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Electricity Externalities, Siting, and the Energy Mix: A Survey

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Abstract

While early literature on electricity externalities was largely concerned with fossil fuel power generation and the associated emissions, nuclear accidents (Chernobyl, Fukushima) and the large-scale deployment of renewable energy facilities have spurred a wave of research on the externalities of nuclear power and renewable energies. The issue is important because many countries have started reconsidering their energy policies, and the externalities from electricity generation play a major role in the benefit-cost analysis of relevant options. This paper reviews the literature on electricity-related externalities. It starts by discussing their nature and the methods employed in valuing them. It finds that appraisals of electricity externalities are complicated because of heterogeneity of both the externalities themselves and the methods applied in measuring them. The paper reviews valuation studies of the externalities from fossil fuel, nuclear and renewable sources, and it discusses the relevance of their findings for the siting of plants and the electricity mix. It concludes by pointing out gaps in our knowledge about electricity externalities that deserve to be addressed in future research.

Keywords: electricity generation; externalities; fossil fuels; nuclear power; renewable energy; siting; electricity mix; property value; willingness to pay; subjective well-being
JEL codes: Q48; Q42; Q51; Q53; Q54
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1. Introduction

Against the background of climate change, technological risk, and insecurity of resource supply, many Western countries are reconsidering their energy policies. In particular, the future structure of the electricity system poses a challenge to decision makers and researchers, involving the issues of affordability, safety and security, and environmental friendliness of electricity generation.

Nations greatly differ with respect to electricity supply choices. In Europe, for instance, Germany has responded to the Fukushima nuclear disaster by proclaiming an "energy transition" (*Energiewende*) that entails an accelerated phase-out of nuclear power and an ambitious goal for phasing-in renewable energy (RE). Similarly, Switzerland and Italy consider phasing out their nuclear power programs. Contrary to this, France has announced to extend the lifetime of its nuclear power stations, thus maintaining the decades-old dominance of nuclear power in the electricity mix, and the United Kingdom is building new nuclear capacity.

Judging from these examples, choices concerning electricity supply may likewise appear event-driven (Germany) or path-dependent (France), rather than being based on an encompassing assessment of the benefits and costs of existing options, as basic welfare economics would suggest.

A big challenge to the benefit-cost analysis of alternative electricity supply options consists of the externalities implied by electricity generation. This challenge involves two dimensions. One is the overall level of externalities created by the respective options. These overall levels are crucial to the choice of the electricity mix. The other dimension is the incidence of those externalities that stems from the local (or regional) nature of some power production externalities. These local externalities are crucial to the siting of electricity generation projects.[1]

[1] Put differently, the benefit-cost analysis of electricity supply involves the dimensions of efficiency and equity.

The measurement of electricity externalities both at the aggregate and the local level have been important areas of research over the past decades. The current energy policy challenges and, in particular, the emergence of new electricity generation technologies have further spurred the need for such measurement as an ingredient to rational policy making in the field of electricity supply.

Externalities from electricity generation consist of several types of environmental and health risks as well as disamenity effects that vary with the type of technology. While electricity generation from fossil fuels is associated with the emission of greenhouse gases and air pollutants, nuclear power involves the (statistical and perceived) risk of radiation and nuclear accidents. Renewable energy facilities impose visual, acoustic or odor nuisance on affected people.

The negative externalities from electric utilities differ by the spatial range of effects. Greenhouse gases, notably carbon dioxide, are a global public bad because each unit of emissions affects the global climate equally, independent of the place from which they originate. Air pollutants, such as sulfur dioxide, nitrogen oxides, and particulate matter, are a regional public bad whose effect diminishes with distance from the place of origin and typically affects people within a range of up to a few hundred kilometers. Nuclear risk is also expected to be of a regional nature and to diminish with distance. The impairments from renewable energies, conversely, are mostly restricted to the surrounding communities.

Depending on the type of externality and the spatial scale involved, the siting of energy facilities often meets with resistance by the people affected. In the case of renewable energy, in particular, there is often a tension between citizens' general preference of renewable energy over fossil and nuclear power and an unwillingness to have RE facilities in their neighborhood – the not-in-my-backyard (NIMBY) issue.

The purpose of this article is to review empirical studies on the externalities from electricity generation and their implications for the electricity mix and the siting of facilities.

The focus of the paper is on the measurement of those externalities by means of stated, revealed, and experienced preference approaches. After discussing the nature of the relevant externalities (section 2) and the methodological background of non-market valuation (section 3), the paper proceeds by reviewing the studies completed to date, differentiating between fossil fuel electricity generation (section 4), nuclear power (section 5), and renewable energies (section 6). Section 7 addresses comparative assessments of several technologies and their implications for the electricity mix. Section 8 offers a discussion and conclusions.

2. The Nature of Electricity Externalities

According to their standard definition, externalities are unpriced, unintended and uncompensated side effects of one agent's actions that directly affect the welfare of another agent (Baumol and Oates 1988). The side effects can be positive or negative.

Externalities from electricity generation are predominantly negative, affecting people through health risks and disamenities and through climate change. As the respective externalities differ by type of technology, replacing one technology by another may reduce the externalities from the technology to be replaced. Though conceptually problematic, valuation studies of one particular technology often consider avoided externalities from other technologies as positive externalities of the technology considered, referring to them as indirect externalities (Mattmann et al. 2016a, 2016b).

Health and amenity impacts of electric utilities typically decrease with distance (distance decay).[2] For this reason, electricity generation is usually categorized as a locally undesired land use (LULU). In addition to distance gradient effects of electric utilities, there may be region-wide effects, for instance on the labor or housing market (Farber 1999). Region-wide effects

[2] This does not apply to climate change (see below).

may be positive or negative. Valuation studies and, more generally, benefit-cost analysis of the location of electric utilities attempt to capture all of those effects.

This section describes the direct negative externalities associated with particular electricity generation technologies in physical and psychological terms whereas the next section discusses how they are incorporated into economic analysis.

2.1 Fossil Fuel Power Plants

The externalities related to fossil fuel electric utilities relate to climate change due to greenhouse gases, mainly carbon dioxide (CO_2), and air pollution. Climate change is related to fossil fuel energy generation in general, not to energy facilities in particular places. The analysis of the costs of climate change and the benefits of climate change mitigation is an extremely complex task, involving so-called integrated assessment models of the economy-climate interaction whose discussion is beyond the scope of this paper (see Foley et al. 2013 for the welfare-economic foundations and IPCC 2014 for a review).

Electricity-related air pollution mainly involves the emission of sulfur dioxide (SO_2), nitrogen oxides (NO_x) and particulate matter (PM). Electric utilities are typically the largest source of SO_2. In the U.S., electricity-related SO_2 amounted to 64 percent of the total SO_2 emissions in 2014, whereas the corresponding share in the EU (as of 2013) was 56 percent. For NO_x, electricity generation is usually the second largest source (after road transport), with shares of 14.3 percent in the U.S. (2014) and 21 percent in the EU (2013).[3] The importance of the electricity sector for primary PM emissions decreased substantially over the past decades due to the mandatory installation of scrubbers in Western countries. In the U.S., for instance, the share of electricity-related PM_{10} (PM with 10 micrometers in diameter and smaller) dropped

[3] On air emissions in the U.S. and the EU see www.epa.gov/air.emission-inventories and European Environment Agency (2015), respectively. The situation tends to be similar in developing countries. In China, for example, the share of power stations in SO_2 emissions was 56 percent in 2006 (Lu et al. 2010).

from 13.6 percent in 1970 to 1.4 percent in 2014. Though emitted in smaller quantities than SO_2 and NO_x, airborne PM has a potentially larger local impact because it settles out from the air relatively close to the emission source. In addition to primary PM, the chemical reaction of SO_2 and NO_x in the atmosphere leads to the creation of secondary PM, in particular fine particles. NO_x emissions can react in the atmosphere to create ground-level ozone.

