‘Truer Costs’ in Energy Systems Change[1]

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Abstract

Costs are fundamental to decision-making about energy systems and associated change. However, there is no universal approach to the way in which such costs are scoped and analyzed. The idea of ‘truer costs’ is explored, here, by reviewing ways to characterize value in energy pathways. In doing so, the article aims to highlight how analytical choices on methods and less obvious dimensions can be significant. Potential directions for practical and theoretical development are also considered.

Key words: energy transitions, system change, cost, value, planning and decision-making

INTRODUCTION

Energy transitions figure prominently in today’s public agendas, particularly shifts which center on security, stewardship, access, or technology leadership.[3] Defined as a systemic change in an energy path, these transitions broadly include shifts in the type, quality or quantity of energy that is sourced, delivered or utilized. Whether one aims to understand the subject from the standpoint of historical lessons or to evaluate strategies for future pathways, the focus eventually turns to costs. A review of scholarly publications on costs and energy transitions reveals a striking increase in coverage over the course of the last decade (Exhibit 1). This can have significance, as public priorities may be settled on the basis of costs.

1 Article abbreviations: CO_2/carbon dioxide; COP21/Conference of Parties 21; DALY/disability adjusted life year; EIA/Energy Information Administration; EPRI/Electric Power and Research Institute; GDP/gross domestic product; GEA/ Global Energy Assessment; International Energy Agency/IEA; IMF/International Monetary Fund; kWh/kilowatt hour; NRC/ National Research Council; Organization for Economic Cooperation and Development; ppp/Purchasing Power Parity; REN21/Renewable Energy Network 21st Century; TFC/Total final energy consumption; TPES/ Total primary energy supply; UNEP/United Nation Environment Programme; USAID/United States Agency for International Development; World Development Indicators/WDI.

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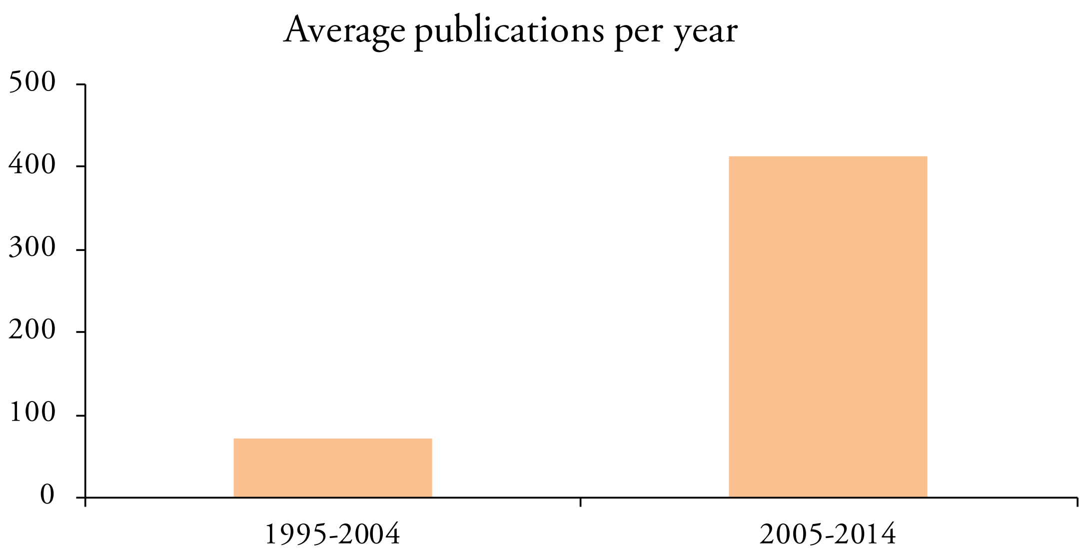
3 See writing such as WEC (2015); REN21 (2015); IEA (undated). ‘Energy transition’ and ‘energy system change’ are used interchangeably in this article.

Exhibit 1

Scholarly Writing on Cost and Energy System Change



Source: Scopus, as of November 22, 2015. Total = 9,228 publications. Search dimensions include energy transition or energy system change and cost in titles, abstracts and keywords.

A closer look at current writing on energy systems and transition costs reveals a number of overarching insights. First, there is no agreement on methods to assess costs of energy systems (IEA, 2015d; EIA, 2015; Wuppertal Institute, 2014). Differences exist in the scoping, definitions and assumptions. Moreover, assessments may focus strictly on visible costs, or incorporate underlying and external costs (Hohmeyer, 1992; National Research Council, 2010). Analysis can be very simple, back-of-the-envelope calculations or use complex models. Calculations can also entail stepwise, bottom-up evaluations or cascade down from aggregated numbers. With this range of options, it should be no surprise that considerable differences can exist in what constitutes 'true costs' of energy (Butraw *et al.,* 2012; Greenstone and Looney; 2012; Plumer, 2012; Yonk, 2015). In line with this, assessments of energy transitions by extension can also differ quite substantially in calculated costs, especially when not all value can or is monetized.

Considering the objectives of the special issue and related research of this author (Araújo, 2014; Araújo, 2015), the current article aims to highlight analytical choices tied to costs in energy systems and their transitions. In line with this objective, the article outlines key concepts, methods, and complexities that often are encountered when valuing costs of energy systems change. It begins by reviewing indicators of global energy system change. Next, the article turns to common approaches to cost analysis of energy systems. An examination of less visible costs and other distortions follows which practitioners should consider in energy cost assessments of system change. Examples are next discussed to highlight analytical nuances that influence energy cost characterizations. The article closes by highlighting some key take-aways for thinking about cost analysis of energy systems change, and further research.

GLOBAL CHANGE INDICATORS

Trends in consumption, emissions, demographics, and economics are often preliminary points of departure for more extended analysis of energy systems and their costs (Exhibit 2).

