agr, F, Eco, M, Cle, RHI, CC	N	0.000509	0.000509
Lu et al. (2012)	/	C, H, N, W	0.00001538 (W)	0.023 (C)
Wang et al. (2019)	AP, CC	C, Bio	0.09 (Bio)	0.026 (C)

(Note: 1 USD= 6.5 RMB; See Appendix for Acronyms and Abbreviations)

Zhang et al. (2007) presented estimated external costs of electricity generation in China under different scenarios of long-term energy and environmental policies. They used Long-range Energy Alternatives Planning software to develop a simple model of electricity demand and to estimate gross electricity generation in China up to 2030 under these scenarios (2003 as basic year)). Airborne pollutant external costs of SO_2, NO_x, PM_{10}, and CO_2 from fired power plants were estimated based on emission inventories and environmental cost for unit of pollutants, while external costs of non-fossil power generation were evaluated with external cost for unit of electricity. The authors also ran the developed model to study the impact of different energy efficiency and environmental abatement policy initiatives that would reduce total energy requirement and reduce external costs of electricity generation. In their study, the authors estimated environmental costs of non-fossil fuel electricity generation in China by comparing electricity generation based on traditional power plants of China with Europe's.

Jiang et al. (2008) applied the impact pathway approach to quantify the external cost of coal power chain in China. They evaluated the health effects of air pollution, agriculture, forests and ecosystems, materials, cleanout, global warming, radiological health impacts and fatality impacts of coal mine accident (data from year 2005). They estimated that the external cost of coal power chain in China is 0.38RMB/kwh, and the external cost of coal-based power plant is 0.32RMB/kwh.

An extended study calculating the externalities of the nuclear power chain using the same approach was conducted by Jiang (2010). The nuclear power chain consists of nuclear power plant, mining and smelting of uranium mine, uranium conversion, uranium enrichment and other manufacture procedures. The study estimated that the external cost of nuclear power chain in China is 0.00331RMB/kwh. The research also compared the external costs of environmental impacts from nuclear power and coal power. The results showed that the total external cost of the coal power chain is 115 times higher than that of the nuclear power chain.

Lu et al. (2012) constructed a decision-making model for optimal investment portfolio in generation capacity considering environmental costs. They estimated the environmental cost of electricity generation in China from four kinds of electricity generation technology in China: coal, hydro, nuclear and wind. However, they didn't specify which kind of environment impact was examined in their model.

Wang et al. (2019) adopted a hybrid life cycle inventory modeling approach to estimate the pollution emissions from fuel power plants and evaluate direct and external economic costs of biomass- and coal-fired power respectively in China. They estimated that external cost (of climate change and air pollution) of coal-fired power was at 0.17 RMB/kWh on average, and that of biomass power was 0.06 RMB/kWh.

4.4 Study of Global Electricity Externalities

There are also some studies to establisha comparison of electricity externalities on a global scale. Rafaj and Kypreos (2007)adopted the Global MARKAL-Model (GMM) to calibrate the impacts from electricity externality. GMM is a multi-regional "bottom-up" partial equilibrium model of the global energy system with endogenous technological learning. The authors examined the costs of environmental and health damages from local pollutants (SO_2, NO_x) and climate change, wastes, occupational health, risk of accidents, noise and other burdens.Klaasen and Riahi (2007)examined the global impacts of a policy that internalizes the external costs of electricity generation using a combined energy systems and macroeconomic model. The impacts they examined were only related to air pollution damage, excluding climate costs. Fuel type, sulfur content, removal technology, generation efficiency, and population density were the factors they considered.

More recently, Karkour et al. (2020) evaluated the external cost of electricity generation in G20 countries by using a global life-cycle impact-assessment method. This method is called life cycle impact assessment method based on endpoint modeling (LIME3).

They showed that the countries relying heavily on coalhad the highest external costs inside the G20, while countries with a higher reliance on renewable energies had lower induced costs. Air pollution and climate accounted for a large portion of the external costs. The above studiesare summarized in Table 5.

Table 5. Overview of Studies on Global External Costof Electricity

Studies	Impact Considered	Power-Plant Type	Low (USD/kWh)	High (USD/kWh)
Rafaj and Kypreos (2007)	CC, AP	Bio, C, Geo, H, NG, O, N, S, W	0.001 (H,S,W)	0.177(C)
Klaasen and Riahi (2007)	AP	C, O, NG, BIO, N, W, S	0.001 (S,W)	0.375(C)
Karkour et al. (2020)	CC, AP	C, O, NG, Geo, N, W, S, H	0.008 (Canada)	0.172 (India)

(Note: See Appendix for Acronyms and Abbreviations)

5. Summary

Imperfect market structure, externalities, imperfect information or public goods cause the failure of the market to provide an effective mechanism for optimal resource use, especially the use of environmental resources such as air and water. By reviewing the international literatures on the cost of externalities fromdifferent electricity generation technologies, it is learnt that externalities differ widely. Based on the ExternE project, the averageratio of external costs of electricity consumption to electricity price for 20 European Countries in 2005 is 35%. The ratio of external costs to electricity price in USA ranges from 13% in SO_2 controlled coal plant of BPA's study to 700% in SO_2 uncontrolled coal plant of California's study. In China, coal is the major energy source. The ratios of external costs of coal power plant to electricity price are 24% (in the study of Ding et al.) and 45% (in the study of Jiang et al.).

In sum, external costs ofelectricity differ greatlydepending on electricity generation technologies and the impact considered.This paper reveals the serious hidden impacts from the external cost of using electricity.

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Appendix: List of Acronyms and Abbreviations

Agr	Agriculture	H	hydropower
AP	Air pollution	HI	health impacts
AR	acid rain	LU	land use
ASC	Advanced Simple Cycle	Li	lignite
Bio	Biofuel	M	Materials
BioL	Biodiversity losses	N	nuclear
C	Coal	NG	natural gas
Con	Conservation	NGCC	natural gas combined cycle
CC	Climate change	O	Oil
CCGT	combined cycle gas turbine	OCGT	Open-Cycle Gas Turbine
CCP	combined cycle power	P	peat
CHP	combined heat and power	PV	photovoltaic
Cle	Cleanout	R	resource
CMA	Coal Mine Accident	Re	Renewable energy
D	Diesel	RHI	Radiological Health Impacts
DSM	demand-side management	S	solar
Eco	Ecosystems	SOC	social cost
F	Forests	W	wind
FF	Fossil fuels	WP	Water pollution
Geo	Geothermal	WTE	waste-to-energy