As to effects, SO_2 and NO_x lead to acid rain, which affects the natural and built materials exposed to it. Exposure to small particles in the air has been linked to respiratory illness and reduced lung function. Particulate pollution is also the major cause of reduced visibility through haze. Low-level ozone may lead to cardiovascular problems. While primary PM is mainly a local or regional problem, SO_2 and NO_x can travel large distances, creating adverse effects in downwind areas several hundred kilometers from the place of origin. Due to dissipation of the pollutants, the effects of SO_2 and NO_x are subject to distance-related decay, depending on wind directions.

CO_2, SO_2 and NO_x are generically related to fossil fuel power generation because they are the chemical result of burning the respective fuels: coal, oil and gas. As the content of the underlying substances (carbon, sulfur, and nitrogen) differs by type of fuel, so does the release of the polluting gases. It is well known, for instance, that natural gas is less polluting than coal in terms of both climate change and air pollution whereas mineral oil takes an intermediate position.

Waste-to-energy incinerators present a special case. As in the case of coal, oil and gas, the underlying chemical process is the burning of carbon. In contrast to those fuels, however, (different types of) waste may contain several substances that lead to the release of a variety of pollutants in addition to CO_2, SO_2 and NO_x and PM. As noted by Kiel and McClain (1995b), incinerators have a perception of creating pervasive potential health risks due to toxic pollutants such as dioxins.

Climate change and air pollution arguably are the most salient issues in debates about fossil fuel power generation. In addition, several local externalities are likely to be important for households living in the immediate vicinity of fossil fuel plants, such as visual disamenities caused by large buildings and tall stacks, noise and vibration caused by engines, and traffic from fuel deliveries (Davis 2011).

2.2 Nuclear Power

The externalities from nuclear power relate to potential radiation releases during normal operation of plants or nuclear waste sites, and the risk of nuclear accidents and disasters with large-scale releases of radiation and ensuing consequences for humans, fauna and flora. Isotopes of concern are Iodine-131, Caesium-137, Strontium-90 and Plutonium-239, all of which are linked to increased risk of several kinds of cancer.

The nuclear risks that manifest themselves in the valuation of nuclear power externalities are *perceived* risks, which may differ from objective factors such as likelihoods of events (Kunreuther et al. 1990). A considerable literature has shown that perceived risks are a function of statistical risks as well as subjective factors, such as dread, involuntariness and lack of controllability (Slovic 1979).

Perceived accident risk from nuclear power plants, R, can be conceptualized as the expected value of damage from a nuclear accident: $R = \pi * D$, where π denotes the subjective probability of an accident and D the subjective expected damage associated with an accident. Likewise, π can be interpreted as a nonlinear probability weighting function, which typically overweights small probabilities and underweights large probabilities (Prelec 1998, Shaw 2015). Since nuclear radiation is subject to spatial decay, expected damage is typically assumed to be decreasing in distance to the power plant: $D = D(dist)$. Similar considerations apply to nuclear waste sites and transportation routes.

2.3 Renewable Energy

Some of the negative externalities from renewable energy are related to their low energy density in comparison with fossil and nuclear power, which implies spatially larger production units (Wüstenhagen et al. 2007). This concept applies, in particular, to hydropower, wind power and (free-standing) solar power facilities, which occupy large areas of land. Hydropower projects affect the landscape, vegetation, and wildlife as well as artifacts of cultural and historical value (e.g. Navrud 2001). Externalities of wind power that affect humans directly include visual impacts via shadowing and the impact on landscape aesthetics (e.g. Pasqualetti et al. 2002), and noise nuisance (e.g. Harrison 2011). In addition, there are effects of wind parks – both onshore and offshore – on wildlife (Drewitt and Langston 2006, Mathew 2006, Leung and Yang 2012, Schubert et al. 2015)). Regarding solar power, possible impairments include glare risks and visual impacts on buildings as well as on landscapes in case of free-standing solar plants (Chiabrando et al. 2009). Biogas plants affect residents through odor nuisance and noise caused by fuel deliveries. In addition, there may be visual impacts from the large-scale growing of maize in areas where biomass plants are located (Soland et al. 2013, Gerdes 2013).[4]

The spatial scope of RE externalities differs by technology as well as by the place of location. Studies that evaluate the landscape disamenity of wind farms at varying distances find a linear but slow decline to 12 km (Bishop 2011). The shadow effect (commonly known as shadow flicker) of wind turbines usually ranges between 1.5 and 2 km (Hau, 2014). Noise disturbance from wind turbines usually occurs within 500 m but depends on local conditions, such as level differences (Pedersen and Persson Waye, 2007). The glare impact of solar installations highly depends on the geometric conditions, such as the slope of solar panels and

[4] There are other possibilities to produce electricity from biomass (e.g. vegetable oil or wood) which may induce other externalities. In contrast to maize fields, blooming canola fields are often experienced as aesthetically appealing (Gerdes 2013).

the direction of solar irradiation (Chiabrando et al., 2009). With respect to biogas plants, Nicolas et al. (2013) find odor nuisance up to a distance of 600 m.

An issue that might be important for externalities of RE technologies is their ownership structure. Private owners of RE installations may enjoy financial and moral benefits (warm glow) which trade of against the various impairments originating from nearby RE facilities. In the case of rooftop solar panels there may in addition be status effects (Dastrup et al. 2012). Some valuation exercises of RE installations may represent a net effect of the externalities generated and the benefits enjoyed by nearby owners of those installations.

3. Measurement and Valuation of Electricity Externalities

3.1 Analytical Framework

From a conceptual point of view, electricity-related externalities are the effect on individuals' utility of the health and amenity risks discussed above. As a framework for the measurement and valuation of those externalities we consider an economy with two marketable goods: housing and a numeraire.[5] We assume that the individual derives utility from those goods and disutility from perceived electricity-related risks (which may differ from actual risks). The individual's indirect utility function specifies the maximum utility she can attain by allocating income optimally to the marketable goods at a given housing price and a given level of risk. The indirect utility function of an individual with personal characteristics θ, takes the following form:

$$u = v(p, y, R, \theta), \tag{1}$$

[5] This subsection is adapted from Welsch and Ferreira (2013) and Welsch and Biermann (2016).

where p, y and R denote the price of housing, income, and perceived risk, respectively. The indirect utility function is decreasing in the first and third argument and increasing in the second argument.