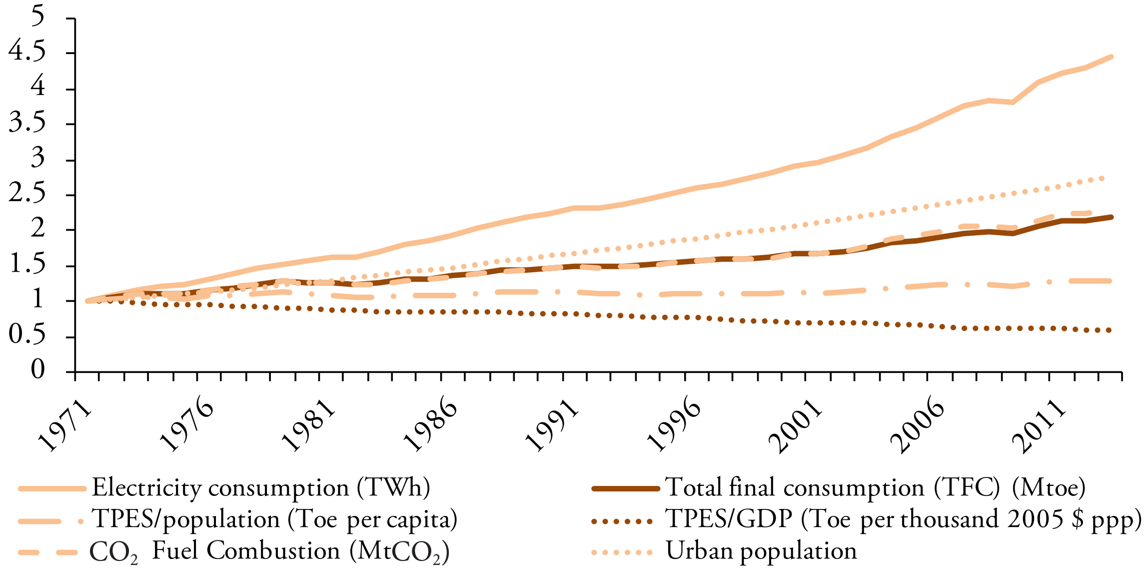
Total final energy consumption, for instance, is one area where system change and cost consequences are closely intertwined. Globally, total final energy consumption (TFC) – equivalent to the sum of consumption in end-use sectors – has more than doubled since the early 1970s, as electricity consumption grew by more than a factor of four.[4] The divergence points to faster growth in the power sector relative to areas, like transport, or heating and cooling. When thinking in energy system change terms, high growth potential presents opportunities for altering practices that include efficiencies or savings with new investment. Along such lines, analyses might focus on reductions in energy and related costs through technology learning, conservation, and economies of scale, among possibilities (Grubler, A. and Wilson, C., 2013; Allcott and Rogers, 2014; Allcott, 2011).

4 Total final energy consumption excludes energy utilized for transformation processes, from 'own use' in the energy producing industries, and backflows from the petrochemical industry. World aviation bunkers and world marine bunkers in transport are included (IEA, 2015b).

Exhibit 2

Global Change in Key Indicators, 1971-2013

(Base year: 1971)



Source: Data on urban population, WDI, 2015; all other data, IEA, 2015a.

If one compares the trend line in Figure 2 for TFC with that for CO_2 emissions from fossil fuel combustion, a close association is evident. This can largely be explained by a preponderance of fossil fuels in the energy mix which produces the CO_2 emissions.[5] Careful inspection indicates a decoupling of the trends after 2004 which can be attributed to a rising share of renewable energy, nuclear energy, and less carbon-intensive natural gas in the energy mix.[6] For those evaluating cost considerations in relation to these patterns, targeted policies *(i.e.* carbon markets or caps), changing preferences, and new infrastructure are areas to examine more fully.

Turning to total primary energy as it relates to the population and economy, a clear divergence can be seen. Total primary energy per capita increased by a factor

5 It is more readily evident in total primary energy (TPES) – raw or untransformed energy – where fossil fuels reflected 86% of the mix in 1971 and 81% in 2013 (IEA, 2015a).

6 In TPES, the breakdown between fossil fuel and non-fossil fuels for 1971 and 2013 reflected 86%:14%, and 81%:19%, respectively (IEA, 2015a). The share of natural gas in the overall mix also rose from 16% to 21% *(Ibid.)*

of 0.3, whereas total primary energy per unit of gross domestic product (GDP) in purchasing power parity terms (ppp) declined by roughly twice the former. This indicates that, on average, individuals are supplied with more primary energy, whereas, each unit of GDP is produced with less primary energy for the period.

In conjunction with the above developments, the world's urban population more than doubled in size between 1971 and 2013 (IEA, 2015a), as the share of people living in urban settings rose from 37% in 1971 to 53% in 2014 (WDI, 2015). Considered in energy cost and transition terms, such trends reflect potential for altering delivery in relation to efficiency, waste and security, among possibilities.[7]

METHODS AND VALUE – MORE THAN MEETS THE EYE

Methods

When evaluating energy systems, a number of primary methods are used to compare fuel choices. These include levelized cost, replacement value and levelized avoided cost, as well as marginal cost. Each method can be used for forward or backward-looking analysis. However, selections, such as the replacement value, are more likely to be used for long-term studies, given the ease of analysis with data that is often difficult to access or estimate.

