RFF REPORT

The True Cost of Electric Power

An Inventory of Methodologies to Support Future Decisionmaking in Comparing the Cost and Competitiveness of Electricity Generation Technologies

Dallas Burtraw, Alan Krupnick, and Gabriel Sampson, with contributions from William Isaac, Jessica Chu, and Blair Beasley

Prepared to support stakeholder dialogue on behalf of REN21.

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RESOURCES FOR THE FUTURE

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I. Introduction

A. Purpose of Project

To support the Renewable Energy Policy Network for the 21st Century (REN21), Resources for the Future was asked to provide a critical review of methodologies for accounting for the *true costs* of electric power across the available generation technologies. By true costs, economists mean the *social costs* of electricity, accounting for private or market costs as well as the external costs. To the extent that policies in a country are designed to force investment and operating decisions in the market to account for true costs, as opposed to simply private or market costs, renewable energy sources are likely to be advantaged.

This report is limited to a focus on the individual facility and asks, ultimately, what the social costs would be for an electric generation facility powered by coal, oil, gas, nuclear, hydro, solar, wind, and other fuels. To fully explore this topic, one would want to examine the entire energy system and address issues such as those arising from network effects, such as how to think about true costs when one needs to pair wind with other, less intermittent technologies. Also, note that this project is about methodologies for developing true cost estimates, not about choosing estimates from the literature. Nonetheless, the reader will gain some understanding of the estimates available and the relative magnitude of various aspects of social costs stemming from different technologies in different contexts.

B. Approach

Our approach was to review the available conceptual and empirical literature on social cost estimation and to draw from that literature—and our experience as creators of some of this literature—to identify the strengths and weaknesses of the various methods used to estimate such

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costs. In this task, we considered use by project developers, utility system planners, research analysts, and government policymakers.

C. Meaning of Terms

The National Research Council provides a very good set of definitions of key terms, which we paraphrase here(NRC 2010, 30–31, Box 1-2).[1] The first set of terms describes the elements of the damage function approach to estimating external costs of energy.

i. *Burden*: The (generally) harmful by-products of economic activity are termed burdens. These include, most prominently, emissions to the air, effluent to the water, and wastes dumped on land, but less obviously, industrial accidents. The burdens are often transformed in the environment and dispersed where they come into contact with people and other living things, causing impacts/effects.

ii. *Impact/Effect*: These are generally physical effects caused as by-products of economic activity. For humans, these include mortality and morbidity, say from air pollution exposure or a well blow-out. For the environment, damage to fish populations and plant life are examples of impacts. Some impacts/effects are not physical. For example, growing dependence on oil or natural gas may reduce a country's energy security; we would place that effect in this category.

iii. *Damage/Benefit*: Damages are the monetary value of impacts/effects. Generally, damages are calculated by multiplying a *unit value* (e.g., dollars per asthma attack) by the relevant impact (e.g., total asthma attacks as a result of air pollution burdens). Benefits are the monetary value of reductions in impacts/effects.

iv. *Value*: Value is a term taken from modern welfare economics that generally refers to the maximum willingness to pay (WTP), averaged over the relevant population, for something, such as one fewer asthma attack. It is a monetization of preferences people have for consuming or, in this case, avoiding consuming things, given their income or wealth. In a market economy, the price of a thing represents its value.

v. *Externality*: Externalities can be positive or negative. With pollution burdens, they are negative. They are effects of one agent on another agent outside the market system. Government intervention is usually justified when negative externalities exist. Unregulated pollution emissions are a good example of a clear case for externalities existing and intervention being justified. Industrial accidents that only affect workers are much less clear cut because in a competitive market with informed workers, there is a mechanism that accounts for the riskiness of a job in the wages and benefits available to workers. Thus, where labor markets are well functioning, many economists would argue that the damages to workers are internalized (included) in the safety decisions of the companies that hire them and do not justify government intervention.

vi. *Social (or True) Cost*: This is the total cost to society of producing the last unit of a product, such as a British thermal unit (Btu) of energy from burning coal to make electricity. Social cost can be thought of as the private cost of that unit (its market price) plus the external cost of that unit (the value of its health and environmental impacts not accounted for in the market). Social costs may be distinguished from private costs.

[1] Krupnick was on the panel that wrote this report.

vii. *Private Costs*: These are summarized in price, but represent the "standard" cost of producing an additional unit of something, in this case electricity, which would include all costs of inputs into producing electricity. A term that often comes up is *levelized costs*, which spread the fixed costs of the capital used to produce something over the lifetime of that capital and add to it the variable costs (labor, fuel, and management) used to produce that thing to arrive at an average private lifetime estimate of the cost of production.

viii. *Benefit Transfer*: This is a term that describes the process of taking an estimate of benefits or damages from (usually) a primary study performed at a *donor site* and applying it (with or without various types of adjustments) to the *transfer site*. The donor site is where an original study takes place, say at the site of an existing power plant, whereas the transfer site is where the study site's estimates are being applied, say a prospective plant location. In our context, benefit transfer involves taking an estimate of the external costs of electricity associated with a specific fuel and technology from one location (in the European Union, for instance) and applying that estimate (again, with or without various adjustments) to coal-generated electricity in another location (for example, South Africa).

D. Use of External Cost Estimates

With the above terminology in place, the objective of estimating the external costs of various forms of energy is then to develop policies that alter the price of energy to take such costs into account and "level the playing field." Generally, renewable forms of energy have far lower external costs than energy generated from fossil fuels, but the market, which doesn't take this fact into account, features lower prices for fossil fuel–derived energy than for renewables-supplied energy. Hence, if one can, through policies, appropriately raise the price of electricity produced by fossil fuel energy relative to renewables, the playing field levels out and renewables can compete with fossil fuel on a fair and economically justified basis.

In practice, however, it is very difficult and controversial to distinguish between damages or benefits on the one hand and external costs on the other. The relatively easy and clear case is where a pollutant is not currently regulated or regulations are not enforced—say for carbon dioxide (CO_2) in the United States or for many conventional pollutants in developing countries. In that case, all the damages are external costs. But if the pollutant is already regulated and the regulations enforced (such as sulfur dioxide [SO_2] in the United States), and if reducing that pollutant's emissions is reflected in the costs of generating electricity, then one could argue that in some cases at least a portion of the damages are internalized, depending on the type of regulatory framework. For example, if SO_2 emissions fall under a cap, such that a unit of additional emissions by one source is offset by reductions elsewhere, one could argue to a first approximation that external costs of new SO_2 emissions (say from a new coal plant) are zero. In contrast, regulation of the pollutant with an emissions fee internalizes the costs of emissions if the fee is equal to the damages. If the fee is less than the damages, then the remainder could be viewed as an external cost. On the other hand, the fee could be greater than the damage, suggesting a negative external cost of production. If regulation of the pollutant is based on a standard requiring the use of a specific control technology, then emissions will be reduced, but the remaining emissions will have an external cost. Because of these complications that hinge on the policy environment, studies of the social costs or external costs of energy or electricity invariably stop after they have estimated damages or benefits and argue for adjustments to energy prices on that basis, but this is not always a correct measure of the external costs.

In terms of the use of such estimates, a wide range of options are possible. Economics suggests that an emissions fee that is set at the level of the external costs is an efficient approach for taking social costs into account. A tax on CO_2 is a good example, but of course in that case tremendous uncertainty exists about the external costs of CO_2. Moreover, the political will to introduce a price on CO_2 may not lead to a CO_2 price that equals its external costs. Similarly, a cap-and-trade system that creates a price on a capped pollutant takes social costs into account, but whether it does so adequately depends on the level of the cap.

Other approaches have also been used in the regulatory process. In the United States, during the early 1990s, a large literature developed around the possibility of using these estimates as *environmental adders*. These were intended for use by utility regulatory commissions and their regulated electricity utilities to apply to investment planning calculations. Instead of counting only levelized private costs, utilities were to be required to calculate these costs from society's perspective and to make generation investment decisions on that basis. Some discussion also focused on *environmental dispatch*, where the actual dispatch of electricity would take place on the basis of pricing based on social costs rather than private costs alone. Neither of these approaches was ever fully implemented, as the role of regulation in investment planning was upended in much of the country as the U.S. electricity sector became consumed with the idea of deregulation.

In a public planning process, government officials will be interested in the social costs of investment alternatives and in the operation of existing infrastructure because it affects the wellbeing of society. Private investors also may be interested in accounting for social costs if they anticipate future liability for external costs or if they have a broad enough perspective to recognize the influence of external costs on the prospects for economic growth and development.

II. Introduction to the Literature

A voluminous, although largely older literature considers the conceptual issues associated with estimating the social costs of energy and empirical attempts to make such estimates. In this section, we first examine methods associated with primary studies that attempt to develop *de novo* social cost estimates. Second, we discuss the damage function approach in contrast with the use of abatement costs as a surrogate measure of damages. Third, we review the distinctions among primary studies and benefits transfer studies. This review gives a shape to the literature in terms of its diverse methodological choices and its results. In the following sections, we consider each of these bodies of literature in turn.

A. Classification of Methods for Primary Studies

Every research team planning to do a primary social cost study needs to make choices about its scope and methods. In this section, we describe the nature of these choices. In the next section, we describe how the four "best" primary studies made those choices. Later, we evaluate the advantages and disadvantages of picking one option over another.

Basis for Screening/Addressing Nonquantifiables

No primary study can address every possible impact pathway leading to a social cost. Some pathways lack the necessary data. Others are, *a priori*, too insignificant to worry about or spend scarce resources researching. Thus, every study team needs to engage in some sort of screening exercise to decide on the appropriate set of impact pathways to value. Even so, for *a priori* significant pathways, policymakers should understand that a nonquantified impact pathway has a nonzero social cost and that, therefore, any social cost estimate for a fuel cycle is likely to be an underestimate, other things being equal.

Location Specificity

It is undeniable that pollution, and to a large extent, other types of burdens associated with energy production, have effects or impacts that depend on the location of the energy production source. The most obvious example is air pollution. A source located near and upwind of population centers will have larger health impacts than a source located on an ocean coast with prevailing winds out to sea. A source of emissions of ozone precursors located in a region prone to atmospheric inversions will contribute more to an ozone problem than one located in another type of area. Thus every study team needs to account for the unique geographic characteristics of the study area.

New vs. Existing Plants

This choice depends on the purpose of the social costing exercise. If the purpose is to help decide on the future mix of policies or technologies for producing energy, then new plants should be the focus of the exercise. If the purpose is to understand the current state of social costs of various fuel cycles or energy types, then the focus should be on existing plants. The focus matters enormously because newer plants will generally have lower burdens than existing plants (in the same location). The technology that is used to generate energy and the technology used to reduce burdens both contribute to the burdens associated with a particular source. New plants will generally produce energy (or inputs needed to produce energy) more efficiently and with fewer burdens (e.g., pollution emissions) per Btu than older plants. New plants may also be required to have newer and more effective abatement measures to reduce burdens because government regulation is often more strict for new sources than for existing sources. For instance, in the United States, new pollution sources usually have to use *best available control technology*, which is more stringent than *reasonably available control technology*, which applies to most existing sources. Choosing to estimate the social costs of new sources carries with it the added task of deciding where such sources are to be located.

Life Cycle vs. Generation Only

The social costs of electricity generation entail more than just the costs associated with generating the electricity. The extraction, processing, distribution, and transportation of fuel; the creation of construction materials and machinery for the power plant; and the burdens associated with building and decommissioning power plants are some of the more important elements of the life cycle. Thus, analyses confined to just the power generation phase will underestimate social costs. On the other hand, the analysis is made vastly more complicated by considering the full life cycle and, arguably, the largest burdens come from the power generation itself. By adding selective elements of the fuel cycle that are likely to contribute significantly to the social cost estimate, such as oil extraction for the oil cycle, an effective compromise can be reached.

Types of Generation Considered

This is probably the core choice of the analysis, but perhaps one of the easiest. If existing generation is the focus, then the coverage should be all types of existing sources. If the focus is new generation, then, again, the purpose of the exercise will dictate its breadth of generation types. If the government or stakeholders want to focus on only a subset of generation types, such as coal, then that determines the choice. Australia's very recent focus on the carbon tax was actually mostly a focus on coal-based electricity generation. Another consideration is the practical one of estimating burdens for generation types that *a priori* have low social costs, such as wind and solar power. A knottier problem is how to address energy efficiency and conservation, which is not a generation type and creates reductions in social costs. Deciding what actual generation types are "backed out" by increased conservation of energy is not an easy problem; it requires modeling and many assumptions.

Types of Impact Pathways to Consider

Every study team needs to make decisions about the type of impact pathways to consider, from burdens through effects. The more impact pathways in the analysis, the more comprehensive and difficult the work will be. These choices are certainly informed by a screening analysis (see above), which is, itself, informed by prior social costing studies and a sense of where the research center of gravity is located. The linkage between air pollution emissions and public health is probably the most studied in and of itself, as well as for impact pathways included in social costing studies.