In the case of nuclear power, perceived risk is conceptualized as the expected value of damage from a nuclear accident: $R = \pi * D$, where π denotes the subjective probability of an accident or the probability weight assigned to it, and D denotes the subjective expected damage associated with an accident. In the case of fossil and renewable energy, D is physical or psychological damage resulting from the electricity-related externality (air pollution and visual, acoustic and odor nuisance), whereas π can be interpreted as individual-specific (taste-dependent) susceptibility to that damage. In accordance with the idea of locally undesired facilities, (expected) damage is assumed to be a decreasing function of distance to the respective facility: $D = D(dist)$.

Given the distance-dependence of damage, people may self-insure against damage by taste-based sorting, that is, by choosing their place of residence according to their subjective accident probability or damage susceptibility.[6] This induces an upward-sloping relationship $\pi(dist)$, that is, more pessimistic or susceptible people locate in more distant places. We thus have $R = \pi(dist)*D(dist)$ with derivative $R' = \pi D' + \pi' D$. In this derivative the term $\pi D'$ suggests that perceived risk decreases with distance whereas the term $\pi' D$ suggests that sorting may attenuate this relationship.

Using $R(dist) := \pi(dist)*D(dist)$ in equation (1), the latter can be rewritten as follows:

$$u = V(p, y, dist, \theta). \qquad (1')$$

[6] See Schneider and Zweifel (2013) in the case of nuclear power plants.

In this formulation, the derivative of *V* with respect to *dist*, $\partial v / \partial dist$, captures the (negative) externality in different places. This derivative is expected to be positive: controlling for housing costs and income, utility increases with distance due to the distance-dependent externality. However, this relationship may be diminished to the extent that people are heterogeneous with respect to their subjective accident probability or damage susceptibility and choose their place of residence accordingly.

The aim of power plant externality valuation typically is to capture the marginal utility of distance, $\partial v / \partial dist$, translated into monetary terms. The translation is achieved by dividing it by the marginal utility of income. As basic microeconomics suggests, the ratio between the marginal utility of distance and the marginal utility of income is the marginal rate of substitution (*MRS*) of income for distance, that is, the utility-constant trade-off between the two:

$$MRS(y, dist) = \frac{\partial v / \partial dist}{\partial v / \partial y}. \tag{2}$$

Conceptually, $MRS(y, dist)$ is the variable the various valuation methods for distance-dependent externalities seek to measure. It is worth emphasizing that distance is capturing the net effect of a combination of externalities – odor, visual, acoustic, local air pollution – depending on the type of energy.

The preceding discussion has focused on the role of distance to the facility considered, reflecting the notion of locally undesired facility. For simplicity, the discussion has conceptualized distance as a continuous variable. In practice, distance may be captured, alternatively, by discrete distance categories such as radius rings around the facility, postcode zones, or administrative units. Which distance measure is used depends largely on data availability which, in turn, may depend on the valuation method applied. In addition, distance may affect utility in a non-homogeneous way, that is, its effect may be mediated by meteorological and topographical conditions.[7]

We now briefly discuss the various valuation methods. More detailed discussions can be found, e.g., in Freeman (2003) and Fujiwara and Campbell (2011)..

3.2 Revealed Preference Methods

Revealed preference methods of valuation seek to infer the value of non-market goods from observed choices concerning market goods. The most widely used revealed preference technique is the hedonic method, which, in the present case, focuses on differences in housing costs and wages at varying distance from the facility in question.

The underlying rationale neatly fits the conceptual framework of the preceding subsection. Concerning housing costs, the standard hedonic model (Roback 1982) suggests that the willingness to pay for housing and, hence, the price of housing is a decreasing function of risk prevailing in the places where houses are located: $p = p\,(R)$. It also suggests that local wages (and thus income) increase in risk: $y = y\,(R)$. Substituting these relationships in (1) gives

$$u = v(p(R), y(R), R, \theta)\,. \qquad (3)$$

In a simple model of residential locational choice, people choose their location in such a way as to balance the disutility from risk against the utility from less expensive housing and higher income so that the utility in different locations is equalized. Otherwise individuals would have an incentive to move. Under the appropriate concavity properties this locational equilibrium condition can be characterized as follows:

[7] Welsch and Biermann (2016) found that the relationship between subjective well-being and the distance to nuclear power plants depends on the wind direction and the presence of mountains (see section 6).

$$\frac{dv}{dR} = \frac{\partial v}{\partial p}\frac{dp}{dR} + \frac{\partial v}{\partial y}\frac{dy}{dR} + \frac{\partial v}{\partial R} = 0 \tag{4}$$

The continuous hedonic model thus predicts that in locational equilibrium dv / dR is zero: Externalities from electric utilities (electricity-related risk) are capitalized in housing prices and income such that the marginal disutility from risk, $\partial v / \partial R$, is just offset by the marginal utility from lower housing prices in riskier places, $(\partial v / \partial p) * (dp / dR)$, and the marginal utility from higher income, $(\partial v / \partial y) * (dy / dR)$.

When we use the relationship $R = R(dist)$, discussed in the preceding sub-section, equation (4) implies:

$$\frac{dv}{d\,dist} = \frac{\partial v}{\partial p}\frac{dp}{d\,dist} + \frac{\partial v}{\partial y}\frac{dy}{d\,dist} + \frac{\partial v}{\partial dist} = 0 \tag{4'}$$

Consistent with equation (4), locational equilibrium thus implies that the marginal utility from lower risk in more distant places equals the marginal disutility from higher housing prices and lower income in more distant (less risky) places.

Relying on this equality, the hedonic valuation method – as applied to distance – uses the distance-dependent variation in housing prices and incomes to measure the monetary equivalent of the marginal (dis)utility from lower (higher) risk in more distant (more proximate) places. In applications, distance can be specified as a continuous variable or in terms of distance categories.

Reliance on locational equilibrium is the most controversial assumption of the hedonic method. Factors that may prevent locational equilibrium from emerging are moving costs (Bayer et al. 2009) and other market imperfections.

Another revealed preference valuation technique is the travel cost method, which infers the valuation of attributes of recreation sites from the travel costs people expend to get to sites with different attributes (such as scenic amenities).

3.3 Stated Preference Methods

While revealed preference methods rely on actual choices (of houses and jobs), stated preference methods establish hypothetical choice situations. The most important variants are contingent valuation and choice experiments. Contingent valuation asks people to state the amount of money they would pay to avoid, or request to accept, certain hypothetical risks or disamenities. Choice experiments present individuals with a set of options involving different risks or (dis)amenities and different monetary outcomes and ask the individuals to choose or rank the options. Since the number of scenarios in a given study is limited, contingent valuation and choice experiments involving location typically will capture distance in a discrete fashion.

A general advantage of stated preference methods in comparison to other approaches is their independence of real-world observations and, hence, their ability of valuing hypothetical options or actual options *ex ante*. This may be especially important for technologies that are not (yet) widespread. Pitfalls relate to the proper specification and description of scenarios (cognitive bias) and to the incentive to misrepresent values (strategic bias). The latter is relevant especially if respondents think that actual compensation or policy may depend upon their response (Freeman 2003, Fujiwara and Campbell 2011).

3.4 Experienced Preference Method

The revealed and stated preference methods rely on (actual or hypothetical) choices and, hence, decision utility, whereas the experienced preference method relies on experienced utility. Experienced utility is the *ex post* hedonic quality associated with an (economic) outcome. Decision utility describes the *ex ante* expectation of experienced utility. (Kahneman et al. 1997).