Levelized cost analysis

The levelized cost of electricity (LCOE) method centers on the cost to build and operate a power-generating plant over its assumed financial life and performance cycle. It is viewed by some as the break-even cost needed for electricity generation from a given project. Calculation of LCOE includes equipment costs tied to the procurement or development of a power plant, operations and maintenance costs, as well as fuel and financing costs, with an assumed utilization rate over the expected lifetime of a project (EIA, 2015). Typically represented in a format,

7 For more discussion of these trends and influences, see Goldemberg and Johansson (2004) and GEA (2012).

like dollars per megawatt-hour or cents per kilowatt-hour, LCOE captures some uncertainty with different price and discount rate scenarios.[8]

A strength of the LCOE approach is that it highlights differences in the relative cost structures of energy technologies, and can show sensitivities to various assumptions about price and discount rate.[9] Projects with costs that are heavily shaped by upfront investment or capital costs, like nuclear, wind, solar, and hydropower plants, for example, are sensitive to discount rate selection and project timespans. By contrast, projects with cost profiles that are defined more substantially by back-end costs, namely fuels, are more sensitive to varying price estimates (Box 1).

Box 1: International Reference on Levelized Costs

The IEA periodically produces a reference on the levelized, average lifetime costs of electricity, evaluating energy technology at the plant level (IEA, 2015c). Focusing on plants that are built between 2015 and 2020, the current edition uses discount rates of 3%, 7%, and 10%, and considers generation costs at more than 180 power plants of varying technologies. Drawing largely on OECD country data, the report includes some non-OECD players, like Brazil, China and South Africa. It does not cover major energy players, like Russia and India, or much for regions of the Middle East, Latin America, and Africa.

A number of limitations are worth highlighting with the LCOE. Comparability of LCOE analyses, for instance, is subject to the scoping and assumptions, particularly for capacity factors of individual technologies.[10] Commodity prices

8 The *discount rate* allows a future value to be translated to today's terms. The choice of the rate matters substantially, since it can skew the analysis toward one technology over another, and often singularly defines how favorable project economics are.

9 LCOE can be used to identify system equivalency 'crossover points' between a traditional technology, like diesel power, and emergent ones, like a hybrid, closed-loop, wind-hydropower energy system (Hallam and Contreras, 2015).

10 The *capacity factor* reflects the actual output of a plant for a period of time relative to the plant potential, if it were run at its stated nameplate capacity for the period.

and interest rates are also difficult to estimate decades in advance. Substantial regional differences present yet another dimension of complexity (Channell *et al.,* 2015).

Broadly speaking, LCOE does not fully capture the intermittency of renewables or the associated grid costs. Paul Joskow, in particular, argues that the LCOE and related, total life-cycle production cost measures do not factor for the dynamic value of electricity supplied over the course of a typical year (2011).[11] In addition, he points out that LCOE tends to implicitly overvalue intermittent generation, like solar photovoltaics or wind generation, relative to dispatchable alternatives, such as combined cycle natural gas, coal or nuclear generation *(Ibid.)*[12]

Replacement value and levelized avoided cost of energy

The replacement value of an avoided fuel is another way to evaluate costs in energy systems. This method can be more simplistic than LCOE and more easily applied to past or future energy transitions. It can be done as a 'back-of-the-envelope' calculation with price often used as a proxy for cost. This method can be particularly suitable when an alternative fuel provides the same costs and benefits as the one being substituted. The alternative should also be the most likely 'next choice', and be expected to be used fairly seamlessly without a tapering-off effect. A situation in which this approach could be used would be in the calculation of forgone oil imports, when domestically sourced fuels are used.

In recognition of the strengths and weaknesses of the replacement value and LCOE approaches, a hybrid approach now exists. The levelized avoided cost of energy (LACE) estimates expected grid costs to generate power that would otherwise be displaced by a new generation asset or project (EIA, 2015; Pentland, 2014). It acknowledges that non-dispatchable electricity may not avoid the capital and maintenance cost of back-up generation, and is calculated by dividing the

11 According to Joskow, the spread between the peak and low hourly prices in the period of one standard year can encompass up to four orders of magnitude (Joskow, 2011).

12 Dispatchable generation is the kind that can be easily turned on and off, in other words dispatched on demand. Output can also be adjusted on demand.

avoided cost of back-up power by the annual output of the non-dispatchable power (EIA, 2015). The calculated value for LCAE can then be considered in conjunction with the LCOE of a given project to determine the way in which value measures up to a fuller expected cost *(Ibid.)*

Marginal costs

Similar to the above methods, marginal costs allow for comparison across energy options in a system. The marginal cost method centers on the additional system cost of including the next unit of energy. It is currently used by some grid operators through merit order dispatch of power, which ranks available power generation options in ascending order based on price and demand for power.[13]

If contemplating use of the above methods for energy systems cost assessments, one should bear in mind that underlying changes, such as those associated with infrastructure, jobs, or quality of service, may be obscured.

Valuing cost dimensions

Beyond calculation methods, important questions arise when evaluating an energy system change. One must decide, for instance, what to include and whether or how to monetize less visible costs and benefits. Choices might include stranded costs, subsidies and taxes, ecological and health impacts, as well as resilience factors, among considerations.

Stranded and sunk costs

Stranded or sunk costs are unrecoverable costs associated with prior investment. An example includes stranded assets which generally are investments that 'suffer from unanticipated or premature write-downs, devaluations or conversion to liabilities' (Caldecott and McDaniels, 2014). One way to calculate these is by deriving the difference between the current market value of an asset when

13 If utilization is coordinated centrally and driven by price and demand, generation is selected by the least cost options, reducing overall system costs. Rationale for altering the dispatch order could include policy aims that favor certain energy types, alter system congestion, or strengthen reliability, etc.

productively utilized and the historical cost of the same asset when depreciated over time using an approved accounting depreciation schedule (Clemson University, undated).[14] Such costs can be controversial, for example, when electricity markets are restructured or when power plants are retired prior to their planned life due to changes in social preferences. Closure of nuclear plants before their anticipated project life is an example that is playing out today.