Techniques for Estimating Impacts

Few general statements can be made about these choices, except that what is needed is a relationship between some impact and the burden causing that impact (in the form of, say, a concentration–response function) and the population bearing the burden. Occasionally, additional information is needed to relate the functional relationships in the literature to actual impacts. For example, the baseline mortality rate in a population is needed to relate a function explaining the percentage change in mortality risk associated with a change in air pollution concentrations to an estimate of the number of people affected.

The techniques linking air pollution to public health draw from two literatures: clinical research and epidemiological research. The latter is superior because it deals with large numbers of people living in a region or multiple regions, but it may fail to differentiate the causes of changes in health status. Clinical research, on the other hand, is laboratory-based. Sometimes, a lack of epidemiological information leads to the use of and extrapolation from clinical research. Mortality and many morbidity endpoints have impact pathways reasonably well estimated, at least for major developed countries. The record is more questionable for developing countries. The units for expressing some endpoints are controversial. For instance, there is a debate about whether mortality risks should be expressed in terms of lives lost or life-years lost.

Types of Impacts Valued and Valuation Approaches

The ultimate purpose of the social costing exercise is to express social costs (or benefits) in monetary units. Hence the impacts need to be quantified in monetary terms—that is, "valued." The two basic approaches to do this are called *revealed preference* and *stated preference* approaches. The former uses an analysis of behavior to estimate the WTP for health, environmental, or other types of improvements. An example is the use of visitors' travel costs to recreation sites to estimate how much they value these sites. The latter uses highly structured surveys to ask directly an individual's WTP for health or environmental improvements. An example is surveys asking about the WTP for mortality risk reductions.

Addressing Time and Space

Any primary analysis of social costs needs to adopt strategies for dealing with the temporal and spatial dimensions of impacts and values. The location-specificity of impacts, as noted above, means that an appropriate level of spatial aggregation must be chosen. For air pollution, will an analysis proceed on a 1-kilometer grid, a 20-kilometer grid, or perhaps over an entire airshed? Modeling and data requirements vary depending on these choices, as do the level of detail and robustness of the results. Impacts have a temporal dimension too. Some burdens accumulate over time in the environment, where they may induce a response after an accumulation threshold is reached. Other burdens have immediate and linear effects on the environment or the public. The temporal aspect of valuation refers to the phenomenon of *discounting*—a concept that is at once controversial among noneconomists and universally accepted as necessary among economists. Despite their acceptance of discounting, economists widely debate which discount rate is most appropriate for aggregating temporally diverse benefits over time. To see the importance of discounting, imagine that one fuel cycle has social costs that occur constantly, year in and year out, whereas another fuel cycle (possibly nuclear power) primarily has costs far into the future. Discounting puts these diverse time paths of costs on equal footing. The spatial aspect of valuation refers to differences in the economic valuation of impacts. Differences in income and other cultural aspects of individual and social preferences may affect the relative marginal valuation of impacts in different settings.

Difference between Monetized Endpoints and the Externalities Recognized for Policy

This controversial concept is probably the hardest to understand. The ability to monetize an endpoint does not mean that the endpoint should be included in a social cost analysis, because only external costs warrant such inclusion. Consider the on-the-job injuries associated with coal mining. Good data are available for estimating the accident risks associated with mining a ton of coal, and many revealed preference studies use wage and accident data to estimate the wage premium associated with being in risky jobs. However, the fact that such wage premia are observed implies that accident risks and attempts by companies to mitigate them in response to government regulations are, at least to some degree, already reflected in the market price of coal and do not necessarily need to be further adjusted to reflect external costs. To make a further adjustment requires further justification, such as that the wage premia are too low because workers underestimate the risks they face or are forced to take and stay at mining jobs because of a lack of other job opportunities. In general, making distinctions between monetary damages and externalities is so difficult and controversial that rules of thumb are often used (e.g., occupational accidents are not counted). We discuss this issue further below.

Addressing Uncertainties

Social costs are not known with certainty, even for the best understood impact pathways and valuation applications. In general, statistical approaches are used to estimate the impact pathways and values. These approaches estimate statistical uncertainties (or confidence intervals) around functional parameters. Similarly, one can have various degrees of confidence about particular elements in the literature. Literature on one impact pathway may be very light or divergent, whereas literature on another impact pathway may be large and unified. These issues can loosely be labeled under the heading of *model uncertainty*. Finally, uncertainty exists about what we cannot estimate at all and even about what is unknown.

An important issue is how to express these various types of uncertainties in an analysis while ensuring that the analysis is tractable. In general, it is possible to describe in a straightforward manner the statistical uncertainty associated with a point estimate of social costs of one component or parameter. But combining the distribution of one estimate with others in the impact pathway chain and across impact pathways is complex unless the system is entirely linear—that is, the marginal effect of impacts is constant. If it is not, Monte Carlo simulation approaches can be used. Expressing model uncertainty and uncertainty about nonquantifiable impacts is less satisfying but can be addressed in a variety of generally qualitative ways, including the structured elicitation of expert judgement (see below).

B. Damage Function Approach vs. Abatement Cost Approach[2]

It is the clear consensus that if data are available, the damage function approach is the appropriate method for estimating damages. In the absence of good data, some studies have used abatement costs as a proxy for damages because abatement cost information is often more available. The logic for this substitution is that if regulation of a substance, say SO_2, is optimal, then this means that the marginal cost of reducing the emissions of the substance equals its marginal damage. In this case, abatement costs are a perfect proxy for damages. Those who use this approach argue that the political process for setting environmental and other regulations reflects society's trade-offs between abatement costs and damages and therefore provides optimal regulation.

Some problems arise from the use of abatement costs as a proxy.

- Regulations are generally not set optimally. Any observer of the political process will realize that the factors that go into passage of a particular law, and the regulations issued in response to that law, are quite numerous and go far beyond the consideration of damages and abatement costs—into equity concerns, legal concerns, interest group pressure, and the like. In many cases, such laws are implemented in the absence of full information—for example, as an exercise of a precautionary principle. The purpose of a damage–cost analysis is to provide a basis for such laws, not to take laws as the basis. In any event, if the regulations are too stringent, marginal abatement costs will exceed marginal damages; if they are too weak, marginal abatement costs will underestimate marginal damages.
- Only certain forms of regulations, such as performance standards, could qualify as optimal in any event. Many regulations are set on the basis of requiring the use of given technologies at all sources—a "one size fits all" regulation. It would be only by coincidence that a technology would have a marginal abatement cost equal to the marginal damage.
- The abatement cost is zero for an unregulated pollutant such as CO_2. However, this does not necessarily imply, by extension, that marginal damages of the unregulated pollutant are zero.

[2] One class of revealed preference approaches for estimating damages permit the analyst to skip over steps in the damage function approach. This class incorporates some hedonic approaches. For instance, the effects of air pollution on health and possibly other endpoints, such as materials, can be captured by a statistical study of the determinants of property values, where air pollution is one of the explanatory variables. Such a study eliminates the need to consider epidemiological studies linking air pollution to health, instead substituting the market's judgements for these links. Because the market would have difficulty making these judgements, this approach is not recommended.

C. Primary Studies vs. Benefits Transfer Studies

In this report, we make distinctions between primary social costing studies and benefits transfer studies. Notably, however, the differences between primary studies and benefits transfer studies are a matter of degree, rather than an absolute. In a primary study, most key elements of the damage function approach are performed with data or findings unique to the study, or at least from data or findings from the country where the analysis is occurring. For instance, a primary study generally would define the type of plant and plant parameters being studied; analyze the linkage between emissions and concentrations in the environment using models or concepts appropriate to the location of the plant being studied; link those concentrations to health or other effects using information available locally, or at least from the country in question; and monetize the resulting impacts using valuation information appropriate at least to the country in question.

A benefits transfer study adapts engineering, health, environmental, or economic data taken from an original study site (which we call the donor site) under particular resource and policy contexts and applies the data to a separate site (the transfer site). Compared to primary studies, a benefits transfer study would have many fewer elements of the damage function approach developed uniquely for the site in question. Benefits transfer studies are usually performed when the necessary time, money, or expertise to do a detailed primary study are lacking, or when the data or literature are not of sufficient scope or quality to support a primary study.

The varieties of benefits transfer studies can be categorized by the strength of the assumptions made about the similarity between the donor site and the transfer site. If one assumes that the two sites are basically identical in terms of the impact of their power plants' burdens, then, for the example of an air pollutant and health effects, one can calculate an estimate in dollars per megawatt-hour (MWh) for each type of fuel and generation technology from the primary study and multiply this by the purchasing power parity to arrive at a dollar estimate of damage at the transfer site. This estimate is credible to the extent that the two sites are identical in the emissions rates, emissions-to-concentration relationships, epidemiological relationships, affected population size and characteristics, and preferences of the populations for avoiding all types of impacts.

In the health effects context, for illustration, some of the following varieties of benefit transfers can be offered that transfer money values, going from the strongest to the weakest assumptions:

- dollar per MWh
- dollar per ton
- dollar per unit concentration
- dollar per exposed population
- dollar per health effect

Thus, if a dollar per unit concentration is applied from the donor study to the transfer site, this means that the researchers doing the transfer feel that the emissions-to-concentration relationships are too different across these sites to make a more gross transfer and that this particular linkage must be calculated uniquely for the transfer site. But the researchers are assuming that the other elements of the damage function approach can be assumed to be reasonably similar across the two sites. Moving down this list, use of the dollar per exposed population estimate reflects the researchers' additional judgement that the populations and the emissions-to-concentration relationships are sufficiently different across the sites to warrant their unique analysis of the population affected in the transfer site.

The transfers also can be made on the basis of tons of emissions, going from the strongest to the weakest assumptions:

- dollar per ton
- health effects per ton
- exposed population per ton
- concentrations per ton

For example, with health effects per ton, such a transfer would assume similarity across the two sites in terms of all the elements of the damage function approach except WTP for changes in health status. For the last bullet, only air meteorology would be assumed transferable.

Many other combinations are possible. One set in particular normalizes on population. The idea is to divide whatever transfer estimate is being used by population because, despite any differences between the donor and transfer sites, an almost guaranteed difference is in population levels. For example, if the dollar per ton number were to be transferred, that would be divided by the relevant population in the primary study to get a dollar per ton per person estimate. Applying this to the transfer site involves multiplying this estimate by the relevant population at the transfer site. Needless to say, any of these approaches can be applied to any particular impact pathway, so a particular transfer study can feature many different transfer approaches, depending on data availability and assumptions the analysts make.

Within any element of the damage function approach, a variety of methods can be used to adapt information used in the primary study to the transfer study. These methods can be grouped into function transfers and value transfers, where the meaning of *value* is broader than simply the monetary value. Probably the most discussed are approaches for adapting the estimates of preferences for reducing mortality risks. In a typical primary study, a value of a statistical life (VSL)[3] is taken from original research papers applicable to the country or region in question. Researchers doing the transfer have the following choices.

i. Draw on original literature in the transfer area for a VSL (this element would not be considered a transfer).

ii. Use the estimating equation in the primary study to calculate the VSL in the transfer study (called a function transfer).[4]

iii. Do a value transfer, rather than a function transfer. These have three varieties:

   a) adjust the VSL from a donor site for income differences between the donor site and the transfer site, assuming that the VSL is proportional to income (implying an income elasticity of WTP of one);

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[3] The VSL is a population's WTP for a given risk reduction divided by that risk reduction. The term *VSL* is often criticized because is suggests a value is being placed on life rather than on small changes in mortality risk. See Cameron, T. A. (2010). "Euthanizing the Value of a Statistical Life." Review of Environmental Economics and Policy **4**(2): 161-178.

[4] The function could be something like WTP = a + b(income) + c(average population age) * d(risk reduction). In this case, the researchers would use the estimates of a, b, c, and d plus the income, average age, and appropriate risk reduction from the transfer site to compute WTP and then divide that by the risk reduction to compute the VSL.

b) apply a different income elasticity to adjust the VSL (the literature suggests 0.5); or

c) make no adjustments and use the VSL from the donor site.

Similarly, one can use functional or unit transfers for the epidemiological part of the transfer study. The unit in this case could be the health effects per unit of affected population.

Although the examples above have all been couched in terms of air pollution and health effects, transfer strategies are needed for many different types of impact pathways. Some examples, such as those involving ecological endpoints, have much less well-developed transfer strategies. It can also be noted that a benefits transfer study can be used as the donor study, although this removes even further the ultimate benefits transfer study from the applicable information.

III. Review of the Best Primary Studies

From the primary external cost literature, four major studies were identified for a detailed examination: National Research Council (2010), European Commission (2005) hereafter referred to as ExternE), Rowe et al. (1995), and Lee et al. (1995) hereafter referred to as RFF/ORNL).[5] These four studies were selected primarily on the basis of their thoroughness and rigor. The RFF/ORNL and Rowe et al. studies were among the first attempts to take a comprehensive, bottom-up approach to the external costs of electricity fuel cycles. Around the same time, the European Commission, in conjunction with the U.S. Department of Energy (DOE) and RFF/ORNL, produced the first incarnation of the ExternE project series aimed at developing a methodology for monetizing the external damages in the European Union resulting from the coal, natural gas, nuclear, and select renewable electricity fuel cycles. That project has been updated repeatedly. The more recent study conducted by the NRC builds on earlier works by ExternE, RFF/ORNL, and Rowe et al. by estimating and monetizing damages from a distribution of most of the power plants in the United States (as opposed to a limited examination of location-specific power plants) and by using a more updated and extensive literature body for parameter inputs.