Experienced utility thus entails a retrospective (or contemporaneous) assessment of outcomes whereas decision utility involves a prospective assessment.

The experienced preference method consists of using survey data on reported subjective well-being (SWB) to measure the left-hand side of the indirect utility function $u = V(p, y, dist)$, together with the relevant right-hand side variables. It econometrically estimates this function directly and uses the implied utility-constant trade-off of *y* for *dist* (marginal rate of substitution) as the economic value of distance/proximity to electric utilities (or other LULUs).[8]

The experienced preference method avoids the locational equilibrium assumption underlying the hedonic method and the cognitive and strategic biases that may arise in stated preference approaches. By relying on the ex post hedonic quality of outcomes it avoids problems of affective forecasting, that is, in figuring out the utility consequences of actual choices (revealed preference) and hypothetical) choices (stated preference). This way, the method is able to capture influences on utility that the individual is not consciously aware of. On the downside, the experienced preference method requires the assumption of (ordinal) comparability of reported well-being, which economists are traditionally reluctant to accept.[9]

Similar to the hedonic method, experienced preference studies may involve continuous or discrete specifications of distance to the facility considered.

4. Fossil Fuel Power Generation

4.1 Valuation Studies

Valuation studies of fossil fuel power plants started to be conducted already in the 1970s. The pertinent papers use the hedonic method to estimate the property value effects of such facilities.

[8] The method is likewise referred to as happiness, life satisfaction, or subjective well-being approach to non-market valuation.
[9] For a detailed discussion see Welsch and Ferreira (2013).

An early study by Blomquist (1974) found that each additional mile from a small (26 MW), mainly coal-fired plant in Illinois, U.S.A., increased property values by $3256 (up to a margin of 11,500 feet). Davis (2011) provides a study of 92 power plant openings in the U.S. in the 1990s. The plants had capacities of greater than 100 MW, 85 of them being natural gas fired. Compared to neighborhoods with similar housing and demographic conditions, neighborhoods within 2 miles of plants experienced a 3 to 7 percent decrease in housing values, which corresponds to about $2770 to $6470 for average-priced houses. There was some evidence of larger decreases within 1 mile. Beyond 4 miles, no effect on housing values was found. Estimates indicate moderately larger effects for big plants, though the differences are not statistically significant. The results provide no evidence of a disproportional impact on homes downwind of plants. The small number of coal plants in the sample precluded differentiation between coal plants and gas plants.

Kiel and McClain (1995a, 1995b) investigated price-distance effects of a municipal solid waste-to-energy incinerator for different stages of the siting process from rumor to operation. While there were no property price effects prior to construction, adverse effects were found for the subsequent stages. During construction, an additional mile from the site raised residential property values by $2671. During initial on-line and operation phases the corresponding figures were $9497 and $7746, respectively. In addition, housing appreciation rates were 2 to 3.5 percent lower during these phases in the impacted community compared to non-impacted communities.

4.2 Discussion

Studies on the local externalities from fossil fuel power stations are (perhaps surprisingly) few in number; yet the pertinent papers differ in a variety of ways. While Blomqist (1974) focused on a single, small, mainly coal-fired plant in the 1970s, Davis (2011) studied openings of 92 large, mainly gas-fired plants in the 1990s. While these differences reduce direct comparability of the results, it is striking that both found sizable and similar house price impacts in the neighborhood of plants. As discussed by the author, the property price effect found in the Blomquist (1974) study is notable because the power plant studied burns relatively clean fuel compared to the average of all other steam-electric power plants. Similarly, the house price effects in the 1990s found by Davis (2011) are noteworthy because the deployment of catalysts and scrubbers as well as fuel switching from coal to gas in the 1990s contributed to a significant decrease in electricity-related air pollution in the U.S. compared to the 1970s. The existence of sizable house price effects in both papers thus suggests that local externalities from fossil fuel power plants in the U.S. are largely due to factors other than air pollution, such as visual and acoustic disamenities. In addition, there is evidence that house price effects include taste-based sorting, with neighborhoods near plants associated with modest but statistically significant decreases in mean household income (Davis 2011).

While air pollution and effects thereof may not figure prominently in those studies, indirect evidence of air pollution's role for power plant externalities can be found in Luechinger (2009). Though not specifically concerned with electricity externalities, that paper used the mandated installation of scrubbers at power plants in Germany together with wind directions in an instrumental-variable analysis of the impact of air pollution on subjective well-being. The validity of the instrument in establishing such an effect suggests the existence of directional well-being externalities from fossil fuel power plants through air pollution.

5. Nuclear Power Generation and Waste Disposal

5.1 Valuation Studies

The literature on preference for distance to nuclear power plants (NPPs) mainly comprises revealed preference (property value) studies, most of which refer to the United States. Nelson (1981) found a positive, but very small, distance effect on property prices with distance from the Three Mile Island NPP in Pennsylvania (prior to the accident at that plant in 1979), whereas

Gamble and Downing (1982) found no significant distance effect for NPPs along the East Coast. Clark and Nieves (1994) found that housing prices in regions with more NPPs (Middle Atlantic, South Atlantic, and Pacific) were lower than in other U.S. regions, which the authors attribute to anxiety over risk. By contrast, Clark et al. (1997) found that house prices in California were *higher* at greater proximity to NPPs, which they attribute to possible macro (income) impacts. Clark and Allison (1999) found a distance effect on property prices that weakened over time, possibly due to relocation, or to preference adaptation attenuating initial price decreases in the vicinity of the plants. Folland and Hough (2000) focused on agricultural land prices and showed that they were lower in counties with NPPs than in counties without them. For Japan, Yamane et al. (2011) found that land prices decreased in an area where the construction of an NPP was announced.

Few studies of NPP externalities exist that use methods other than hedonic pricing. Schneider and Zweifel (2013) report the results of a stated choice experiment conducted in Switzerland. The main result is that stated willingness to pay for increased insurance coverage against nuclear accidents decreases with distance from plant once attitudes influencing choice of residential location are controlled for. Welsch and Biermann (2016) applied the experienced preference method, also focusing on Switzerland. They investigated the relationship between Swiss citizens' life satisfaction and the distance of their place of residence from the nearest nuclear power plant and found a statistically and economically significant satisfaction-distance gradient. Its monetary equivalent amounts to CHF 291 (USD 305 as of 2015) annual income per km at mean income. The gradient is smaller for those who may feel protected by wind direction and topographical conditions, and it differs by age, sex, and the level of education.

Several other papers focused on nuclear waste sites and nuclear waste shipment routes, again mostly in the United States. Smolen (1991) found that the announcement of a proposed low level radioactive waste site created a positive and significant house price-distance gradient of roughly $4000 per mile, which became insignificant after the proposed site was cancelled.

Gawande and Jenkins-Smith (2001) found that being 5 miles away from a nuclear waste transportation route was associated with a 3 percent increase of average house value compared to property on the route. For Japan, Yamane et al. (2011) found that land prices fell in the neighborhood of a spent fuel reprocessing plant at the time of the pilot carry-in of spent fuels. Riddel et al. (2003) found in a stated choice experiment that perceived risk decreased with distance to a planned nuclear waste transportation route and that higher perceived risk resulted in a higher probability of moving away from the route.