The subject of stranded costs gained attention in the lead-up to the Conference of Parties 21 and Summit in Paris. One study indicates that up to $2 trillion in oil, coal and gas projects will not be needed, if action occurs to limit global warming at 2 degrees Celsius (Reuters, 2015; CarbonTracker, 2015).[15] Energy reserves could then become stranded assets. Energy companies respond to such claims by pointing out that payback periods for projects, among other factors, are front-loaded, so would be paid before more stringent laws take effect *(Economist,* 2014). Here, the timing and robustness of policy will matter for such costs in relation to any low carbon energy shift.

Subsidies and taxes

Subsidies and taxes also have cost implications for energy transitions. Both are forms of economic support that are extended to attain economic or social aims. Such policies can be quite controversial as they tie to equity decisions about wealth transfer and cross-subsidization *(i.e.* allocation of funds accrued from one area to another), technology favoritism, entrenched political dependencies, and other forms of lock-in that can undermine critical areas of development.

For subsidies, a useful working definition is a governmental action directed primarily at the energy sector that: (1) lowers the cost of energy production, (2) raises the price received by energy producers, or (3) lowers the price paid by energy consumers (EIA, 2015). In 2014, the IEA estimates that global subsidies for fossil fuels totaled $490 billion *versus* $135 billion for renewables

14 This assumes that the capital has no alternative use or salvage value (Clemson University, undated). For more extended discussion, see Lucas (2016) and Congressional Budget Office (1998).

15 It also finds that the private sector has as much exposure as its state-owned counterpart, based on production choices through to 2035, and capital expenditures to 2025 (CarbonTracker, 2015).

(IEA, 2015d).[16] The IEA notes that the former would have been $610 billion, if reforms beginning in 2009 had not occurred. To calculate these numbers, the IEA employs the *price-gap methodology* in which the average end-user prices paid by consumers in local markets are compared with international market prices (IEA, undated).[17]

Subsidy = (Reference price – End user price) x Units consumed

Needless to say, data requirements are enormous for calculations, like those of global subsides. Data collection is also affected by differences in government reporting *(i.e.* definition, transparency, etc…) which may be corrected with targeted harmonization. Calculations are also sensitive to reference prices. For the IEA subsidy analysis, subsidized research and development as well as related kinds of support, such as that for fossil fuel production, are not included *(Ibid.)* Impacts on economic efficiency and trade are also not fully captured. This approach has been criticized for not accounting for local market differences (Levi, 2010).

Similar to subsidies, taxes also distort the cost of producing or using energy.[18] Exhibit 3 shows, for instance, how taxes for industrial electricity can significantly alter a cost profile. One need only compare Italy and Sweden to see substantial variation. Here, distinctions in how 'tax' is defined merits closer attention, as subsidies and stranded costs may be treated differently in the two countries.

With net importing countries, subsidies may be explicit, reflecting spending on the domestic sales of imported energy at subsidized prices, or may also be implicit *(Ibid.)* Indonesia, for instance, produces domestic fuels and imports. In

16 Specific to renewables, the IEA estimate evaluates biomass, geothermal, wind, small hydro, solar photovoltaics, solar thermal, and marine in generation and/or biofuels. Large hydropower and biomass with carbon capture and storage are not included (IEA, 2012b).

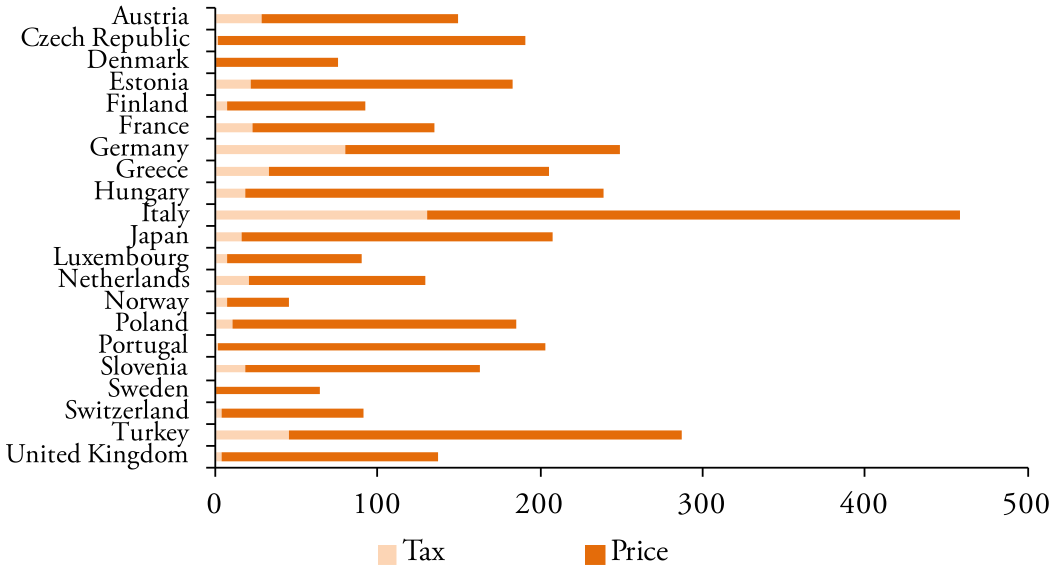
17 For energy exporting countries that provide lower cost fuels domestically, subsidies may be implicit and have no direct fiscal budget impact, provided the price encompasses the cost of production. In such instances, the subsidy is the amount that could be earned (opportunity cost), if end-users paid international prices. For IEA analysis, this approach adjusts for differences in variables, like transportation costs (IEA, undated; IEA, 2012a).

18 Taxes and subsidies are sometimes co-mingled in reporting, particularly if an explicit subsidy is passed on to tax payers.

Exhibit 3

Electricity Prices and Taxes in Industry

(2014, $/unit, using ppp)



Source: IEA, 2015a.

this example, subsidy estimates reflect direct expenditures and opportunity costs (Ibid). For more discussion, see IEA (undated and 2012a.)