The RFF/ORNL study examined seven fuels and all stages of the fuel cycles (beginning with plant construction and fuel extraction, but not including effects upstream from there) for plant technologies assumed to be constructed in the year 1990 at specific geographic sites. For example, damages for a new coal-fired power plant in the RFF/ORNL study refer to two study sites: one in east Tennessee and the other in northwest New Mexico. In most cases, several different technologies were evaluated as alternatives at the same geographic location. The key technical parameters of the hypothetical power plants were designed to meet New Source Performance Standards. A damage function approach was used to estimate the damages accrued within 1,000 miles of the source plant. For upstream fuel cycle damages, the authors addressed coal mining (assuming expanded production at an existing mine or wellhead rather than opening of a new mine), preparation, and transportation. As part of the results, the authors found that health damages from air pollutants were dependent on population and spatial distribution. For instance, damages from a coal-fired plant at the highly populated southeast reference site were estimated to be roughly 62 times higher than the southwest reference site. Moreover, external damages from coal transportation either by rail or by truck were found to be of the same order of magnitude as health effects from air pollution. Coal mining damages were thought to be largely internalized in wage premiums.

[5] RFF/ORNL refers to a study conducted jointly by Resources for the Future and Oak Ridge National Laboratory.

The report by Rowe and others focused largely on developing a methodology for estimating external costs resulting from electricity supply and using a damage function approach. The authors examined more than 300 possible impacts over 23 new and relicensed electric resource options. The potential externalities were then screened into four categories, such that externalities in category one were estimated, and externalities allotted to the other three categories were either identified for future research or presumed to be zero. External cost estimates were computed for three case study locations in New York: an urban site near JFK Airport, a rural site along Lake Ontario, and a suburban site outside Albany. For example, total damages from a natural gas combined-cycle facility were estimated to be approximately 10 times higher at the urban JFK site than the rural Lake Ontario site. And damages from the natural gas combined-cycle facility at the suburban Albany site were nearly twice as large as the rural Lake Ontario site. For an oil distillate combustion facility, the distinctions between external damages at different locations were less pronounced.

In the early 1990s, the ExternE project series launched in collaboration with the U.S. Department of Energy, which sponsored the RFF/ORNL studies. The aim was to produce a systematic approach to the evaluation of external costs over a wide range of different fuel cycles. The project used a representative site[6] for each fuel cycle and computed monetary external damages associated with human health, crops, ecosystems, climate change, and materials. For ecosystem and climate change impacts, the project team also computed marginal and total avoidance costs (where ecosystem costs are defined as the costs necessary to treat regions where critical pollutant loads are exceeded by 50 percent and climate change costs are defined as the shadow price for reaching Kyoto targets). Similar to the studies outlined above, ExternE's estimates for the coal fuel cycle displayed the highest variance, with nearly an order of magnitude difference between low and high estimates. Nuclear, hydro, solar, and wind energy all had low external cost estimates. Subsequent to the first ExternE project, several incarnations have been developed in Europe (e.g., New Energy Externalities Development for Sustainability, Generalization of Research on Accounts and Cost Estimation (for transportation), and Cost Assessment for Sustainable Energy Systems) using the methodology originally established by ExternE and RFF/ORNL.

As part of the NRC study, the authors computed the external damages resulting from the air pollutant emissions associated with electricity generation from 406 existing coal-fueled plants and 498 existing gas-fueled plants. The authors also quantified the emissions resulting from upstream operations for the coal and gas fuel cycles, but the impacts were not monetized. Likewise, damages resulting from air pollutant emissions and greenhouse gas (GHG) emissions associated with nuclear, wind, and solar power were also quantified but not monetized. On average, the damages per kilowatt-hour (kWh) associated with coal plants were 20 times higher than the damages associated with gas plants. However, the results also showed high variance among the distribution of damages from coal and gas plants on a kWh basis, suggestive of the importance of emissions intensity and demographic attributes of the exposed population around the plant site. In this way, the coal plants exhibiting the least damages per kWh were shown to be cleaner than the gas plants exhibiting the most damages per kWh.

Table 1 outlines estimates taken from each of the four major studies summarized above. The estimates are given in 2010 dollars, but have not otherwise been reconciled for heterogeneities in methodological approach. ExternE's estimates represent the range of estimates associated with

[6] New and existing plants meeting current environmental requirements were used.

emissions from 15 E.U. countries. The cost estimates for the coal cycle reported by RFF/ORNL represent only the health-related damages from air pollutant emissions and are taken from their southeast reference location in Knoxville, Tennessee. The illustrative cost estimates summarized from Rowe et al. are taken from the rural Lake Ontario power plant site and represent the lowest damages of their three case studies. Rowe et al.'s range of coal estimates are derived from three coal fuel cycles: fluidized bed, gasification combined-cycle, and pulverized steam. NRC's damages are presented as 5th percentile lower bound and 95th percentile upper bound estimates.

Table 1. Summary of Estimates from Four External Cost Studies, in mills per kWh (2010$)

	Coal	Peat	Oil	Gas	Nuclear	Biomass	Hydro	PV	Wind
RFF/ORNL	2.3	—	0.35–2.11	0.35	0.53	3	—	—	—
Rowe et al.	1.3–4.1	—	2.2	0.33	0.18	4.8	—	—	0.02
ExternE	27–202	27–67	40.3–148	13.4–53.8	3.4–9.4	0–67	0–13	8.1	0–3.4
NRC	2–126	—	—	0.01–5.78	—	—	—	—	—

Note: a mill is one-tenth of a cent or one-thousandth of a dollar; PV is photovoltaic.

Importantly, the RFF/ORNL, Rowe et al., and NRC studies do not include monetized climate change damages in their estimates. The ExternE study does include monetized damages from climate change at the global level, estimated using a shadow price of $6.90–27.80 per ton of CO_2 for reaching Kyoto GHG target reductions.[7] Another important distinction involves the damage pathways and pollutant burdens included in the study. The degree to which estimates of upstream damages to occupational and public health and to transportation infrastructure are featured is especially topical.

Krupnick and Burtraw (1996) compiled a quantitative reconciliation of three of these studies: RFF/ORNL, Rowe et al., and the first version of ExternE (European Commission 1995). The authors focused on differences in the bottom line from these studies—for example, differences in the estimated cost per MWh of electricity generation for the same fuel cycles. The paper aimed to address whether the damage estimates were credible—that is, provided data reliable enough for policymaking—and whether the approaches and estimates were transferable to other locations. With respect to the first question, the study found the different estimates to be consistent after adjusting for essential differences in the study sites. The greatest sources of variation among the study sites and studies were atmospheric modeling and the population affected by changes in air quality. The authors concluded that a measure that avoids this component, such as dollars per person per unit change in pollution concentration, would be preferred for benefit transfer (European Commission 1995).

In general, the results in Table 1 and from the literature support a rank order of fossil fuels wherein the coal fuel cycle is more damaging than the oil fuel cycle, which is more damaging than the natural gas fuel cycle. This difference would be magnified with consideration of climate change impacts. The estimates also suggest that damages from the biomass fuel cycle are of the same order of magnitude as the coal or oil fuel cycles when climate change is not taken into account. However, over its fuel cycle, biomass involves relatively low GHG emissions and would rank more favorably in a study

[7] In this context, the shadow price can be described as the marginal cost of strengthening the constraint on greenhouse gas emissions by one ton of CO_2.

where climate change damages are featured.[8] The nuclear fuel cycle has low external costs in general, although the remote probability of accidents adds a very high consequence factor into the estimates. Photovoltaics and wind are essentially emissions-free energy sources at the use stage, but impacts over the life cycle occur.

A. Important Methodological Distinctions

Notwithstanding the generalizations made in the preceding discussion, significant differences exist for fuel-specific damage estimates across the four primary studies. The differences can be attributed to a variety of causes, including: distinctions in parameter assumptions, technology specification, inclusion or exclusion of physical endpoints, and types of burdens featured in the damage function. Table 2 summarizes the key methodological judgements.

B. Physical Endpoints

All four of these studies dedicated substantial resources to the estimation of health effects related to air pollution. Among the most palpable differences among the four studies are the inclusion of climate change impacts and the degree to which upstream damages were featured. As alluded to earlier, the ExternE project is the only study of the four to monetize estimates of climate change damages resulting from GHG emissions. In comparison, the Rowe et al., RFF/ORNL, and NRC studies discussed climate change impacts in an illustrative fashion and summarized literature estimates of damages. A second major source of distinction among studies is the inclusion of upstream occupational and transportation infrastructure damages. Specifically, the ExternE and RFF/ORNL studies emphasized estimating the damages incurred to the public by fuel transportation accidents and also damages to roadways. And although the RFF/ORNL study assumed that occupational damages from mining and transportation were internalized, the ExternE study assumed a range of partial internalization. Moreover, the ExternE study featured estimates of damages resulting from facility and transmission line construction. The Rowe et al. study distinguishes itself in the emphasis placed on damages incurred to aquatic and terrestrial system endpoints, which manifested as fisheries and aquatic ecosystem impacts and the loss of open space services.

[8] There is substantial ambiguity about upstream emissions from biomass production and transportation and the effects on land use–related emissions. The range of estimates for the biomass fuel cycle produced by ExternE reflects the numerous technologies available for gas cleaning.

Table 2. Summary of Methods for Each of the Four Primary Studies

	ExternE 2005	Rowe et al.	RFF/ORNL	NRC 2010
Scenario				
Plant (new or existing), fuel, year (if new plant)	Nuclear, fossil, and renewable fuel	New/relicensed fossil, nuclear, biomass, wind	Coal, new, 1990	Coal, natural gas, wind, solar, biomass
Geographically specific or representative	Representative site for each fuel	Site-specific for case examples	Site-specific	Representative
Energy cycle				
LCA	Yes	Yes	Yes	Yes
Occupational damages from mining and transport	Assume a range of internalization	Yes (nuclear)	Assumed internalized	Assumed internalized
Public death and injuries from transport	Yes	Not monetized	Yes	Not monetized
Road damages	Yes	Yes	Yes	No
Facility construction	Yes	Assumed zero	No	Not monetized
Pollutants/burdens				
SO_2	Yes	Yes	Yes	Yes
NO_x	Yes	Yes	Yes	Yes
PM fine	Yes	Yes	No	Yes
PM coarse (≥ 10 μm)	Yes	Yes	Yes	Yes
Ozone	Yes	Yes	Yes	Yes
VOCs	Yes	No	Not monetized	Yes
NH_3	Yes	No	Not monetized	Yes
CO_2	Yes	No	Not monetized	Not monetized
CO	Yes	No	Yes	Not monetized

Lead	Yes	Yes	Yes	Not monetized
Metals	Yes	Yes	Not monetized	Not monetized
Impacts and damages				
Method	Damage function	Damage function	Damage function	Damage function
Calculated or transferred	Transfer	Transfer	Transfer	Transfer
Physical endpoint				
Water	Yes	Yes	Yes	Yes
Crops	Yes	Yes	Yes	Yes
Mortality	Yes	Yes	Yes	Yes
Morbidity	Yes	Yes	Yes	Yes
Infrastructure/materials	Yes	Yes	Yes	Yes
Climate change	Yes	No	No	No
Timber	Yes	Yes	Yes	Yes
Visibility	Yes	Yes	Yes	Yes
Recreation	Yes	Yes	Yes	Yes
Ecosystem	Yes	Yes	Yes	No
Noise	Yes	No	Yes	No
Valuation				
Mortality (2010 dollars)	VOLY: $64,000	VSL: $2.4–$9.4 million, midpoint $4.7 million	VSL: $2.8–$15 million, midpoint $6.1 million	VSL: $8 million

Notes: LCA, life-cycle analysis; NH3, ammonia; CO, carbon monoxide; NOx, nitrogen oxides; PM, particulate matter; VOCs, volatile organic compounds; VOLY, value of life year.

C. Plant Characteristics

Damage estimates are presented in terms of mills per kWh, which serves to normalize across the damages according to power plant generation. The emissions intensities employed across and within studies are designed to account for differences in coal composition, plant design parameters, and post-combustion control technologies. For instance, coal composition across the two case study plants used in the RFF/ORNL study differed substantially. Coal for the eastern (Tennessee) plant had an 18 percent lower moisture content, 12 percent higher fixed carbon content, 5 percent higher ash content, and 1.5 percent higher sulfur content than the western (New Mexico) reference plant. Accordingly, the emissions intensity for SO_2, nitrogen oxides (NO_X), and particulate matter (PM) were higher at the eastern reference site than the western reference site.