A number of papers were concerned with effects of nuclear accidents, most notably the nuclear disasters at Chernobyl/Ukraine in 1986 and Fukushima/Japan in 2011, using revealed or experienced preference methods. Yamane et al. (2013) found that property values around the Fukushima-Daiichi plant decreased with increasing levels of local nuclear contamination, but not with proximity to the plant. Other papers studied property price changes in places remote from the Fukushima event. While Fink and Stratmann (2015) found no change of property prices in the vicinity of NPPs in the U.S., Bauer et al. (2013) found that house prices near NPPs in Germany dropped by up to 11 percent.

Nuclear accidents were also the subject of several experienced preference studies. Danzer and Danzer (2016) investigated the causal effect after 20 years of the Chernobyl disaster by linking geographic variation in radioactive fallout to several outcome variables according to individuals' place of residence at the time of the disaster. Excluding individuals who were exposed to high levels of radiation, they found that persons receiving subclinical radiation doses exhibit poorer SWB and higher depression rates. They estimated long-term annual welfare losses to amount to 2-6 percent of GDP.

With respect to the Fukushima accident, Ohtake and Yamada (2013) used Japanese data elicited after the disaster to explore the spatial and temporal well-being pattern after the disaster. They found that media reports of damage had a significant negative effect on SWB in districts affected by the disaster whereas effects in other places were initially insignificant but became significant with the accumulation of news over time.

Rehdanz et al. (2015) used panel data elicited in Japan before and after the Fukushima disaster to analyze the disaster's effect on people's SWB. They found no well-being variation with distance from the Fukushima-Daiichi plant before the disaster but a significant distance gradient after the disaster. For individuals living within 150 km from the power plant, there was a drop in well-being whose monetary equivalent amounts to 240 percent of average annual income. Effects directly related to the radiation level could not be established given that the period of analysis ended less than a year after the event and radiation-related impairments are of a more long-term nature (as was found in the case of Chernobyl by Danzer and Danzer 2016).[10] For Japanese nuclear power plants other than the Fukushima-Daiichi plant, a well-being variation with distance was found neither before nor after the disaster.

Several other papers studied possible well-being effects of nuclear accidents in places remote from the respective event. Such effects may have occurred due to media coverage and, if they exist, may reflect a reappraisal of nuclear risk. In such a vein, Berger (2010) and Goebel et al. (2013) studied the Chernobyl and Fukushima disasters, respectively. Both found an increase in environmental concern in Germany after the disasters, but no change in subjective well-being. Differentiating their analysis by distance from the nearest nuclear plant, Goebel et al. (2013) found that those results apply equally to individuals within a 50km radius from the nearest plant and individuals outside that radius.

Welsch and Biermann (2016) found that the satisfaction-distance relationship in Switzerland changed significantly after the Fukushima disaster. In particular, life satisfaction of individuals whose nearest nuclear plant was at an intermediate distance (40-85 km) dropped, which the authors take to indicate that, due to an information shock provided by the spatial

[10] Almond et al. (2009) found long-term effects on school outcomes in children exposed to radioactive fallout from the Chernobyl nuclear meltdown.

extent of the Fukushima event, individuals at places previously considered safe reassessed distance-dependent expectations of potential damage size. People more proximate did not seem to update their expectations, nor did people farther away.

5.2 Discussion

The existing literature predominantly finds evidence of negative spatial externalities from nuclear facilities. The externalities manifest themselves in higher property prices, lower willingness to pay for insurance, and higher subjective well-being in places more remote from nuclear power plants.[11] Property price effects refer not only to nuclear power plants but also to nuclear waste sites and nuclear shipment routes.

While most papers found property prices to be lower at greater proximity to NPPs, one study found the opposite (Clark et al 1997). The authors suggest that this may be due to the influx of workers for construction and operation of the plants. This ambiguity suggests that it is important to control for context factors in property value studies of NPP externalities, in order to disentangle the channels that influence property value effects.

The small literature on the variation of subjective well-being with distance from NPPs suggests that the distance gradient of well-being may depend on topographical and meteorological factors, as evidenced by the case of Switzerland. The latter case also suggests heterogeneity with respect to gender, age, and the level of education, that is, distance matters less for male, older and more highly educated individuals than for individuals with the opposite characteristics. In addition, cultural and psychological differences may play a role, as evidenced by the apparent lack of a general happiness-distance gradient in Japan.

[11] There are also a different kind of studies, event studies, that have looked at the impact of nuclear accidents on the stock prices of energy companies (Ferstl, et al. 2012, Kawashima and Takeda 2012, Betzer, et al. 2013, Basse Mama and Bassen 2013, Lopatta and Kaspereit 2014).

An important aspect of NPP externalities, as considered in most of the existing literature, is that they typically relate to latent risk (anxiety) rather than actual risk. The Fukushima nuclear meltdown provided some preliminary evidence of the role of actual risk, that is, the risk incorporated in radioactive fallout. As mentioned above, subjective well-being did not vary with differences in radioactivity levels (Rehdanz et al 2015) whereas property prices did (Yamane et al. 2013). These findings can be reconciled by observing that subjective well-being largely relies on past and current outcomes (experienced utility) whereas property prices capitalize expectations as to future outcomes (based on decision utility). Lower property prices in more contaminated places thus may reflect expectations as to future health impairments that do not (yet) affect current well-being. Future research may shed light on the long-term well-being consequences of the disaster-related release of radiation and on whether these consequences confirm or refute the expectations implicit in property prices.

6. Renewable Energies

6.1 Valuation Studies

Much of the existing research on externalities from renewable energies focuses on the newer technologies involving wind, solar and biomass, whereas the literature on established technologies such as hydropower is more limited. That literature found external costs of hydropower projects on the basis of their impact on landscapes, vegetation, wildlife and recreational opportunities (e.g. Navrud 2001) but those studies are typically not very explicit with respect to the spatial dimension. Hydropower externalities will therefore be discussed in section 7 in the context of the overall energy mix rather than with respect to local externalities.

Most studies of local RE externalities have been concerned with wind energy development, using various methods. A relatively small number of papers have analyzed the effect of wind turbines on property values, often finding negative effects. Using data from Germany, Sunak and Madlener (2016) found in a difference-in-differences framework that the value of properties whose view was strongly affected by wind turbines decreased by 9 to 14 percent, whereas properties with a minor or marginal view on turbines experienced no devaluation. Jensen et al. (2014) were able to differentiate the visual impact from the noise impact and found that the presence of wind turbines within 2.5 km reduced house prices in Denmark by up to 3 percent (visual impact) and 3-7 percent (noise impact) and that house price effects decreased with increasing distance. Heintzelman and Tuttle (2012) found that nearby wind facilities significantly reduced property values in two out of three counties in northern New York State, whereas in the U.S. overall, neither the view of a wind facility nor the distance of the home to such facilities had a statistically significant effect on sales prices (Hoen et al. 2011).