Unlike outright taxes, *tax preferences or forgone tax revenues* are less obvious in energy systems, yet can still influence adoption pathways. In 2011, for instance, $30 billion was spent on tax preferences for energy in the US – $24 billion on renewable energy and $6 billion on fossil fuels (Biebl, 2012). This reflects a major shift from earlier periods, like that between 1968 and 2010, when tax preferences for oil and gas totaled $193.4 billion ($ 2010) relative to $24.6 billion for renewable energy (Ibid).[19]

19 Tax preferences for renewables started in 1979 (Sherlock, 2011). Tax preferences for fossil fuels included provisions to speed up the capital cost recovery for investment in oil and gas exploration and production by allowing the expensing of intangible drilling costs (IDCs) and dry hole costs. For IDCs, tax-related deductions could begin fully in the initial year, rather than being capitalized and depreciated over time (Sherlock, 2011). Another tax preference for oil and gas included the percentage depletion provision that allowed for the deduction of a fixed percentage of gross receipts, instead being based on the actual value of the extracted resource *(Ibid.)* When initially introduced, the percentage depletion rate was 27.5% for oil and gas. It is still in effect for certain conditions at 15% for oil and gas, and 10% for coal *(Ibid.)*

Health effects

Health effects reflect a distinctly different area of energy costs that can substantially alter cost assessments of energy systems and related change.

At the global level, a study for the *Global Energy Assessment* estimated that as many as 5 million premature deaths occur a year with another 5% of illness *(i.e.* measured as lost healthy life years) being directly caused by energy systems (Smith *et al.,* 2012). Household air pollution and outdoor exposure to partial fuel combustion of fossil fuels and biomass were found to be the greatest energy determinants of negative global health impacts. Additional contaminants like ash, sulfur, and mercury also play a role.

When evaluating health costs or effects of energy at a systems level, the life cycle assessment approach allows for comparison across technologies for the full span of impacts. Specific to airborne and related pollutants, impacts are measured as a temporal-spatial relationship between the pollutant concentrations and the people affected. Measured as *intake fractions,* this metric is calculated as the inhaled amount of a primary pollutant that is emitted (rather than downstream derivatives) by a given group divided by the amount that is emitted *(Ibid,* citing Bennett *et al.,* 2002). Location and weather conditions will matter significantly, as ventilation and wind dispersion can have a significant impact.

At the household level, the most damaging energy contributor to health effects is believed to be indoor cooking and heating, from partly combusted fuel. Estimates for 2005 indicate that 2.2 million premature deaths or 41.6 million disability adjusted life years (DALYs) were associated with use of solid fuel for cooking (Smith *et al.,* 2012, citing Riahi *et al.,* 2012). A DALY or lost year of healthy life is calculated as:

$$\text{Disability adjusted life years} = \text{YLL} + \text{YLD}$$

or the sum of years of premature lost life (YLL) and the years prematurely lost to disability (YLD) for a population (WHO, 2015). Disease associated with the utilization of solid cooking fuels is calculated by developing estimates of the share of people using solid fuels, together with an estimate of the share that is attributable to exposure. This number is then multiplied by the DALYs, equaling total number of deaths and DALYs that result from the use of solid fuels (Smith *et al.,* 2012, citing Riahi *et al.,* 2012).[20]

Ecological costs

Natural resources are the principal feedstock in energy systems. Given this, it should be no surprise that ecological costs factor in energy system costs, and vice versa. Important metrics on this include: disruption (Goldemberg and Johansson, 2004), footprints (Moscovici *et al.,* 2015), and water requirements (Gerdes and Nichols, 2009; Mielke *et al.,* 2010). It is worth underscoring that these indicators, similar to the health effects mentioned earlier, are not monetized.

Another way to gauge the ecological effects of energy systems is by valuing *ecosystems services*. This term refers to the welfare benefit of natural capital (Costanza *et al.,* 2014) or the direct and indirect contributions made by ecosystems (Barbier, 2011).[21] Such services are not typically marketed, and are a challenge to gauge or quantify in terms of structure, function, and procedural flows to people *(Ibid.)* In 2011, the global value of ecosystem services was estimated as $125-145 trillion/year ($ 2007) (Costanza *et al.,* 2014). These services encompass more than energy-related functions. Nonetheless, they intersect with cost and value considerations of energy systems. Water inflows for hydropower dams, for example, can derive from melting ice and snow. In ecosystem services terms, ice and snow provide a form of energy storage service (Moomaw, 2015). Such value dimensions are rarely captured in energy cost assessments, and represent an area for much further analysis.[22]

Accidents

Accidents play a role in costs of energy pathways and related change. Such costs typically bridge ecological, health, and built environments, and are monetized

20 For more extensive discussion of analytical details, see http://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/

21 Specific to contributions or benefits, some evaluators focus solely on human impacts, whereas others include anthropogenic effects plus those to the natural system.

22 A related area of research includes the effects that are evaluated in environmental impact and strategic environmental assessments of prospective energy projects. For coverage, see writing such as that in the *Environmental Impact Assessment Review.*

in insurance rates and legal penalties. However, they often do not represent the totality of damage.

Sovacool *et al.* (2015) completed one of the more comprehensive analyses to date for this subject with 11 energy technology systems. Reviewing accidents from 1874-2014, they found that nearly 1,100 accidents occurred with over 210,000 human fatalities, and almost $350 billion in property damages *(Ibid.)*[23] Across this set of data, hydropower was found to be the most fatal, at 85% of the total. Wind technology involved the most frequent accidents, roughly equaling one third of the total,[24] and nuclear accidents were the most costly, accounting for roughly 70% of the overall damages *(Ibid.)*

Among energy accidents in recent memory, two stand out. The Deep Water Horizon oil spill that occurred in 2010 was estimated to cost $53.8 billion to date (Bawden, 2015). An estimate for the 2011 Fukushima nuclear accident anticipates the entire cost of the disaster at $325-406 billion *(Economist,* 2015). While these estimates are not fully comparable, as their assessment approaches differed, they nonetheless are useful for discrete reference points. With cases such as these, decision-makers might identify with thresholds that exceed their society's willingness to accept risk in future energy pathways.