D. Spatial Boundaries

Spatial ranges and boundaries depend on the particular impact pathway in question. For instance, noise impacts are generally restricted to a couple of miles or less, whereas GHGs require examination on a global scale. Limitations endogenous to the available dispersion modeling packages can also compel research groups to impose ad hoc boundary restrictions to damage functions. To provide an example, ozone models must account for chemical reactions of nitrogen oxides in the atmosphere after initial emission. The ozone models used by Rowe et al. assumed zero secondary PM formation within 50 kilometers of the emissions source while also assuming zero ozone scavenging (where NO_X reacts with ozone to reduce ozone and yield nitrogen dioxide and oxygen) beyond the 50-kilometer boundary. At a broader level, spatial boundaries establish which receptors are or are not counted in the damage assessment. For instance, the ExternE project includes all E.U. member states and Norway in its analysis, whereas NRC includes all lower 48 states in the United States. And although Rowe et al.'s analysis focused on New York State, damages occurring outside the state and outside of the United States (e.g., Canada) were also included.

E. Air Quality Modeling

The ExternE, RFF/ORNL, and Rowe et al. studies all used some form of the U.S. Environmental Protection Agency (EPA)-approved Industrial Source Complex Long Term (ISCLT) dispersion model for short-range air quality modeling. On the other hand, the NRC study used a more recent model—the Air Pollution Emissions Experiments and Policy (APEEP) model—that features a reduced-form process modeling strategy to assess damages at the county level. The ExternE and Rowe et al. studies switched over to longer-range air dispersion models given that EPA's approval for using its ISCLT model is limited to a 50-mile range.

To model ozone pollutants at the regional scale, the ExternE study used the European Monitoring and Evaluation Programme (EMEP) Lagrangian Photo-Oxidant Transboundary Air Pollution model. The EMEP model traces air parcels over 98-hour trajectories to 740 receptor points across Europe. The RFF/ORNL study relied on the Empirical Kinetic Modeling Approach trajectory model to estimate concentrations of ozone resulting from NO_x emissions in a NO_x-limited environment. The Rowe et al. and ExternE studies also modeled secondary PM formation. ExternE employed the Windrose Trajectory Model (WTM) to estimate the concentration and deposition of particulates from acid species at the regional level. In a similar way, Rowe et al. estimated particulate concentrations across the regional level using their original model framework.

F. Population

Damage estimates, when normalized by plant generation, are highly sensitive to the size of the affected population. The difference between the RFF/ORNL coal fuel cycle damage cost estimates for the southwest and southeast reference plants provides a salient example. The population estimated within a 50-mile radial distance of the southwest and southeast reference sites were 98,000 and 870,000 respectively. Given a coal plant of equal design, the externalities associated with airborne pollutants on health care were 0.91 mills per kWh at the southeast site and 0.01 mills per kWh at the southwest reference site (a difference of nearly two orders of magnitude). The arrangement of population subgroups (such as the elderly or individuals with respiratory complications) and the baseline health conditions of the affected population (such as mortality rate) are also salient sources of dissimilarities between damage estimates.

G. Screening

Many potential effects of electricity use might be suggested for study, and analysts need a method to conduct preliminary analysis so they can direct study resources to their highest valued use. This preliminary analysis is referred to as screening. The strategies used to screen the potential impact pathways were similar across the four studies. All based the decision on whether to include a given impact pathway in their examination on the existence of literature and, to some extent, the expected size and frequency of damages. Rowe et al. developed a systematic approach to screen the potential impacts into four categories. Category one impacts received additional quantification because they were expected to have the most significant associated externalities while also possessing an adequate literature base. Category two impacts were assigned a damage value of zero because they were not considered externalities, were fixed, or had extremely low expected damages. Category three impacts were assigned a damage value of zero because the development of a damage function was considered infeasible, despite the scope of existing literature. Category four impacts were also assigned a value of zero as a result of scarcity in literature and data. The assignment of a zero value when the existing literature was inadequate is questionable. Below we discuss other methods to convey uncertainty and acknowledge potentially important and undescribed effects. NRC and RFF/ORNL used a slightly different approach by making monetary estimates for the impacts they considered most important, leaving other impacts quantified but not monetized.

H. Discounting

For the nuclear fuel cycle and pathways involving cumulative or lagged risks (e.g., lifetime cancer risks), the choice of discount rate can make a significant difference in damage estimates. On the other hand, fuel cycles like coal, where pathways involving the effects of damages that are cumulative or delayed are extremely limited, have lower sensitivity to discount rates. ExternE used discount rates ranging from 0 percent to 6 percent. Rowe et al. used a 3 percent discount rate, and RFF/ORNL used a 5 percent discount rate.

I. Uncertainty

The four primary studies address uncertainty in different ways. The NRC study used the relatively forthright but limited approach of choosing an elasticity of the VSL parameter along with low, medium, and high carbon prices. On the other hand, Rowe et al. approximated a probability distribution using a three-point estimation technique to propagate uncertainty in key parameters. In a more intricate approach, the RFF/ORNL study featured confidence intervals and used Monte Carlo simulations to propagate uncertainties in select parameters across their damage computations. Finally, ExternE used lognormal probability distributions with geometric standard deviations assigned to air dispersion, dose–response, and valuation parameters.

IV. Critical Review of Methods for Primary Studies

The primary studies identified in Section III provided a template for methods that could be used; they also developed many of the estimates that have subsequently been employed in transferring values to new locations. In this section, we evaluate further the methods used in the primary studies and make choices where possible.

A. Basis for Screening Potential Effects/Methods for Addressing Nonquantifiable Effects

All of the primary studies we reviewed do some screening of impact pathways. Such a procedure is necessary to guide the rest of the study—that is, to target how the study's scarce resources will be used. In addition, the screening analysis can identify what is not being analyzed, which is essential for placing the results in the proper context. We like a slight modification of the Rowe et al. approach that creates four categories:

i. externalities to be analyzed
ii. externalities small enough to be assigned zero
iii. externalities that could be analyzed but are not being pursued because of a judgement that doing so would be too time consuming relative to the size of the damages that would result
iv. externalities with insufficient literature or data

Note that we do not agree with Rowe et al. about assigning zero values to cases iii and iv. These externalities may well be quite large relative to those in case i.

B. Location Specificity

To perform an analysis of damages from a plant, that plant needs to be placed in a location. Logically, this location can be real or some type of composite or model location. The choice is not obvious. A real location has the advantage of being "real," of course, but the choice of that location must be arbitrary to some degree. A composite or modeled location, say a location that is in some sense an average location for a power plant or wind farm, or other type of facility, has the advantage of avoiding this false specificity. But defining an average location is not straightforward and would be controversial.

A further complication is that the point of this exercise is to compare the damages and externalities associated with different types of electricity generation as neutrally as possible. One way to do this is to put all plants in the same location, assuming that location can support all types of generation plants. Another way is to allow locations for different plant types to be different according to some rule. One rule would be that the location reflects the place that "the next" power plant of that type would be built. This is attractive because the location choice recognizes the economic factors that affect location. This idea can be operationalized by choosing the last location in which a plant of that type *was* built. Another rule could be that the site be the "average" site for that plant type. It is not clear how to operationalize this rule.

Ultimately, location choice may not matter that much. Where the elements of the damage function approach are linear, such that a doubling of the damage estimate would result from a doubling of any parameter in the impact pathway (such as population exposed), the damages can be normalized for the linear elements. Thus, in this case, damages per person would be independent of location, and comparisons of damages across technologies could take place in these units. Where there are nonlinearities in the damage function, however, such as with the effect of NO_x emissions on ozone concentrations, location will matter. In that case, using several different locations for each technology may be a reasonable compromise. Decisions on which elements are reasonably linear and which are not can be delegated to experts.

C. New vs. Existing Plants

The focus of this paper is on leveling the playing field between plant types that have very different externalities for the purpose of influencing new investment. Therefore, the focus is primarily on new plants. Above, we note that a focus on a small subset of existing plants may be a good approach to address location specificity needs for new plants. We also note the complication that when a new plant becomes operational it will affect the dispatch order of existing plants, possibly adding to or reducing damages. It may also lead to the early retirement of plants (generally leading to reduced damages on net). These complications are probably best ignored (and have been ignored in previous studies) when examining the costs associated with a single facility. However, consideration of true costs from a dynamic systems perspective could yield significant values from re-dispatch and so on. This is important information for a planning function and it is the intended focus of future analysis.

D. Fuel Cycle vs. Generation Effects Only

Examining damages over the complete fuel cycle is critical (at least until a screening analysis can help decide which life cycle elements need scrutiny). Compared to the effects of generation, less economic attention has focused on the life cycle analysis of fuel supply. The effects of coal extraction are highly dependent on the type of coal, the location, and the estimation and valuation of ecological effects. Substantial knowledge gaps remain with respect to the potentially large effects of hydroelectric and biomass supply. Currently, a major debate centers on the emissions of GHGs from the shale gas life cycle (related to fugitive methane [CH_4] emissions, among many things) compared to that of the coal cycle in terms of global warming potential and the suggestion that the former may exceed the latter (Howarth, Santoro et al. 2011). Such considerations should inform social costing studies. We also note that life cycle analyses generally take a short-term time horizon in which one assumes that technological change along the life cycle is zero and that no new infrastructure (say, a new coal mine) is built to support this life cycle. We do not recommend relaxing such assumptions because the analysis will become unwieldy. However, it would be useful to have a table to make qualitative (directional) adjustments to the damage estimates.

E. Fuel Cycle Elements Considered

Fuel cycle elements, and the next several elements considered below, can benefit from what is called a value of information (VOI) analysis, which involves asking how the benefits of obtaining new information compare to the costs. The benefits of new information can be defined in different ways. One useful definition would be in terms of changing the ranking of alternative plant types. For instance, if new information is reasonably likely to move natural gas ahead of coal as having the largest damages, then we would say that the expected benefits of additional information are high.

Hence, better understanding fugitive CH_4 emissions associated with shale gas production would probably rate high in a VOI.

F. Types of Generation Considered

In general, all types of generation should be considered, although even for a specific type, many different technological options may be available, both for how the fuel is used and for how burdens are abated. All of these combinations probably cannot be investigated, so VOI-informed judgements are needed. It would not be correct to automatically assign zero to renewables. One additional issue is how to treat energy conservation. Energy conservation is not a fuel cycle or a type of (negative) generation. It implies reduced generation and consumption at the system level. Various conservation measures will affect the system differently. Some will reduce total consumption, whereas others may shift generation from one time block to another. The only unambiguous way to account for the benefit of conservation is to take externalities associated with generation types into account; this automatically levels the playing field with respect to consideration of the value of energy conservation.

G. Types of Burdens Considered

The choice of burdens to consider should be VOI-driven, with consideration for data availability and based on the screening analysis. From our review of the literature, the most important and doable burdens to consider include the conventional air pollutants, because of the large and carefully analyzed epidemiological literature linking these pollutants (and their secondary forms, such as ozone and fine PM [$PM_{2.5}$]) to health effects, as well as GHGs, because of the active involvement of governments. Estimates of the damage from GHGs remain controversial, but a large literature addresses the question, and governmental bodies in many jurisdictions have identified values that are used in other planning functions.

H. Transformation of Burdens in the Environment

Before burdens have an impact, they will often travel through air, water, or land, with both dispersal and chemical transformation possible. To reasonably characterize these processes is essential for a credible primary study. As noted above, each of the reviewed primary studies uses a slightly different technique or model. Without budget constraints, the best approach is to use a state-of-the-art, or at least generally accepted, air quality/water quality/soil movement model of the relevant processes, parameterized for the location in question. Few studies have this luxury, as these models are very expensive to parameterize and need very specific expertise to run.

A variety of fallback approaches are available, however. One is to use a screening-level model, such as the ISCLT noted above, which has modest parameterization needs and is easy to run. The big drawback of such models, aside from being less accurate and more aggregative than the state-of-the-art models, is that they focus on the relatively easy to model dispersal/diffusion process, doing little if anything to address chemical transformations. Thus, the RFF/ORNL study was able to reasonably convert SO_2 emissions into SO_2 concentrations over space and then couple this information with SO_2-based epidemiological studies. But the study was not able to consider the transformation of SO_2 into ammonia sulfate, a constituent of $PM_{2.5}$, or its interactions with NO_x in the air. From there, the study could have hooked into the much more persuasive and larger literature on the effects of $PM_{2.5}$ concentrations on health. Another drawback is that typically the simple models do not address the long-range transport of pollutants.

Another approach is to use what are termed source–receptor matrices. These matrices link emissions at specific locations to concentrations at many locations, and are built up by doing multiple runs of a major model. APEEP is an example (as noted above). A variant of this approach is to use a black-box model that links emissions to concentrations through regression analysis. Another variant is the intake fractions approach (Levy, Wolff et al. 2002). The drawback of these fallback approaches is that such models ignore actual physical processes, relying on statistical techniques to make the links between the observed data. Nonetheless, increasingly in the major developed countries, source–receptor matrices are becoming available. These may be embedded in damage function modeling frameworks that contain much of the modeling structure and default information for implementing the damage function approach. Again, of course, one needs a source–receptor matrix that either covers the source and receptor locations in question or assumes that weather, hydrologic, and other conditions are the same at those locations.