The bulk of the literature on externalities from wind power (both on- and offshore) used a stated preference methodology. Stated choice experiments typically establish the existence of negative externalities from wind turbines, resulting in a positive willingness to pay (WTP) of respondents for an increase in the distance to the nearest wind turbine (for overviews see Meyerhoff et al. 2010 and Knapp and Ladenburg 2015). However, existing studies usually rely on pre-defined spatial attributes of proposed wind energy projects, whereas analyses employing "an actual distance decay framework are almost non-existent" (Knapp and Ladenburg 2015). In contrast to the preference for distance, evidence concerning the preference for having few large wind farms in comparison to many small ones is inconclusive (Meyerhoff et al. 2010). With respect to the magnitude of wind power externalities, Drechsler et al. (2011) estimate in a choice experiment that external costs make up approximately 14 percent of the total investment costs.

In addition to revealed and stated preference studies, a small number of papers has used the experienced preference method to elicit individuals' valuation of RE externalities. Krekel and Zerrahn (2015) studied the relationship between German citizens' subjective well-being (measured as stated life satisfaction) and the presence of wind turbines in their vicinity and found well-being to be significantly lower in individuals who live within 4 km of distance from wind turbines. The monetary equivalent of the presence of one wind turbine amounts to up to 59 Euros per year. In addition, they found well-being effects to be transitory due to hedonic adaptation, vanishing after five years at the latest.

Von Möllendorff and Welsch (2017) also used German data on SWB and combined them with data on several types of renewable energies. With respect to wind turbines, they found statistically and economically significant local externalities. Quantitatively, the presence of at least one wind turbine in one's postcode district is associated with a reduction in 11-point life satisfaction by about 0.0346. In monetary terms, this corresponds to 11 percent of equivalized monthly income or 181.9 Euros. An increase in installed wind power capacity by 1 MW is equivalent to a 0.35 percent change in equivalized monthly income, which is about 5.8 Euros. Considering the average capacity of turbines in the sample, this translates into 6.2 Euros per turbine per month. Similar to Krekel and Zerrahn (2015) they find the well-being effects of wind turbines to be transitory, becoming insignificant in the second year after installation.

Studies on the local externalities from renewables other than wind power are much fewer in number. In particular, there seem to be neither revealed nor stated preference studies of local externalities from solar facilities and only one stated preference study on biomass.[12] In addition, there exists an experienced preference study on solar and biomass facilities.

Lipscomb (2011) measured the impact of a proposed biomass facility on prospective property values in the Midwestern United States using the contingent valuation method. The paper found no statistically significant difference in respondents' willingness to pay for a house when presented a scenario that (i) described the status quo of the study area and (ii) another that

[12] There are many stated preference studies eliciting the WTP for renewable energy in general, some of which provide a comparison of several technologies (e.g. Borchers et al. 2007 and Cicia et al. 2012). See section 7.

also mentioned a proposed biomass facility within one-half a mile, highlighting the stack height of the biomass plant (265 feet) as a major attribute.

Von Möllendorff and Welsch (2017) investigated the relationship between German citizens' subjective well-being (life satisfaction) and the presence of solar and biomass facilities in their neighborhood (along with the presence of wind turbines, see above). With respect to solar power, they found no significant well-being effects of solar panels in residents' own postcode districts, but significant negative effects from adjacent districts. The latter amount to 6.8 Euros per MW per month. As an explanation for the lack of effect in close vicinity (own postcode district), they refer to financial and moral benefits (warm glow) to local owners of solar panels, which may offset negative externalities.[13] In contrast to this, the presence of biomass plants negatively affects the life satisfaction of individuals in the same postcode district and in adjacent ones. In monetary terms, a 1 MW increase in installed biomass capacity in the own district and the adjacent districts is associated with a drop in life satisfaction corresponding to 20.5 Euros and 6.6 Euros per month, respectively. In contrast to wind power, the well-being externalities from biomass remain significant over time and do not decrease in magnitude.

6.2 Discussion

With the large-scale deployment of renewable energy facilities worldwide, a considerable literature has developed that analyzed renewable energy externalities. The bulk of that literature focused on wind power. With few exceptions (e.g. Hoen et al. 2011), it established the existence of local externalities from wind turbines that manifest themselves in property value impacts due to visual and noise nuisance and a willingness to pay for living at greater distance from wind turbines. However, the magnitude of wind power externalities seems to depend not only on distance but on topographical conditions and on the characteristics of wind

[13] Dastrup et al. (2012) established an effect of "green" social status on the price of houses with rooftop solar installations.

farms. In particular, whether wind farms with few large or with many small wind turbines are preferred seems to be site specific. In addition to property price effects and a willingness to pay for living at greater distance, wind power externalities were found to have a sizable impact on the subjective well-being of nearby residents. The papers on this issue agree, however, on the transitory character of well-being externalities from wind power.

In comparison with wind power, few studies exist that investigate externalities from other types of renewable energy. With respect to solar power, no significant well-being externalities were found at the level of postcode districts, possibly because at this level of aggregation negative externalities are mitigated by financial and moral benefits of local solar panel owners. Shedding more light on this issue would require differentiating between owners and non-owners and between rooftop and free-standing solar facilities.

With respect to biomass facilities, one case study that focused on visual aspects of a hypothetical facility found no impact on the stated willingness to pay for nearby property. In contrast to this, one study showed that the presence of biomass plants in people's neighborhood strongly affected their subjective well-being and that, different from wind power, the well-being effect of biomass facilities was non-transitory.

7. The Electricity Mix

The literature discussed up to this point has focused on local externalities, largely referring to single technologies. These studies are of relevance for the siting of electric facilities of a particular type in particular places but are less helpful when it comes to the overall electricity mix. Choices concerning the electricity mix should be based on a comparative and encompassing appraisal of the different technologies, accounting for both local and non-local external costs (along with private costs).

This section discusses the literature relevant to the electricity mix, distinguishing between (primary) studies that address several technologies and meta-analyses that synthesize results across several (single technology or multi-technology) studies.

7.1 Multi-Technology Studies

Stated preference studies of the willingness to pay (WTP) for several energy sources were conducted by Borchers et al. (2007) and Cicia et al. (2012). Borchers et al. (2007) report a choice experiment involving the expansion of several types of green electricity (wind, solar, farm methane, and biomass) in one county in Delaware, U.S.A. They found positive mean WTP for all sources, except for biomass in one of their treatments. Consistently across treatments, the ranking of WTP was: solar (most preferred), wind, farm methane, biomass (least preferred).

Cicia et al. (2012) report a choice experiment in Italy that involved not only three types of renewable energy (wind, solar, agricultural biomass), but also fossil fuel electricity and nuclear power. They found a positive WTP for replacing fossil fuel electricity by wind and solar power and a negative WTP for replacing it by nuclear power and electricity from biomass. Latent class analysis yielded some heterogeneity with respect to whether solar or wind power was most preferred and whether nuclear or biomass was least preferred.

Similar conclusions concerning the preference among several electricity technologies can be drawn from experienced preference studies. Welsch and Biermann (2014a) used survey data for almost 140,000 individuals in 25 European countries, 2002-2011, to measure the relationship between people's life satisfaction and the shares of various technologies in the national electricity mix. Their estimation results imply that solar and wind power as well as electricity from gas are preferred to nuclear power. Electricity from bio fuels is the least preferred type of electricity. Individuals are indifferent between gas and solar and wind power and between nuclear, coal, oil, and hydropower.