Resilience, theft, and modernization[25]

The availability and quality of an energy system are additional features that factor in cost considerations of energy systems. These dimensions are widely recognized as priorities in today's public agendas, as governments evaluate needs

23 Accidents were defined as unintentional incidents or events at an energy facility that resulted in one or more deaths, or at least $50,000 in property damage. This work extends earlier work by Sovacool (2008).

The energy systems, here, accounted for most commercial energy conversion, distribution and use. Cases were derived from English-based, published sources. Cost of total economic loss considered property damage, emergency response, environmental remediation, evacuation, lost products, fines, court and insurance claims, but did not account for damages, like non-fatal injuries. When data was missing, calculations used proxy data (Sovacool *et al.,* 2015).

24 The modular nature of wind technology may account for this frequency.

25 Other types of costs that merit coverage include those associated with security, industry/jobs, and political impacts. For discussion of learning curve costs, *see* Grubler and Wilson, 2013, and Araujo, 2014.

for infrastructural modernization and resilience in relation to extreme weather, theft, terrorism and cyber-attacks.

A recent study estimates damages for the U.S. power system on the order of $18-33 billion per year for the effects of extreme weather on lost output and wages, spoiled inventory, delayed production, and associated grid damage (Council of Economic Advisers, 2013). If one is deciding whether to reinforce an existing energy system or to opt for more substantial overhaul, such damage estimates provide a basis for more fully characterizing the tradeoffs.

Cost considerations that may be missed with conventional energy assessments include those tied to theft. With electricity, for instance, theft factors not only in outright expenses that must be recovered, but with ancillary costs tied to safety risks and damage from theft. A recent estimate of loss due to energy theft worldwide indicates costs on the order of $25 billion per year (Jiang *et al.,* 2014). For such challenges, smart grid enhancements may offer a solution that includes detection and a line of defense.[26] However, others point out that ‘smarter’ technology like that in advanced metering infrastructure also opens the system to new kinds of cyber vulnerabilities (McLaughlin *et al.,* undated).

COST ASSESSMENTS IN GLOBAL ENERGY TRANSITIONS

The following energy transition estimates reflect different scoping, assumptions, and to some extent data and methods. While not entirely comparable, they highlight varying kinds of cost dimensions.

Low Carbon

The shift toward a low carbon pathway is one of the most widely recognized energy transition aims today. With the energy sector contributing two-thirds of

26 A study by the Electric Power and Research Institute estimates costs between $338 billion and $476 billion over the next 20 years to deploy smart grid technology from U.S. utility control centers and power networks to consumers’ homes. It also indicates that delivered benefits would approximate $1.3-2 trillion over the same period. Benefits are said to include greater grid reliability, integration of solar rooftop generation and plug-in vehicles, reductions in electricity demand, and stronger cybersecurity (EPRI, 2011).

the world's greenhouse gas emissions, low carbon energy shifts are considered to be a high priority on many agendas (IEA, 2015c and 2015d). Such a structural shift can align with a variety of other interests, like reducing related environmental impacts, fostering a more local energy footprint, supporting technology leadership and jobs, or strengthening security. Synergies of aims make integrated analysis important for cost assessments.

Stern Review – 2006

One of the most well-known and systematic estimates of global costs for a low carbon transition is that of the *Stern Review,* released in 2006. Focusing on energy and other contributors to climate change, the *Stern Review* found that the costs of change to avoid the worst effects of global CO_2 (exceeding a 500-550 ppm range) could be limited to roughly 1% GDP per year, if early action were taken (Stern, 2006). Further, it indicated that shifting the world to a low carbon path could benefit the economy on the order of $2.5 trillion a year. These findings contrasted with global costs equaling 5-20+% of the GDP each year infinitely, if a business as usual path were left unabated and global CO_2 exceeded the 500-550 ppm range. Compared to earlier reports, this study estimated much higher, future damages and lower abatement costs (Baker *et al.,* 2008). The choice of discount rate; treatment of risk, uncertainty and equity; and calculation and comparison of costs and benefits were also subject to criticism (Nordhaus, 2007; Dasgupta, 2006; Arrow, 2007).[27] Notably in 2008, Stern revised his estimate to 2% of GDP for achieving stabilization at 500-550 ppm to account for rapid changes (Jowitt and Wintour, 2008). More recently, he indicated that the risk estimates could have gone even further (Stewart and Elliott, 2013).

Citigroup – 2015

A second study of a global, low carbon transition was completed recently by Citigroup in which the costs of adopting a low carbon path were compared

27 Using mainstream economic analysis, Stern adopted a rate of 0.1 % a year to discount time, treating all generations nearly equally with a limited risk of extinction, and 1.3% per year for the growth rate of per capita consumption.

Earlier studies focused on increases of 2-3 degrees Celsius, whereas Stern drew on contemporary science that pointed to significant risks of temperature increases above 5 degree Celsius by the early part of the next century (Baker *et al.,* 2008). For discussion of key responses, *see* Ackerman (2007).

to one of business-as-usual or inaction. In *Energy Darwinism II: Why a Low Carbon Future Doesn't Have to Cost the Earth,* Citigroup considered capital and fuel expenditure alongside potential damages of climate change (Channell *et al.,* 2015). Expenditures on energy were estimated to be $200 trillion in the next quarter century with marginal differences found in expenditure between the low carbon and business-as-usual path over the period to 2040. The low carbon path was estimated to cost $190.2 trillion, while the business-as-usual path was expected to be $192 trillion. In terms of the liabilities of not acting, 'lost' GDP was found to equate to $44 trillion by 2060 on an undiscounted basis. Viewed in terms of affordability, the extra expenditure that would be needed in the 'Action pathway' for energy (not counting savings) in relation to global GDP would annually equal roughly 0.1%-1% of GDP. This study made the case that 'Action' investment could strengthen growth *(Ibid.)*

IEA – 2015

A third study of global, low carbon energy change was completed by the IEA the same year as the Citigroup study (2015d). It estimated that $270 billion was spent on renewable energy technology for power generation in 2014.[28] Looking forward, it anticipates annual investment in renewable technologies with new policies to equal a cumulative $7.4 trillion between 2015 and 2040, roughly 15% of total investment in the global energy supply.[29] It is worth emphasizing, here, that the contribution of renewables has been noted by some to be consistently underestimated (Roselund, 2015).