I. Impacts and Techniques for Estimation

Once choices are made about the types of burdens to analyze, the set of impacts to consider is narrowed. Yet many choices must still be made. For instance, 20 to 30 possible health endpoints could be considered, although epidemiological relationships may not be available or reliable enough for more than a handful. Thus, some sort of VOI analysis is useful here to narrow the task. We recommend that impacts associated with GHG emissions not be re-estimated as these are global, and numerous analysts and government agencies have already made choices—albeit controversial ones—about the appropriate impacts to include and how to value them.

For a given impact, the literature may offer a variety of information, some of which is conflicting, for capturing the relationship between a burden and that impact. Sorting out the technical issues in this situation is a major and challenging task. Epidemiological relationships may take different forms as to function (e.g., linear or non-linear; continuous or with thresholds, etc.) and variable completeness and specification (e.g., does age enter at all, and if so, as itself or in a square form; does pollution enter as a contemporaneous effect or through a lag structure). And some studies may have results that are more persuasive than other studies for a variety of technical reasons related to sampling, correlation among the independent variables, low power, poorly performing statistical estimations, and so on.

The authors of a new primary study do not have to reinvent the wheel by building the system to make all the needed calculations, finding all the relevant studies in the literature, or making all of these choices about what to include and how to include given studies in consistent ways. Several modeling systems are available for use in spreadsheets or other software packages that can create the mathematical architecture to make all the necessary calculations over all the necessary steps and can permit the substitution of epidemiological relationships included with the model for ones indigenous to the country in question. These systems do the same thing for the valuation step. They also permit the easy use of benefits transfer techniques. In addition, many consultants are available to shepherd these efforts. We list some of the available systems below.

i. The Tracking and Analysis Framework (TAF), written in Analytica, is operated and maintained by Resources for the Future. From inputs on air pollution concentrations over space, it addresses the impacts (primarily health) and valuation steps of the damage function approach.

ii. The Environmental Benefits Mapping and Analysis Program (BENMAP) is operated and maintained by U.S. EPA's Office of Air Quality Planning and Standards. It performs the same functions as TAF and has a very nice GIS interface to keep track of the spatial elements of the analysis. It is available online.

iii. The Regional Air Pollution Information and Simulation model (RAINS), is an integrated air pollution assessment model operated and maintained by the International Institute for Applied Systems Analysis (IIASA). It is a broader model than TAF and BENMAP in that it begins with the emissions step and also covers both health and ecological effects, focusing on PM and ozone.

iv. The EcoSense integrated environmental impact assessment model was developed by the ExternE project for the European Commission. EcoSense combines the Windrose Trajectory Model WTM and industrial source complex atmospheric models with receptor databases, dose–response functions, and monetary values. It is based on the damage function approach. Two more simplified software tools were also developed by the ExternE project: EcoSenseLE and RiskPoll. EcoSenseLE is an online tool that provides damage cost estimates for a typical source. RiskPoll is an application for Windows that approximates impacts and costs according user-inputted data.

J. Types of Impacts Valued and Valuation Approaches

Values are needed only for impacts that are actually estimated. One of the most important values that need to be addressed in social cost studies is the VSL. Another important value is the damage per ton of CO_2 emissions. We recommend that a primary study use a value already chosen by a government or other type of stakeholder. For instance, in the United States, in 2010 an interagency working group identified a value of $21 per ton CO_2-equivalent, to be used in all cost–benefit analyses of major new prospective regulations affecting GHG emissions (Interagency Working Group on Social Cost of Carbon 2010).

K. Addressing Temporal and Spatial Aspects of Burdens

Choices about temporal issues include the time period for the analysis and the discount rate for appropriately totaling the time stream of damages. In theory, the time period for the analysis should be the length of the longest-lived generation investment. A shorter time period would underestimate damages for such investments. In practice, the analysis can actually be reduced to a single period if most or all of the damages are of the “flow” type (as opposed to the “stock” type). Flow-type damages are those for which the cumulative effect of exposure over time, say years, is merely the sum of the annual effects. Air pollution effects on respiratory symptoms are generally thought to be of the flow type, as would be air pollution damages to annual crops. Stock-type damages are those where cumulative effects are present—that is, the size of damages in the future is dependent on previous years’ exposures. The effect of acid rain on ecosystems is a good example. Thus, where stock effects are important, the analysis should be conducted over a long enough period to pick up those effects. For comparison with shorter-lived technologies, the standard assumption is to anticipate that the technology will be rolled over through reinvestment so that lifetimes are comparable.

A more convenient approach for comparing the effects of different technologies, especially where those effects accrue at different points in time, is to annualize the damages. However, to do so requires the use of a discount rate, which is highly controversial. For this reason, we recommend that the analyst defer to existing government or other studies to make this choice. In the United States, for analyses of externalities, a 3 percent real rate of interest is often used by EPA, with an analysis employing a 5 percent rate used to examine the sensitivity of the results to alternative choices for this rate.

L. Difference between Monetized Endpoints and Externalities Recognized for Policy

As shown in the above review, most primary studies ignore the difference between damages and externalities, except to rule out certain types of damages. We agree with this approach. More specifically, we recommend that if the damages are not obviously and fully internalized by regulation or, in certain instances, private behavior, they be treated as externalities.

A notable exception is the effects of various electricity fuel cycles on occupational health. For example, the effects from coal mining can be very large. Yet there are good reasons to expect that operation of the labor market may act to internalize most such damages, unless the labor markets are noncompetitive, which could occur, for instance, if potential workers are immobile, do not understand the risks they face, or have only one or a handful of major employers to choose from. Although we suggest damages be treated as externalities in most instances, in the case of occupational health and safety, we think the burden of proof on including these kinds of damages should be with the analyst.

Another situation where the default should be to assume that the damages are already internalized is when the pollutant is capped by policy (presumably where pollution permits are traded). In this case, a new plant will need to buy permits for its emissions, while the annual emissions are left unchanged. The price of permits might rise with the added demand from new plants, but that effect is within a market and so is not classified as an externality. This simple story can be misleading, however. For one thing, the spatial distribution of emissions can change, leading to more or fewer health effects with the new plant's demand reflected in the permit market versus without it. Second, emissions from such programs are often banked, leading the cap to be nonbinding in any given year. New demands for permits may alter the actual emissions under the cap; or authorities may actually change the cap and/or adopt regulations that effectively wipe out the permit bank as occurred in the U.S. SO_2 emissions allowance market. Thus, with the burden of proof on the analyst, it is possible that a new plant's emissions can be treated as additions to the stock of emissions even with a cap-and-trade system in place.

Finally, Burtraw and Krupnick (1996) point out that, in some situations, the inclusion of damage estimates in planning exercises could lead to worse outcomes, specifically, when doing so provides the incentive for energy users to switch to even more polluting sources of fuel. For example, incomplete consideration of social costs might cover the electricity industry but leave other ways of generating energy uncorrected for social costs. For example, electricity prices could rise, which could lead consumers to unregulated energy sources, such as self-generation with generators or the use of biomass for home heating, which is likely to have even greater environmental consequences than that from the electric sector. Ideally, policymakers need to apply social cost concepts across the board. If not, policymakers need to anticipate the behavioral response to the inclusion of social cost estimates as part of the planning exercise.

M. Addressing Uncertainties

As noted above, uncertainties are pervasive in analyses of this kind. How to appropriately address them is not a settled matter, so many options are available. First, it is helpful to understand more about the types of uncertainties. Statistical uncertainties are based on analyses of data that yield, say, 95 percent confidence intervals around an estimate or specific parameter used in a study. In this case, it is possible to produce a range of estimates of that effect or parameter, in addition to the *central* or *best* estimate. Where statistical uncertainties are present in multiple places within the damage function model, specific techniques can be used to *propagate* those uncertainties to the ultimate damage estimates. One is termed Monte Carlo analysis, whereas another, somewhat simpler approach is referred to as Latin Hypercube analysis.

Model uncertainties stem from the underlying models used to estimate various effects or parameters. For these types of uncertainties, it is more difficult and arbitrary to produce a range of estimates, but sensitivity analyses can be used to give some feel for how sensitive the damages are to alternative models. There are also uncertainties in a broader sense, where one lacks data to estimate relationships and therefore must guess, make assumptions, or avoid providing an estimate. Where estimates are provided, again sensitivity analyses can be used.

Even where data are present, the quality of the data and of the analyses using them could be highly variable. Thus, one may have more faith in some elements of an estimated impact pathway than in other elements; this can ultimately lead to greater confidence in some damage estimates than others. Several approaches can be used to address this issue. In expert elicitation, important gaps in data are addressed through a structured process to elicit the considered opinion of experts in the field. This approach has gained increasing credibility in recent years. Figure 1 illustrates this approach with an example in which the authors used an informal expert elicitation process to assign qualitative weights assessing the value of additional information to improve estimates of the social cost of electricity. The figure provides graphical qualitative measures to express relative weights across the rows and columns, with greater weight indicating a greater value of additional information (Burtraw, Krupnick et al. 1998).

Another approach, used by RFF/ORNL is the NUSAP system (Funtowicz and Ravetz 1990), which is an acronym standing for elements of the notational system describing the uncertainty: **N**umerical information, **U**nit of measurement, **S**pread of value, **A**ssessment of value, **P**edigree. For more on this system, see any of the RFF/ORNL volumes, such as *Estimating Externalities of Biomass Fuel Cycles,* Appendix G (Lee, Krupnick et al. 1998).

Alternatively, Rowe et al. and, much later, the U.S. EPA, have developed a useful approach for addressing omissions and nonstatistical uncertainties in tabular form. The idea is to provide qualitative judgements about how resolving uncertainties would affect the outcomes of the social cost analysis. This involves listing the effect or parameter in question, stating what the uncertainties are, and then stating how resolving that uncertainty in a particular way would increase or decrease the damage estimates in question.[9]

Finally, increasing attention is focusing on the structured elicitation of the judgement of experts to ensure that areas of uncertainty are properly characterized, and in some cases to interpret the results of models (Cooke 1991; Aspinall 2010). Recently, performance-based methods have been developed that quantitatively score the performance of experts on various metrics, using these scores to construct weights and then applying these weights to expert opinion about new questions. Structured elicitation of expert opinion is relatively inexpensive and can provide a great deal of information to decisionmakers as a complement to modeling exercises, and in some cases as a placeholder in the absence of modeling.

[9] An example of a textual variant of this approach can be found in EPA's 2008, Proposed Lead NAAQS Regulatory Impact Analysis (http://www.epa.gov/ttnecas1/regdata/RIAs/pb_ria_6-25-08_proposal.pdf), pages 7-5 to 7-11.

Figure 1. Qualitative Assessment of the Value of Additional Information for Developing Estimates of Social Cost

Categories ● high ◉ high-mid ◒ mid ⊙ low-mid ○ low	<u>1. Link between science and economics:</u> Are benefit endpoints well established? Does science provide information for economic analysis?	<u>2. Economic methods:</u> Are economic methods adequately developed?	<u>3. Data availability:</u> Are data available from science and from economics for an assessment of benefits?	<u>4. Expected benefit:</u> Are expected benefits large?	<u>5. Value of additional information:</u> To improve benefit estimates, where is the greatest priority for research?
Health: Mortality	◉	◉	◉	●	●
Health: Morbidity	◉	◉	◉	◉	◉
Visibility	◉	◒	⊙	◉	◉
Materials & cultural resources	⊙	◒	○	◉	◉
Nonuse values: Ecosystem health	⊙	⊙	⊙	●	◒
Aquatics: Recreation	◉	●	⊙	⊙	◒
Forests: Recreation	⊙	◉	○	⊙	◒
Agriculture & commercial forestry	◉	●	◒	◒	⊙
Radiative forcing	⊙	○	○	⊙	○

Source: Adapted from Burtraw et al. (1998).

V. Review of Benefits Transfer Studies

In 2006, a grant from the European Commission funded the external cost study, CASES, and was coordinated by Fondazione Eni Enricho Mattei (Markandya, Bigano et al. 2010). The CASES research project was conducted from 2006 to 2008 and involves results from four non-E.U. countries: China, India, Turkey, and Brazil. All four non-E.U. studies involved a benefits transfer approach, however the more detailed process of adapting the primary results for the policy site were quite distinct across studies. Work was conducted by researchers within each of the four countries and then submitted to the CASES team. For certain pollutants, however, the CASES team replaced values used by the original researchers with their own agreed upon values. For instance, in the Chinese studies the CASES team replaced the original author's values for CO_2 with a value derived from ExternE. See the appendix for annotations of these studies.