Focusing on nuclear power alone (vis à vis all other technologies), Welsch and Biermann (2014b) found in a similar set-up that European citizens' life satisfaction was unrelated to the nuclear share before the Fukushima disaster, but significantly negatively related to the nuclear share at the time after the disaster (12 March to 31 December 2011).

The preference for solar and wind over bio fuels derived from national production shares (Welsch and Biermann 2014a) is consistent with the finding that zonal well-being externalities from biomass facilities in Germany are far greater (by a factor of more than three) than those from wind and solar power (von Möllendorff and Welsch 2017). These findings suggest a considerable amount of nuisance from the large-scale growing of biomass (in particular maize) and the delivery of fuels to the plants that are absent in the case of solar and wind power.

7.2 Meta-Analyses

An approach to generating an encompassing assessment of electricity supply preferences from several sources consists of meta-analyses of existing primary studies. Such analyses aim at synthesizing the preferences elicited in individual studies (controlling for differences in context and methodology) and identifying those attributes of technologies that determine the overall preferences obtained.[14]

Meta-analyses have focused on the preference for hydropower (Mattmann 2016a), wind power (Mattmann et al. 2016b), preferences for renewables in general (Sundt and Rehdanz 2015), preferences for several types of renewables in comparison with each other (Ma et al. 2015), and preferences for several conventional and renewable technologies in comparison with each other (Sundquist 2004). Except for the latter article, they primarily refer to stated preference primary studies.

[14] The latter is achieved by including in the meta regressions dummy variables that indicate whether or not a particular attribute (such as, e.g., visual effect or noise) were tested in the respective primary studies.

Mattmann et al. (2016a) presented a meta-analysis of the valuation of already existing and hypothetical hydropower facilities in 14 countries using 89 observations from 29 studies, of which 24 used stated preference methods (9 choice experiments and 15 contingent valuation exercises) and 5 used the travel cost or hypothetical travel cost method. The studies focused on impacts of hydropower facilities on landscape, vegetation, wildlife, recreation, and aesthetics, but also featured avoided greenhouse gas emissions. The WTP for hydropower was positive in all cases and amounted to 171 USD on average. It was smaller for small (97 USD) than for medium-sized (203 USD) and large facilities (299 USD). The meta-regressions revealed a significant negative effect of deteriorations in landscape, vegetation, and wildlife on the WTP for hydropower, whereas the mitigation of recreation opportunities as well as the type of facility (run-of-river, pumped storage) did not significantly affect WTP.

Mattmann et al. (2016b) conducted a meta-analysis of the valuation of hypothetical wind power deployment programs. They used 52 observations from 32 stated-preference studies (34 choice experiments and 18 contingent valuation exercises) designed to elicit the WTP for expansions of wind power generation in 17 countries. The expansion scenarios focused on the visual, acoustic and biodiversity impacts of wind power, but also featured avoided air pollution and greenhouse gases, as well as reduced fuel dependence. The studies included aimed at an overall evaluation of wind power in comparison with the respective status quo. The WTP for wind power expansion was positive except in two cases, implying a general preference for wind power over the status quo. The mean WTP amounted to a 198 USD increase in the annual electricity bill. It was significantly greater for large expansions (284 USD) than for medium-sized (193 USD) and small expansion programs (116 USD) and greater for offshore projects (261 USD) than for onshore projects (148 USD), though the difference between offshore and onshore was not statistically significant due to large sample variance.

With respect to the determinants of the WTP for wind power, the effects on animals and the reduction in air pollution and greenhouse gases were found to be non-significant, whereas visual impairments were found to significantly reduce the WTP for wind power, the effect size amounting to about one half of the mean WTP. Noise effects and wind power's contribution to fuel independence could not be included in the meta-analysis because the number of pertinent studies was too small.

Sundt and Rehdanz (2015) report results from a meta-regression analysis of consumers' WTP for a larger share of renewable energy, not differentiated by type of technology, in their electricity mix. Their analysis is based on 18 contingent valuation and choice experiment studies referring to 10 countries and yielding 85 WTP values. The mean WTP in their sample amounts to 13.13 USD per household per month or 3.18 US cent per kWh. Mean WTP per kWh is significantly higher in Europe than in Asia and the Americas and significantly lower in countries that currently have a higher share of hydropower in their electricity mix.

Ma et al. (2015) conducted a meta-analysis of 29 contingent valuation and choice experiment studies referring to 14 countries and yielding 142 WTP observations. In their sample, the mean WTP for renewable energy, understood as a premium on current payments, amounted to 1.5 US cent per kWh. A particular feature of their analysis is the differentiation between several types of renewable energy, i.e., solar, wind, biomass, hydropower, and a generic "green" electricity that does not specify the particular energy source. The meta-regression analysis shows that consumers have significantly higher WTP for solar and wind power than for biomass and hydropower. Specifically, substitution of solar or wind power for biomass raises WTP by 0.67 cent and 0.52 cent, respectively, whereas no WTP difference exists between biomass and hydropower. No analysis of the particular externalities (or avoided externalities) that drive the preference for renewables was conducted.

Since the papers discussed so far established positive WTP (on average) for having more renewable energies in the electricity mix, they indicate a general preference for renewables over "conventional" energy sources. A more encompassing and differentiated perspective on this issue is provided by Sundquist (2004). His meta-analysis differentiates between coal, mineral oil, natural gas, nuclear power, hydropower, wind power, solar power, and electricity from biomass. His data set includes 132 observations from 38 externality studies conducted 1984 to 2004. A particular feature of the meta-analysis is that some of the primary studies considered investigated externalities at several stages of the fuel cycle. In addition, the primary studies applied a variety of methodologies, classified into the abatement cost approach, the top-down damage cost approach, and the bottom-up damage cost approach, whereas the meta-analyses described above refer to studies from the bottom-up category.[15] Focusing on the latter category, the external costs in the primary studies range from 0.001-0.80 US cent per kWh in the case of wind power to 0.11-72.42 US cent per kWh in the case of coal. Studies using the other two methodologies tend to yield higher estimates of electricity externalities.

The meta-regressions estimate the probability that a given energy source falls into a "low externality" (as opposed to "high externality") category. Controlling for the type of method and the inclusion/omission of the fuel cycle, the probability estimates imply the following preference ordering: solar (most preferred), wind, hydro, nuclear, biomass, gas, coal, oil (least preferred). While solar, wind and hydropower belong to the low externality category and coal and oil belong to the high externality category, the allocation of nuclear, biomass, and gas to the high/low externality categories is ambiguous (insignificant).

7.3 Discussion

Though applying a variety of methods, comparative assessments of externalities from several electricity technologies yield a number of insights that are highly consistent with each other. Stated preference studies of several types of renewable energy consistently find solar and

[15] The abatement cost approach uses the costs of controlling or mitigating damage as an implicit value for the damage avoided. This method is referred to as "regulatory revealed preference approach", on the presumption that regulators make optimal decisions, that is, they know the true abatement and damage functions. The top-down damage cost approach attributes estimated aggregate (national) damage costs to power plants, whereas the bottom-up damage cost approach relies on damage costs from individual sources.

wind power to be preferred over electricity from biomass. The same preference ordering can be derived from findings concerning the respective local well-being externalities. Similarly, a cross-country analysis of the relationship between subjective well-being and the national electricity mix also indicates a preference of solar and wind over biomass. With respect to renewables in comparison with several types of conventional electricity technologies, the latter study found an indifference between solar and wind power and gas-fired electricity production, all of which are preferred over hydropower, nuclear power and coal and oil based electricity, whereas electricity from biofuels is least preferred.