28 This total compared to an average annual investment on renewable energy of $165 billion for the period 2000 to 2014. Total cumulative investment in renewable energy amounted to $2.5 trillion for the period, equaling 1,000 GW of new capacity (IEA, 2015d).

29 This includes $7 trillion for renewables in power generation, and $360 billion in transmission and distribution (IEA, 2015). If biofuels are factored for the transport sector, another $390 billion is added *(Ibid.)*

New policies and other implementing measures that affect energy markets are those that were adopted as of mid-2015, including energy related elements of Climate pledges submitted for the Conference of Parties (COP) 21 up through October 1, 2015, as well as stated policy intentions, irrespective of whether the implementation mechanics may not have yet been adopted (IEA, 2015d).

Specific to climate change, the projected path is expected to slow the growth of energy-related CO_2 emissions, but is not seen by the IEA as sufficient to limit the rise in long term, average global temperatures to 2 degrees Celsius.[30] To avoid overshooting the limit, the IEA recommends additional measures that include: increasing investment in renewables within the power sector from $270 billion in 2014 to $400 billion in 2030; increasing efficiency in buildings, transport and industry; progressively reducing the least efficient coal power plants and banning construction of new ones; gradually phasing out fossil fuel subsidies and reducing methane emissions in oil and gas production (IEA, 2015).

Across the three studies, general energy supply and demand estimates were derived with forecasting and back-casting techniques.[31]

Universal access

Another energy transition that can be considered in cost discussions is the shift toward universal access. Currently, there is an estimated 1.2 billion people lacking access to electricity (17% of the population), and another 2.7 billion (38% of the population) relying on traditional biomass for cooking (IEA, 2014).[32] In 2013,

30 The 2 degrees Celsius endpoint is used as a rough limit for avoiding the worst of climate change.

31 *Forecasting* predicts what might happen, based on certain assumptions and methodologies. The method often presupposes a stable relationship in dominant trends, and is unlikely to produce options that factor for discontinuities (Robinson, 1982 and 1988).

Backcasting can be more effective for situations in which decision-makers are looking to strategically alter energy paths. This form of modeling begins with a desired end-point, and then one works backwards to determine how to achieve the aim. This method can highlight a range of options that would otherwise be missed in conventional forecasting. Goals might include self-sufficiency, minimum social or other kinds of costs, universal access, and specific shares of energy mixes. Such models can be broken down into short, medium and long term time horizons. The method reveals possibilities, feasibilities, degrees of policy freedom, and implications of varying energy paths (Robinson, 1982, 1988).

32 Modern energy services are seen as fundamental to the quality of human well-being and economic development. To attain universal access by 2030, the United Nations launched the Sustainable Energy for All initiative in 2011. This has been followed by a post-2015 Sustainable Development Goal.

Estimates indicate that nearly 97% of those without access live in sub-Saharan Africa and developing Asia (IEA, 2015d).

In line with related concerns about security and carbon emissions, the energy transition to universal access is estimated to increase global energy demand by 1% and CO_2 emissions by 0.6% in 2030 (IEA, 2012c).

the IEA estimated that $13.1 billion was spent on capital investment to enhance cooking and power access (IEA, 2015e).

Looking ahead, costs to achieve universal access were estimated to total $979 billion or $49 billion per year for the period between 2011 and 2030 (IEA, 2014). This amount approximates 3% of global energy infrastructure investment (IEA, 2012c). As a point of reference, analysis of the necessary investment to attain universal access found that roughly $9 billion was spent in 2010 (World Bank and IEA, 2015). If such a pattern continues, the 2030 goal will not likely be met.[33]

Given that data on access is incomplete, bottom-up collection is done with periodic updates to fill select information needs. This information is harmonized and extrapolated to fill additional gaps. These data development stages are followed by econometric modeling of electrification rates and biomass reliance tied to regional variables. Modeled outcomes associate access with variables like 'per capita income, population growth, urbanization, fuel prices, level of subsidies, technological advances, energy consumption and energy access programs' (IEA, 2012c).

This initiative is unique for its scale, robustness of aim, and level of data assessment for information that in many respects did not exist or was not systematically captured beforehand. The methodological approaches for gauging access are recognized by the World Bank and IEA as needing refinement, as more is understood about the studied phenomenon. For example, the binary representation of grid connectivity does not adequately account for unpredictable

33 To assess a path to universal access by 2030, the IEA defines modern energy access as 'a household having reliable and affordable access to clean cooking facilities, a first connection to electricity, and an increasing level of electricity consumption over time' (IEA, 2012c). In focusing on the household level, other categories of electricity need, such as that for businesses and public buildings *(i.e.* schools and hospitals), are not included *(Ibid.)*

Specific to clean cooking, the IEA characterizes access as 'the provision of cooking facilities which can be used without harm to the health of those in the household and which are more environmentally sustainable and energy efficient than the average biomass cookstove currently used in developing countries. This definition primarily encompasses biogas systems, liquefied petroleum gas (LPG) stoves and advanced biomass cookstoves' *(Ibid.)*

outages and affordability (World Bank and IEA, 2015). Given that this initiative has roughly 14 years remaining, one can expect ongoing learning with the methods of analysis.