For the Chinese coal and natural gas cycles, the authors examined a typical power plant with a capacity of 100 megawatts. Only the power generation stage was examined for both fuel cycles. External costs from coal-fueled electricity generation were estimated using typical emissions rates and prescriptive environmental costs taken from Chinese Pollutant Charge Standards (PCS), with the values for PCS given in yuan per kilogram of pollutant emitted. External costs were then estimated by multiplying a pollutant's emissions rate by the values taken from PCS. In this study, the "transfer" occurred when the authors applied PCS damage estimates to the transfer site. For the coal plant, damages from SO_2 and NO_x emissions were the highest, followed by CO_2. Total damages from the coal plant were estimated to be 14.2 mills per kWh before application of the CASES value for CO_2. After applying the CASES agreed value of CO_2 ($28 per ton), the damage estimate increased to 34.5 mills per kWh, with CO_2 constituting nearly 70 percent of total damages. For the natural gas plant, total damages were estimated to be 2.5 mills per kWh, or approximately one-sixth the magnitude of the coal plant before application of the CASES value for CO_2. After applying the CASES agreed value of CO_2, the damage estimates increased to 12.6 mills per kWh, with CO_2 accounting for over 80 percent of total damages.

The Indian team examined the seven major coal fuel cycle stages: mining, coal preparation, transportation, generation, transmission, waste disposal, and plant decommissioning. However, damages arising from plant decommissioning were not quantified. To monetize the priority impact pathways, the team conducted a value transfer using U.S. market prices for SO_2 and NO_x and European carbon market prices for CO_2 and CH_4 (all units were in dollar per ton). Indian industrial prices were used for water pollution damages, and damage estimates for particulates were taken from Indian epidemiological studies. It is unclear what, if any, adjustments were made to the borrowed economic data prior to applying it to the Indian case study. Total damages for the major fuel stages of the coal cycle were estimated to be 81.3 mills per kWh.

The authors of the Turkish lignite coal fuel cycle study use a medium-sized reference plant located in Mugla Province along the southwestern corner of the country. Unlike the Chinese and Indian case studies, which did not examine plant construction and decommissioning, the Turkish team offered a nonquantitative examination of the cement and steel used in plant construction as well as the transportation of materials. And although the original report did not attempt to monetize the damages from primary pollutants, a benefits transfer using the same data was subsequently conducted by Zhu et al. (2005) using damage estimates from the ExternE chapter on Britain. Monetary damage estimates per kWh were borrowed for CO_2, PM, SO_2, and NO_x over the transport and power generation fuel stages. To adjust the value transfers to Turkish conditions, Zhu et al. used the relationship between U.K. and Turkish purchasing power parity and gross national product per capita. According to Zhu et al., the damage estimates arising from NO_x emissions from lignite transport were too inflated compared to other studies. Omitting NO_x damages gives a total external cost estimate of 45.6 mills per kWh, with the power generation stage constituting 98 percent of the total. On the other hand, if NO_x damages from the transport stage are not omitted, the total damage estimates increase to 118.9 mills per kWh, where the power generation stage constitutes only 38 percent of the total.

The Brazilian case study examined both the natural gas fuel cycle and hydro fuel cycle. For the natural gas cycle, the authors used a reference complex consisting of both a gas-fired thermodynamic cycle plant and a combined-cycle plant. To estimate mortality damages, the authors borrowed a VSL estimate from ExternE and adjusted it for Brazilian application using a scalar involving the relationship between European and Brazilian purchasing power parity, gross domestic product (GDP), life expectancy, health expenditures, and income elasticity. The study's remaining damage estimates were computed using primary data. The authors estimated health damages from wet nitrogen deposition from the thermoelectric complex to be 5.2 mills per kWh. Afterward, Zhu et al. used values (given in dollar per kWh) borrowed from ExternE to estimate the damages incurred from CO_2, nitrous oxide (N_2O), and NO_x emitted during the power generation stage of the case study's combined-cycle power plant. Zhu et al. estimated total damages from the power generation stage to be 16.3 mills per kWh.

For the Brazilian hydro fuel cycle, three case study hydro plants were examined by the authors. Public health damages from facility construction and decommissioning as well as from power generation were quantitatively examined. As in the natural gas case study, the only borrowed value used in this analysis was the VSL, and the same scalar was used to adjust the value.

Table 3 summarizes the units of the transfers made for the various studies outlined in this section. For the most part, the authors made strong assumptions on the similarities between the donor site and transfer site. The Brazilian case studies involved the least amount of transfers and the weakest set of assumptions (omitting the subsequent transfers made by Zhu et al.).

Table 3. Summary of Transfers and Donors

Study	Units of transfer	Donor
Chinese coal	\$ per ton for CO_2 and \$ per kg for the rest	ExternE and China PCS
Chinese natural gas	\$ per ton for CO_2 and \$ per kg for the rest	ExternE and China PCS
Indian coal	\$ per ton for SO_2, NO_x, and GHG	U.S. SO_2 and NO_x market and ExternE
Turkish coal	\$ per kg	British chapter of ExternE
Brazilian natural gas	VSL and \$ per ton	European VSL and ExternE
Brazilian hydro	VSL	European VSL

Table 4 summarizes the estimates for the four non-E.U. countries covered in the CASES study. Damage estimates are highest for the Indian coal fuel cycle and lowest for the Brazilian hydro cycle and Chinese natural gas cycle. In general, use of the CASES agreed values inflates the damage costs when compared to the results given by the original authors.

Table 4. Summary of Damage Estimates for non-E.U. Countries

Study and fuel	Damage estimate (mills per kWh)	Damage estimate (mills per kWh) using CASES agreed values
China coal	14.2	34.5
China natural gas	2.5	12.6
India coal	—	81.3
Turkey coal	—	45.6
Brazil natural gas	5.2	16.3
Brazil hydro	0–1.8	—

Although not focused exclusively on electricity generation, another report on China authored by Johnson et al. (1997) for the World Bank sought to estimate the economic damages stemming from air and water pollution. Damages for urban ambient air pollution and rural indoor air pollution were estimated using premature mortality data from U.S. WTP studies and human capital data (i.e., discounted lost wages) from Chinese age-specific mortality studies. The estimates from the U.S. VSL studies were scaled to use in China by multiplying the VSL by the ratio of average per capita incomes. Damages from lead pollution were estimated using U.S. data on the average benefit of reducing average blood-lead levels by 1 microgram per deciliter. To adjust for Chinese application, the damage estimates were then scaled using per capita income ratios and the comparative number of children under the age of six living in urban areas. Data for water pollution and acid rain damages were obtained from Chinese case evidence. Total damage estimates per annum resulting from air and water pollution ranged from $33 billion using a human capital approach to over $72 billion using the WTP approach.

In addition to the CASES research and these other studies, a substantial body of academic literature uses benefits transfer techniques for estimating electricity fuel cycle damages. For example, Bigano et al. (2000) use ExternE estimates in a comparative study of different hypothetical approaches to using external costs to regulate generation in the Belgian electricity sector. For emissions-related damages, the authors borrowed values for SO_2, NO_x, and PM (all in dollar per ton) from ExternE. Adaptations were then made on the basis of technological characteristics and fuel cycle. For damages that were not emissions-related, the authors borrowed values per kWh, also from ExternE. Viscusi et al. (1994) used extensive benefit transfer methods to estimate nonglobal warming externalities associated with energy use in the United States. Banzhaf, Burtraw et al. (2004) conducted detailed equilibrium modeling of the U.S. electricity sector and used an integrated assessment model to estimate localized changes in SO_2 and NO_x emissions pollution and their downwind health effects; they then calculated the efficient level of emissions fees (true costs). Muller and Mendelsohn (2009) applied similar methods with greater geographic detail but without solving an equilibrium electricity sector model.

Thanh and Lefevre (2000) estimated the potential health impacts of SO_2 and course PM (PM_{10}) emissions from four power units with multiple fuel sources (lignite, oil, natural gas, and coal) at four facilities in Thailand. Damages from ambient air pollution were estimated using the results of an epidemiological study in Bangkok City (Thailand) examining four health effect endpoints: premature mortality, respiratory and cardiac hospital admissions, and days with acute respiratory symptoms. Monetary valuations were conducted by transferring values from a U.S. WTP study, with the human capital data collected from the Bangkok City study. The U.S. valuation data were scaled for use in Thailand by using a transferring ratio of average per capita income ($PC\text{-}GNP_{Thailand}/PC\text{-}GNP_{United\ States}$) as a way to correct for income differences between the nations. Total damage estimates annually were $2.4 million (US$), or between $0.006 and $0.05 (US$) per kWh (1995$).

Finally, on a larger scale of benefits transfer, Rafaj and Kypreos (2007) use a model of the global energy system to examine the impacts of internalizing the external costs of power generation. The authors borrowed values for the costs of pollutants per kWh from ExternE and then scaled the values to five global regions. Two regions included the developed Organisation for Economic Co-operation and Development (OECD) nations; one region included the transition economies of eastern and central Europe and the former Soviet Union; and two regions included the developing countries of Asia, Latin America, Africa, and the Middle East. Scaling was determined by a region's population density, sulfur content in coal and oil fuels, emissions control systems, and potential future conversion efficiency improvements. Population densities were grouped into medium and high classifications, though changes in populations over time were not featured.

In a similar way, Klaassen and Riahi (2007) examined the global impacts of a policy where all environmental damages from power generation are internalized. Again, values for NO_x, SO_2, and PM were borrowed from ExternE (on the basis of dollar per kWh) and then adjusted according to population density, fuel, technology, and abatement efficiency.

VI. Critical Review of Methods for Benefits Transfers

Benefits transfers can never be as accurate as primary studies. But, by using the results of primary studies and the framework models that embody their work (such as RAINS, TAF, BENMAP, and EcoSense) as a foundation, a benefits transfer can take advantage of all the expertise in epidemiology, air quality modeling, and economics that is embedded in such studies and models. Furthermore, a benefits transfer provides faster and less costly analyses. But as we have seen from the above review, there are credible and less credible ways to do a benefits transfer, and all benefits transfer techniques are not equally accurate; indeed, one technique is unlikely to dominate all others all of the time. Below, we review the literature on the performance of benefits transfer techniques.

A. Strengths and Weaknesses

Unit value transfer (or direct benefit transfer), which is considered the easiest approach to benefits transfer, involves the transfer of the mean unit value(s) from the donor site to the transfer site. This approach works best when the projected impacts can be measured in homogeneous divisible units (i.e., health impacts) and where the site context is comparable between the locations.

Although this approach has often been used in social costing analyses, the unit value transfer approach lacks the flexibility to adjust for differing site conditions. Often, the transfer and donor sites might differ in terms of income, education, and demographic composition, which may be affecting true costs at the transfer site, but which a unit value approach will ignore.

Value function transfer (VFT; or benefit function transfer) is perhaps the most commonly used benefits transfer method. In contrast to other methods, VFT involves using an estimated relationship between social cost (or damage) and basic attributes of the donor site. The same attributes from the transfer site are then plugged into the function to estimate the social cost (or damage) at the transfer site. Generally, this method is advantageous simply because it allows for more information to be effectively transferred between sites (Navrud 2000) and allows for further "fine tuning" of site characteristics to improve accuracy. VFT also improves the performance of benefits transfer in situations where substantial contextual differences between donor and transfer sites occur.

According to Navrud (2000), the major downside to VFT is that the list of variables used in the function may not match well with the differences between the donor and transfer sites. However, this problem can be mitigated by selecting donor sites with (i) sufficient variation in attributes and user populations, (ii) conditions that are comparable to those of the transfer site, and (iii) similar preferences for the targeted good at the transfer site (Ready and Navrud 2005).

B. Transfer Performance

Despite the prevalence of detailed guidelines for performing primary valuation studies, currently no guide for benefit transfer is universally accepted (Johnston and Rosenberger 2010). The most widely accepted performance metric within the benefits transfer literature is known as transfer error. Transfer error is defined as the difference between the transferred value estimate and the true (often unknown) value estimate at the transfer site. Several studies have assessed the validity of benefit transfer. This typically involves comparing value estimates between two sites—both of which have primary study results—and estimating the size of the transfer error from a hypothetical benefits transfer. The error is estimated by calculating the percentage difference between the values transferred from the designated donor site and the value projected at the designated transfer site. Although the literature describes other types of validity tests, recent studies suggest that the size of the projected transfer error is the preferred metric (Ready and Navrud 2005; Johnston and Rosenberger 2010).

According to Ready and Navrud (2005), studies evaluating the accuracy of benefit transfer find, on average, errors between 40 and 50 percent, but errors can range anywhere between a few percentage points and several hundred percentage points. When comparing the performance between transfer methods, the general consensus in the benefits transfer literature is that function transfer methods usually outperform unit value transfer methods, with the literature on the VSL being the only major exception (Muthke and Holm-Mueller 2004; Johnston and Rosenberger 2010).