Meta-studies of the willingness to pay for renewables broadly confirm several of the above results. In the first place, they establish the existence of a positive willingness to pay for a greater production share of green electricity in general and wind power in particular. In addition, they yield a higher willingness to pay for solar and wind power than for electricity from biomass. The preference for solar and wind power over biomass also follows from a meta-analysis of studies encompassing all electricity technologies. In relation to non-renewable energy sources, that meta-analysis found solar, wind and hydro power to have the lowest level of externalities and electricity from coal and oil to have the highest, whereas biomass, nuclear, and gas take an intermediate position.

Though the bulk of stated preference analyses suggests a preference for renewable energy over conventional electricity technologies, a frequently voiced criticism refers to the hypothetical nature of the underlying scenarios and respondents' lack of familiarity with the choices to be made. In addition, respondents may consider a positive attitude towards renewables to be socially desired. In view of these criticisms it is reassuring that the experienced preference approach, to which these objections do not apply, yields very similar results concerning renewables, at least with respect to solar and wind power.[16]

[16] It should be noted that experienced preference studies rely on statements of subjective well-being elicited without any reference to electricity supply. Preferences are inferred from the

While solar and wind power are preferred over conventional electricity generation, the literature is less clear with respect to different types of conventional electricity, in particular nuclear power in comparison with coal-based electricity. While people have a taste for clean and safe energy (solar and wind), it is not clear what they value more, greater cleanness with respect to greenhouse gases and air pollution (nuclear power) or greater (perceived) safety with respect to accidents and spent nuclear fuels (coal).

8. Discussion and Conclusion

While early literature on electricity externalities was largely concerned with fossil fuel power generation and the associated air pollution, large-scale nuclear accidents (Chernobyl, Fukushima) and local resistance to the deployment of renewable energy facilities have spurred a wave of research on the externalities of nuclear power and renewable energies. This paper has reviewed the literature on externalities from electricity generation.

Appraisals of electricity-related externalities are complicated because of heterogeneity of both the externalities themselves and the methods applied in measuring them. With respect to the nature of externalities, nuclear power and renewable energies differ from fossil fuel electricity in that they are far less intensive in health-relevant air pollution. Instead, they involve externalities of a different kind. Externalities from nuclear power refer to the latent risk of nuclear accidents and the uncertainties surrounding the disposal of spent fuels, and those risks affect individuals through perceptions rather than statistical probabilities. Externalities from renewable energies mainly refer to local disamenities in terms of visual and acoustic impairments.

With respect to measurement, the literature reviewed has used property value, willingness to pay, and subjective well-being methods of preference elicitation (likewise

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purely statistical association between well-being and external circumstances, such as the characteristics of (local or national) electricity supply.

referred to as revealed preference, stated preference, and experienced preference methods). These methods may capture different aspects of externalities in different ways. In particular, property value and willingness to pay studies capture the *expected* utility consequences of (actual or hypothetical) outcomes whereas the subjective well-being method captures the *actual* (experienced) utility consequences. Both types of approach have potential drawbacks: Reliance on expected utility may fail to incorporate habituation to outcomes (the presence of wind turbines, say), whereas actual utility (current well-being) may inadequately respond to long-term effects (of radioactive fallout, say).

While early literature considered non-local air pollution as the main externality from fossil fuel electricity, recent property value literature has indicated a role for local externalities not only from nuclear and renewable energy facilities but also from fossil fuel power stations. This begs the question as to the relative effect size of local externalities from different technologies. Studies that permit such a comparison of fossil fuel, nuclear and renewable energy facilities seem to be non-existing. Within the category of renewable energies, however, there is clear indication that biomass facilities lead to far greater (well-being) externalities than do solar and wind power facilities. Moreover, dynamic well-being analysis suggests that, due to habituation, externalities from wind turbines quickly fade off over time in contrast to those from biomass facilities.

A major implication of local electricity externalities consists of siting conflicts. Given their rapid deployment worldwide, this concerns especially the renewable energies. Decisions on the siting of renewable energy plants depend on regional attributes (e.g. wind speed) and legal restrictions (e.g. minimum distances to residential areas), but also face issues of public acceptance in the affected locales. While standard economics would suggest that compensation payments raise the willingness to accept energy facilities in one's neighborhood, political science identified an important role for non-economic factors such as fairness considerations, the availability of information, participation options and trust in the operator.[17] In addition, it is up for debate whether compensation payments may not crowd-out individuals' intrinsic motivation to act in the public interest.[18]

Notwithstanding such considerations, basic welfare economics suggests that siting decisions should account not only for site-specific private costs of alternative technologies, but also for the external costs involved. The literature reviewed above has assembled considerable knowledge on the local external costs of several electricity generation technologies. Future work may strive to extend that knowledge in particular with respect to the dynamics of those externalities, on which the evidence is relatively scarce. Synthesizing the existing knowledge towards a comparative appraisal of several technologies is another obvious direction of future work.

While synthesizing analyses of local electricity externalities are lacking, several such assessments of the electricity mix were recently published. As discussed above, they come to results that are fairly consistent across several methodologies, notably that (notwithstanding siting issues) solar and wind power tend to be preferred over fossil fuel and nuclear power. There are, however, indications of preference heterogeneity between subgroups of the population (by gender, age, and the level of education) as well as between nations (e.g. Germany vs. Japan). Further exploring such heterogeneity is another issue to be studied in future research.

While most of the literature reviewed is concerned with externalities from the presence and normal operation of electricity facilities, a small number of papers addressed the externalities from an electricity-related disaster, the nuclear accident at Fukushima, Japan. Assessment of those externalities is complicated because the disaster consisted of the combination of an earthquake, tsunami and nuclear meltdown, whose effects are difficult to

[17] For reviews see Wüstenhagen et al. (2007) and Batel et al. (2013).

[18] Frey and Oberholzer-Gee (1997) found motivation crowding-out in the case of a hypothetical nuclear waste repository in Switzerland.

disentangle. Moreover, some of the impacts, namely those from radiation, may become effective only in the medium and long term. Consistent with this circumstance, no effect of radiation on subjective well-being within one year from the event could be established (n contrast to other dimensions of the combined disaster). In contrast to this, property prices in heavily contaminated places dropped. Reasons for these diverging results are unclear. A possible hypothesis might be that property prices capitalize future effects, whereas subjective well-being does not (or to a smaller extent). Following up on this issue, by tracing the dynamics of both property prices and well-being, may be interesting from both a substantive and a methodological point of view.

The dynamics of externalities from both the opening and operation of electric facilities as well as from related accidents is an issue that poses no generic conceptual or methodological problems. A different and potentially more challenging issue stems from the fact that electricity generation creates not only intra-generational but also inter-generational externalities, such as those related to climate change and nuclear waste disposal. Analysis of the willingness to pay for wind power showed that it is not significantly influenced by concerns over greenhouse gases. A more general and systematic analysis of whether effects on future generations affect present people’s utility (via inter-generational altruism) appears to be lacking.

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