Additional Considerations

The global nature of the universal access and of low carbon energy transition assessments highlights some of the recurring challenges that can arise when valuing costs of energy systems change. With definitional scoping, for instance, cascading layers of choice characterize the analyses. If universal access were to include schools and hospitals, for example, additional collection and estimates would likely be needed. Choices about how to differentiate types of users and to avoid double counting may also be necessary (IEA, 2012c).

RELATED CONCEPTS WHEN VALUING ENERGY SYSTEMS[34]

Bounded rationality of decision-making and analysis

When considering cost analysis of energy systems change, one could ask what initially guides the scoping of options. Energy practitioners might point to time, resources, and feasibilities in the preliminary vetting of options. Viable opportunities are, however, sometimes missed in the pre-selection process.

Bounded rationality offers some theoretical explanation for these limitations (Simon, 1972, 1982). Defined broadly as ways in which one's thinking is constrained by available information, cognitive limits, and finite aspects of time when making decisions, this concept might, at first, seem tangential to a discussion of costs in energy transitions. In fact, it figures prominently, as it basically points a behavioral lens on historical review and forward-looking scoping that shapes the selection frontier. In scoping, for example, bounded rationality influences assessment choices if one resorts strictly to traditional reporting and conventions,

34 For more in-depth discussion of ideas on lock-in, urgency, tradeoffs, and innovation, *see* Araujo (2014).

while missing opportunities to account for new technologies, practices, and policy regimes or integrated opportunities. An example might be found with energy forecasting that relies on conventions of anticipating growth in demand at 2-5%. Absent broader, outside-of-the-box and integrated analysis, this conventional approach could carry forward existing challenges (Davis and Socolow, 2014), rather than altering the path.

More broadly, bounded rationality applies not only to the thinking of analysts and policy-makers, but also to citizens, users, and producers involved in an energy transition.[35]

Citizens of a region may be presented with conditions that are defined by the orientation (bounded rationality) of their governing decision-makers or associated analysts. Decision-makers who are pro-market or pro-regulation, for instance, may not consider governance approaches or the cost dynamics outside their sphere of familiarity. Distributed or altered cost structures tied to partnerships and co-production (Ostrom, 1990 and 2014; Ackerman, 2004; Nevens *et al.,* 2013), as well as bottom-up, civil society measures that do not entail market inducement (Foxon, 2013) may, for instance, not be factored. Such pivotal aspects of an energy system can affect not only the costs of an energy system and its potential for change, but also be embedded within the sectoral structures (Arthur, 1994; Garud and Karnoe, 2012).

New financing

Financial instruments and markets reflect another critical dimension that can impede or enable energy systems change by affecting costs through the availability of funds.

One relatively new mechanism for financing, for example, is associated with crowd sourced funding (Vasileiadou *et al.,* 2014; Douw and Korin, 2015). Drawing on ideas in microfinance (World Bank, 2013, citing Murdoch, 1999) and crowdsourcing (World Bank, 2013, citing Poetz and Schreier, 2012), this

35 These groups typically overlap. An energy consumer is also often, but not always, a tax payer.

phenomenon emerged after the financial crisis of 2008. It includes equity and debt fundraising that leverages social networks, social profiles and the viral nature of web-based communications. The approach can function as an alternative to conventional funding to catalyze efforts and fill gaps that are otherwise unmet. It has potential to be pivotal, particularly for people and regions that are looking to leapfrog past traditional market structures, regimes, and technologies. Accreditation, however, is a challenge with this nascent approach, as high income/net worth of funding pools do not necessarily correlate to advanced understanding of capital markets (Luzar, 2013).

Broadly, this approach could serve a role in energy system change by covering funding cycles which precede mainstream financing stages. The World Bank estimates, for instance, that $2.7 billion was raised worldwide in 2012 through such business models and platforms (2013). While this still is in its infancy, crowd-sourced funding has significant potential and will depend on the conditions and culture of entrepreneurship, as well as the presence of supportive policy (or at least neutral policy).

TAKING STOCK WITH DIRECTIONS FOR FUTURE RESEARCH

Having reviewed a range of cost considerations tied to energy systems and their change, a number of critical takeaways emerge.

- The notion of 'true costs' can be misleading, as the definitions, assumptions, scoping, methods, and data can produce significantly different outcomes. Elements that distort cost as well as less visible effects (even sunk/stranded costs) may not enter into a cost calculus, yet can have significant bearing not only on estimates, but on the pace or robustness of a system change. These dimensions should be factored and merit further attention.

- Organizational 'distance' between decision-maker and analyst often places analysts in unusual positions to provisionally 'settle' many early decisions about what is evaluated, while assuming away real-life contingencies. The danger with such approaches is that the complexity of models obscures value choices, and legitimacy or process biases may default to analysts' choices.

- Decision-makers may leverage quantitative, modeled analysis to determine choices. Some qualitative values and choices, however, are not conducive to this form of evaluation, and might be inadvertently left entirely out of the decision-making process.

- In practical terms, decisions may be treated as discrete in analysis, yet be interlocking or cascading in practice with compounding effects and/or inter-regional dependencies. Closely tied to this idea, net and cumulative effects of costs (and benefits) as well as distributional impacts present new lines of inquiry for today's decisions tools, with opportunity to improve evaluative techniques.

In the end, cost assessments usually reflect a limited 'snapshot' of an energy transition or the associated system. Not all cost-like features (or benefit-like ones) may be recognized. Further, some people might not even be willing to embark on a path if they knew what was in store for them. Here, an appreciation of strengths and limits to cost appraisals, with cross-referencing to other modes of analysis and knowledge accumulation will allow for a more grounded understanding of value in energy system change.

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