However, although the performance of benefit transfer remains consistent, some important caveats and exceptions remain. For example, Brouwer and Bateman (2005) compared the performance difference between unit value and function transfers of the WTP estimates and socioeconomic functions for reducing health risks associated with solar ultraviolet exposure. The study included survey respondents from four countries (New Zealand, Scotland, England, and Portugal) with a mix of similar and dissimilar sample populations. Respondents were asked their WTP for a new product (a bottle of sunscreen) that would provide complete protection from the negative effects of the sun. Based on their analysis, the authors projected an average error of 40 percent for unit value and 19 percent for function transfer methods (Brouwer and Bateman 2005). More generally, some studies have begun to point out that unit value methods can outperform function transfer methods when contextual factors between sites are very similar (Muthke and Holm-Mueller 2005; Brouwer and Bateman 2005). Said another way, the general consensus of the literature indicates an inverse relationship between site similarity and transfer performance (Rosenberger and Stanley 2006). However, VandenBerg et al. (2001) and Piper and Martin (2001) find that targeting communities with shared experiences of environmental impacts (i.e., groundwater contamination or air pollution) could yield better performance than transfers across political boundaries. Of course, the analyst charged with doing a benefit transfer may not have the luxury of finding a donor site that appropriately matches conditions in his own country.

Overall, the empirical evidence has failed to unequivocally determine the superiority of any specific type of benefits transfer (Johnston and Rosenberger 2010). However, Rosenberger and Loomis (2001) have outlined a series of factors that could affect transfer reliability in general.

i. The quality of the primary study can substantially affect the performance of the benefits transfer.

ii. Most primary studies are not designed for use in a benefit transfer

iii. Analysts should be aware of the types of values measured in the primary study (i.e., use vs. nonuse values).

iv. Adjustments for the spatial and temporal context of the primary study should be considered.

v. Differences between the characteristics of the donor and transfer sites can greatly affect performance.

VII. Meta-Studies

The variety with which an external cost study can be conceptualized and conducted is shown in Sundqvist (2002) and Soderholm and Sundqvist (2003). Both studies critically reviewed the conceptual limitations to externality valuation techniques while also aggregating estimates of 63 prior electricity-related external cost studies conducted during the 1980s and 1990s. External cost estimates were found to differ substantially on the basis of issues we introduce above, including fuels, technologies, site characteristics, parameter assumptions, preexisting policies, and scope. That is to say, the spatial, temporal, and demographic dimensions of a study region are just as germane to the external cost estimate as the fuel source and power plant characteristics.

At the fuel-specific level, Sundqvist and Soderholm (2002) found that external cost estimates vary by as much as four orders of magnitude in the literature. When the low estimate of external cost is near zero, the percentage difference in estimates can be very large. For example, the low and high estimates for the external cost of coal-fired electricity generation differ by nearly 1.7 million percent (Table 5). Similarly, nuclear-powered electricity estimates differ by more than 21 million percent. These widespread differences serve as an indication of the sensitivity that such cost estimates have to the multidimensional components of the external damages arising from electricity generation.

Table 5. Summary of 63 External Cost Estimates from the Literature (Cents per kWh)

	Coal	Oil	Nat. Gas	Nuclear	Hydro	Wind	Solar	Biomass
N	36	20	31	21	16	18	11	22
Min	0.01	0.04	<0.01	<0.01	0	0	0.00	0
Max	90.61	53.43	17.69	86.23	35.14	1.18	2.94	29.56
Mean	18.75	16.48	6.17	9.53	4.50	0.41	1.12	6.62
Median	8.54	12.19	3.51	1.08	0.43	0.43	1.02	3.59

Source: Sundqvist and Soderholm (2002).

In a more subtle way, estimates were found to vary significantly according to the damage assessment approach used (e.g., damage function versus abatement cost). All other things being equal, Sundqvist and Soderholm (2002) found that external cost estimates are, on average, higher when an abatement cost approach is used. A possible explanation for the relatively higher estimates generated from the abatement cost approach is the use of existing regulations rather than least-cost regulations in the formulation of the costs of abatement. Another is the inherently incomplete basis of damage function estimates, a factor that could be anticipated by policymakers in setting the level of regulations. Another could be risk aversion expressed in public policy (e.g., the precautionary principle), although damage function methodology generally embodies risk neutrality using expected values for relationships along the damage function pathways. Again, these differences in cost estimates reinforce the importance of properly framing the conceptual backdrop when conducting an external cost study.

Looking forward, a number of conceptual weaknesses were identified in the existing literature. Although conventional fuel cycles have been researched at length, the external costs of renewable fuels like solar have received relatively little attention. In fact, in their meta-study, Soderholm and Sundqvist (2003) identified 45 studies addressing externalities from the coal fuel cycle but identified only 10 and 15 for solar and hydro, respectively. Moreover, few studies have attempted to estimate the external costs of electricity in developing countries. This is an important gap in the literature as distinctions in income, population density, and environmental impacts can yield estimates that are dissimilar to those of a developed country.

VIII. Perspectives of Investors and Policymakers and Methods for Including True Costs in Decisionmaking

Decisionmakers within industry and government will have different perspectives that point to different methods for making use of information about the true costs of energy. These perspectives include what types of activities or damages are included and the spatial and temporal limits of those damages.

A. Perspectives

The perspectives of decisionmakers in private industry could be organized into at least three groups. One is the institutional investor who is interested in project-level financing. When construction is complete, ownership or operation will transfer to another party through direct sale or through a power purchase agreement. Among private sector parties, investors in development projects may have a relatively narrow perspective with respect to true costs because their involvement is limited to a specific facility for a specific period of time. Of course, a firm specializing in construction has an indirect interest in environmental and regulatory issues over the lifetime of the facility because performance during its operational lifetime ultimately affects the demand for and profitability of construction activities.

In contrast, private sector decisionmakers in generation companies have a specialized interest in and knowledge of the operation of power plants. Hence, these investors seemingly have a broader view because they have a direct interest in issues such as the occupational health and safety of their workers, the reliability of the fuel supply, and safety and environmental performance of the ongoing operation of a facility.

A third type of private decisionmaker is the integrated firm that provides retail electricity services. The integrated firm may directly own generation facilities and may buy or sell power. Like a generation company, the integrated firm is interested in how the performance of a facility affects its workers and its environmental performance. Moreover, it is likely to have a stronger interest in how environmental performance affects the surrounding community. This is partly because its employees live in the community and partly because of its relationship with its retail customers who experience environmental outcomes directly and hold preferences for environmental quality. Consumers may express these preferences in their consumption behavior or through the political process. The integrated firm has a temporal perspective associated with its longest-lived assets, which may extend beyond the horizon of an individual project. Moreover, the integrated firm fulfills the private sector role of system planner because of its direct interest in how individual facilities are integrated within a system.

Policymakers in government provide a fourth perspective. In principle, their perspective is likely to be relatively expansive, reflecting concern for their entire jurisdiction; but if the jurisdiction is local, their perspective is unlikely to be global or even regional. Even the perspective of federal policymakers may fall short of the focus of social cost analyses, which can capture impacts wherever they occur, even across national borders.

The discount rates of these decisionmakers and policymakers may also vary because of their different perspectives and their exposure to the risk of changes in information about environmental outcomes over differing time horizons, and possible subsequent changes in policy. Government policymakers would be expected to make decisions with a social discount rate, which is generally less than the private discount rate.

B. Methods of Including True Costs in Decisionmaking

Decisionmakers may choose to use information about the true cost of energy in a variety of ways. Economic theory would suggest that this information be included directly into prices, in the form of emissions fees and other charges that reflect social costs.[10] In practice, the information is more likely to find its way into decisionmaking in other ways. As noted in the introduction, true costs could affect regulations in two ways. One is in planning and permitting for new investments, and the second is through the operation of existing facilities.

In the planning and permitting process, typically a certificate of need or some other authorization is required for energy investments to enable construction to begin. If the government's permitting process requires the consideration of full social costs, investors would have to explicitly demonstrate that an investment option is least-cost when taking true costs into account. The process can lead to different investment outcomes than would occur if only private costs were taken into account. However, the limitation of this approach is that it does not restrict how a facility is operated after it is built.

[10] Advances in public finance indicate that this may not always be efficiency enhancing because the introduction of a new fee (or regulation) interacts with existing policies. For example, an emissions fee can exacerbate the inefficiency associated with existing taxes on capital or labor income. The net effect depends in part on how the funds raised by the emissions fee are used. The advice from public finance is that revenue under an emissions fee should be used to reduce other preexisting taxes. This type of policy is explicit in British Columbia, for example, where revenue from a carbon tax is used to reduce labor income taxes. But in general it may not be possible to explicitly indicate how revenues from a policy will be used. For the purpose of this discussion, we put aside this issue and focus on a reflection of true costs into the prices of energy; in this context, an emissions fee may be thought of as the best policy.

A more influential result is obtained if true costs are considered, not only in the investment planning process, but also in the operation of facilities to ensure the minimization of true cost in the operation of the system. In this case, the integrated energy company serving retail customers (or possibly a government or private system operator) would be centrally involved. This approach would affect investment as well as operation of the system, because investments will be evaluated by taking into account their operation over the long run.

IX. Getting Started

This paper illustrates that an analysis of the true costs of electricity can be conducted at various levels of detail and rigor. In some settings or countries, it may not be possible to do full-scale original (primary) analysis. This should not be a barrier to getting started. In situations where extensive resources and expertise are not available, benefit transfer methods offer a high value for the cost of the analysis. In general, the value of incremental information from a partial analysis will improve decisionmaking and will help identify priorities for further research.

One guideline is useful in all cases. Analysts should employ a consistent accounting framework so that various types of damages from the different technologies that are investigated can be compared on a like basis. This will ensure, for example, that consistent assumptions about population demographics, exposure to pollution, and discount rates are used. The primary studies provide an excellent template for accounting frameworks that can be easily replicated or used directly, thereby preserving information for benefit transfer where useful and swapping out other information, such as atmospheric transport, as appropriate.

The way forward will differ in various jurisdictions depending on the resources available for the study, institutional capacity, and so on. In Table 6, we illustrate two situations, which we label Country A and Country B. In Country A, we assume that a high level of expertise is available as well as an interest in putting all generation options, including renewable energy and energy efficiency investments, onto a level playing field. We describe the purpose of a study in Country A to support a full evaluation of alternative investments, accounting for full social cost (true cost). We then describe the attributes of the type of study we might recommend for Country A and many of the initial choices that would be encountered in launching the effort.

In the case of Country B, we assume that a low level of expertise is available, but that the country has access to expertise. Given a lower level of available resources, Country B might not consider all generation options, for example nuclear may not be an option, and it would want to concentrate on near-term investment options. Nonetheless, these options should include, not only fossil fuel choices, but also renewables and investments in energy efficiency. We describe the purpose of a study in Country B to expedite infrastructure development and achieve sustainable development goals, accounting for social costs.

To illustrate the difference between the choices that might be made in these two settings, consider the type of screening analysis one might pursue. Country A may want to do a complete screening of every plausible external cost. Country B may want to limit its screening to focus directly on consideration of a small number of high-profile issues and those for which data are available. It might want to emphasize priority pollutants such as $PM_{2.5}$ and GHGs. But it would not want to entirely omit potentially important damage pathways for which data are poor. A qualitative representation of those pathways would be constructive and could set the groundwork for ongoing research.

Table 6. Initial Considerations in Designing a Study of True Costs at the Country Level

	Country A	Country B
Assumptions		
Resources available	High	Low
Generation comparisons	All	Not nuclear
Institutional capacity	High	Low
Expertise	High	Low (but have access)
Purpose of study	To support full evaluation of alternative investments, accounting for full social costs (*true costs*).	To expedite infrastructure development and achieve sustainable development goals, accounting for social costs.
Attributes of Study		
Study type	Primary	Benefit transfer
Screening analysis	Complete. Study should be clear about what is excluded.	Partial. Identify areas that must be included.
Modeling framework	Use country-specific framework, if available. If not, obtain BENMAP (USEPA), RAINS (IIASA), or EXTERNE (E.U.) because these models incorporate atmospheric transport.	Obtain TAF (RFF), BENMAP (USEPA), RAINS (IIASA), or EXTERNE/EcoSense (E.U.).These models would be used as an accounting platform and provide substantial basis for benefits transfer. In some cases, representation of atmospheric transport would require additional effort (see below for pollution distribution and transformation).
Use of modeling framework	Generate complete analysis.	Educate decisionmakers, identify important information gaps for analysts.
Location choice	Multiple, real candidate sites	Single, representative site
Energy life cycle	Yes. As far upstream as possible, subject to screening analysis and VOI analysis.	Partial. Limit to generation and indigenous resource extractions.
Pollutants	All	Priority pollutants from screening, e.g., $PM_{2.5}$ and GHGs.
Emissions factors	Specific technologies and facility characteristics	Representative technologies for each generation type
Pollution distribution and transformation	Best available models	Borrow from other studies or assume generic distance decay function for each pollutant estimated from other studies.
Unit Impacts	Use modeling framework default or use country-specific studies.	Implicitly use impact relationships in donor study.
Population	Actual/projected	Actual/projected; use to adjust benefit transfer estimates.

Population parameters (e.g., death rates)	Actual/projected	Actual/projected; use to adjust benefit transfer estimates.
Valuation of in-country effects	Use modeling framework default or use country-specific studies.	Use value relationships in donor study; possibly scale for elasticity of WTP of income.
Valuation of climate effects	Use nationally identified value.	Use nationally identified value or borrow value from donor study. Possibly scale for elasticity of WTP of income.
Treatment of uncertainty	Full, including Monte Carlo and expert elicitation methods. Use uncertainty to advance understanding of policymakers.	Best estimates and scenario analysis; expert elicitation methods
Mapping damages to externalities	Full except in labor markets and where there is liability	Full unless labor markets are competitive

We also note that Country A might examine multiple real-world geographic locations, with specific technology characteristics such as stack heights and boiler design. Country B might focus on a single, representative site and representative generation technologies. Country A might use the best available models of pollution distribution and transformation and apply them to each specific location, whereas Country B might borrow from other studies or assume generic decay rates for the effects of pollution over distance and time. Moreover, Country A may have original valuation studies to apply in estimating the monetary damages from pollution. Country B may borrow value relationships from another study, and it may want to scale those values according to the sensitivity of its population's preferences for avoiding various types of damages to income levels—what economists call the "elasticity of WTP with income." Making such adjustments is relatively uncontroversial when the object of the decision is self-contained in a particular country (as opposed to leading to comparisons across countries). More controversial is our call for Country B to adjust a "social cost per ton of carbon" estimate from Country A for its lower income level.

This study provides the background for stakeholders and analysts to begin a process. The ultimate results of an analysis should prove extremely valuable to sustainable energy development. However, the process of the analysis and stakeholder discussion can be just as important as the final results in providing guidance to decisionmakers. These methods, and the consideration of true costs, should be a component of decisionmaking for all energy investment worldwide.

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Appendix. Annotated Bibliography

(Bhattacharyya 1997)

Bhattacharyya used a source–receptor and control cost model to examine the external costs of a hypothetical 210-megawatt coal-fired plant in India. Damage functions for the effects of PM, NO_X, and SO_2 on human health and the effects of PM on rental prices were borrowed from literature. Values for the cost of life and cost of illness were also borrowed from the literature. The external costs were estimated to be $0.02 per kWh.

(Biegler 2009)

For the study's empirical examination, Biegler employed a benefits transfer to estimate the external costs of coal and natural gas power plants in Australia. To estimate damages from CO_2, the author borrows the central value of €19 per ton CO_2 from ExternE. No adjustments were made prior to applying the borrowed value to local conditions, other than converting euros to Australian dollars. For coal fuels, the external cost estimates due to CO_2 ranged from a low of $3 per MWh for a typical ultra-supercritical integrated gasification combined-cycle plant with carbon capture and storage to a high of $37 per MWh for a typical subcritical pulverized coal plant. For natural gas fuels, the external cost estimates of CO_2 ranged from $17 per MWh for a combined-cycle plant to $22 per MWh for an open-cycle plant.

To estimate health damages, Biegler examined emissions of PM_{10}, SO_2, and NO_X. Again, the damage estimates for PM_{10}, SO_2, and NO_X were borrowed from ExternE on the basis of dollars per kilogram emitted. These damages were adjusted for local application using population densities. Total health-related damage costs were estimated to range from $1.5 per MWh to $50 per MWh for a typical coal plant and $0.7 per MWh for a typical natural gas plant.

(Bigano, Proost, et al. 2000)

The authors compared four ways of using external cost estimates to regulate generation in the electricity sector using a dynamic partial equilibrium model. Two alternatives set the emissions tax equal to the marginal cost of externality estimates. These two alternatives differ in that, in the first scenario, the utility and independent producers are taxed, but in the second, taxes are restricted to the utility only. The third alternative restricts emissions permits to the optimal level derived by the emissions tax framework. In the fourth alternative, investment decisions are regulated in function to their external costs (*adder system*). External damages in terms of dollars per ton of emissions were borrowed from the ExternE core estimates. Adjustments for transfer site application were made using technological and fuel cycle characteristics. Total emissions damages were shown to be 45 percent higher under the restricted tax scenario than the unrestricted tax scenario, as a result of higher damages caused by independent producers. Under the adder system, emissions damages are shown to have the least reduction and the worst social welfare results.

(Klaassen and Riahi 2007)

Klaassen and Riahi examined the impacts of a policy under which all environmental damages of electricity generation are internalized. The data sets and model frameworks used in the paper are taken from Scenario Generator (SG), MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact, a bottom-up systems engineering model), MACRO (a top-down macroeconomic model), and the technology database CO2DB among others. SG is a simulation model that uses base year (1990 and 2000) and prior year time series economic and energy data. Inputs to SG are population trajectories for 11 world regions and parameters determining regional GDP growth per capita. Final energy demands are then disaggregated into six demand sectors: industrial specific, industrial nonspecific, residential/commercial specific, residential/commercial nonspecific, transportation, and noncommercial.

The assumptions and parameters used in the authors' baseline scenario are taken from the B2 marker scenario developed by the Intergovernmental Panel on Climate Change. External damages in terms of dollars per kWh are borrowed from ExternE and scaled according to population density (i.e., for medium population density, average damages per ton were used).

Compared to the baseline case, the initial costs of internalizing the externalities are 1.8 cents per kWh (or 30 percent higher). By 2050, the costs of internalizing the externalities were estimated to decrease to 0.2 cents per kWh above the baseline (or 3 percent higher).

(Krewitt and Heck 1999)

Krewitt and Heck used a bottom-up method to determine average external costs from fossil electricity generation in Germany and Europe. For human health, the authors borrowed the VSL from ExternE and from there calculated a value of life year lost as a function of discount rate (e.g., $127,000 for a 0 percent rate and $111,000 for a 3 percent rate). For agricultural damages, an exposure–response function is borrowed from ExternE. For the effects of SO_2 and wet deposition on building materials, a dose–response function is borrowed from the U.N. Economic Council for Europe. Climate change damages were borrowed from ExternE on the basis of dollars per ton CO_2. For modeling, the authors pair ExternE's EcoSense model with the Core Inventory Air Emissions (CORINAIR) database on wide-range pollutants.

Average damage costs from fossil-fired power plants were estimated to range from 1.3 cents per kWh to 11 cents per kWh for Germany and 9 cents per kWh for the 15 member countries of the European Union.

(Maddox, Scaife, et al. 2004)

Maddox et al. conducted a life cycle analysis for all coal-fired generators in New South Wales (NSW), Australia, to determine total emissions of PM_{10}, SO_2, NO_X, and CO_2. Damage estimates were borrowed from ExternE results on the basis of dollars per kilogram emitted. A scaling factor for transferring ExternE results to NSW conditions was calculated using the relative population densities within 1,000 kilometers of the generators included in the ExternE and NSW studies. Total external damage costs for the NSW grid were estimated to be 40 dollars per MWh.

(Pearce 1995)

Pearce looked at the likely size of the environmental externalities in the United Kingdom from electricity generation. He examined the damage costs associated with SO_2, NO_X, particulates, CO_2, disasters, and routine radiation for the coal, natural gas, and nuclear fuel cycles using values borrowed from the literature.

(Rafaj and Kypreos 2007)

The authors used a Global MARKAL-Model to examine the impacts of internalizing the external costs of electricity production. Countries were aggregated into five regions: two regions representing the OECD countries, one region representing the transitioning countries, and two regions representing the developing countries. Their external cost specifications in dollars per kWh were borrowed from ExternE outcomes and adjusted according to regional average population density, sulfur content in coal and oil fuels, emissions control systems, and potential future conversion efficiency improvements. The authors assumed that the sulfur content of coal is 1 percent across the five global regions under consideration. Results showed that inclusion of global external costs into electricity pricing could reduce SO_2 and NO_X emissions by 70–85 percent and carbon emissions by two gigatons by 2035 relative to the baseline. Total energy system costs were expected to increase by 9.6–13 percent relative to the baseline scenario.

(Roth and Ambs 2004)

Roth and Ambs sought out to develop a levelized cost of electricity for 14 different generation technologies at a hypothetical plant in the northeast United States. Their full cost approach encompassed all stages of the fuel cycles. Externalities covered in the analysis included air pollution damages, energy security, transmission and distribution costs, and other environmental impacts. For air pollutant externalities, the authors used emissions factor values obtained from US EPA data along with a range of abatement costs, in dollars per ton emitted, borrowed from literature. No adjustments were made to the borrowed abatement costs prior to transfer. For the other environmental externalities (e.g., land use change and groundwater contamination), the authors borrowed external cost estimates, in cents per kWh, from the literature. Damages from nonenvironmental externalities, in terms of cents per kWh, were also borrowed from the literature.

Coal and oil boiler technologies were estimated to have the highest external costs at 13 cents per kWh and 15 cents per kWh, respectively. Photovoltaics, biomass, and landfill recovery gas were estimated to have the lowest external costs, ranging from 1 to 3 cents per kWh. The generation technology with the lowest estimated levelized cost was landfill recovery gas (7.3 cents per kWh), whereas photovoltaic solar was estimated to have the highest levelized cost (59.5 cents per kWh).

(Soderholm and Sundqvist 2003)

The authors reviewed a number of electricity externality studies in the interest of ascertaining explanatory factors for large observed disparities in external cost estimates. They cite a prior study (Sundqvist 2002) of 132 external cost estimates that found assessment methods (e.g., abatement cost versus damage function) to be a statistically significant cause of disparities between damage estimates. Coal-fired electricity external costs were found to vary by more than two orders of magnitude in the literature. Oil- and natural gas–fueled electricity have similarly large ranges.

(Spalding-Fecher and Matibe 2003)

Spalding-Fecher and Matibe expanded on previous work to examine the external costs of electricity generation in South Africa. External damage estimates for climate change are borrowed from literature on the basis of dollars per ton of carbon emitted. Air pollution damages, in cents per kWh were borrowed from a prior study conducted by the South African utility Eskom. The borrowed air pollution damages were adjusted according to population growth, changes in emissions, and inflation. However, the external costs associated with the underpricing of water resources to power stations were not monetized. Total external costs for coal-fired power, including the benefits from electrification, were estimated to range from 0.1 cents per kWh to 0.2 cents per kWh.

(Sundqvist 2004)

Sundqvist provided an econometric meta-analysis of the disparity among 63 electricity externality studies. Using analysis of variance (ANOVA), Sundqvist examined the effects of (i) methodological approach, (ii) fuel type, (iii) fuel stages, (iv) income, and (v) population density on the total external cost estimate produced by individual studies. The dependent variable was categorized by comparing the individual cost estimates to the mean cost of new capacity (3.97 cents per kWh) provided by the International Energy Agency. Methodological approach was categorized as top-down, bottom-up, or abatement cost. Fuel stages captured whether the full fuel cycle other than generation was addressed. Income was measured by GDP per capita. Population density was measured by people per square kilometer.

Top-down and abatement cost methods were found to give higher external cost estimates than a bottom-up approach. Studies that examined the entire fuel cycle were also more likely to give a high damage estimate than studies that examined only a portion of the fuel cycle. Other variables, like income of the exposed population and population density, were shown to be not statistically significant at the 5 percent confidence level.

(Sundqvist and Soderholm 2002)

The authors outlined conceptual issues of importance in estimating external costs.

- The existing literature focuses on traditional fuels like coal, oil, gas, and nuclear. Few studies attempt to estimate the externalities of future/renewable technologies.
- Screening environmental impacts may lead to externality estimates that have a substantial downward bias. Complications arising from choosing which parts of the fuel cycle to include, and this is exacerbated by site-specific dependencies.
- Within studies of the same fuels, there are differences in impacts and fuel cycle stages covered and in the methods.
- The methodological differences among studies matter. For example, higher estimates emerge more often when using abatement cost approaches than damage function. Damage cost approaches have largely dominated the external cost literature since the mid-1990s. As another example, VSL gave estimates that are twice as great as the value of life years lost in ExternE.
- Few studies have attempted to estimate the external costs of electricity in developing countries. Differences in income and environmental impacts may yield estimates that are dissimilar to those from a developed country. Such distinctions raise problems for studies attempting to perform a transfer. For example, ExternE uses $2.6 million as a VSL for the European Union whereas Spalding-Fecher and Matibe (2003) use $2.9–5.6 million for South Africa.

  Consequently, external cost estimates vary widely across studies (see Soderholm and Sundqvist 2003), as illustrated in the table below.

Cents/kWh	Coal	Oil	Gas	Nuclear	Hydro	Wind	Solar	Biomass
N	36	20	31	21	16	18	11	22
Min	0.004	0.03	0.003	0.0003	0	0	0	0
Max	67.72	39.93	13.22	64.45	26.26	0.88	2.20	22.09
Difference	16930%	1331%	441%	214833%				

(Tolmasquim 2001)

The authors made a conceptual argument for the inclusion of external environmental damages caused by power generation in the Brazilian Power Sector long-term plan. They also proposed techniques for the valuation of said degradation costs. However, no empirical data were provided, and no formal analysis of external damage data was described in the paper.