Valuing Air Quality Using the Life Satisfaction Approach

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Abstract

We use the life satisfaction approach to value air quality, combining individual-level panel and high-resolution SO_2 data. To avoid simultaneity problems, we construct a novel instrument exploiting the natural experiment created by the mandated scrubber installation at power plants, with wind directions dividing counties into treatment and control groups. We find a negative effect of pollution on well-being that is larger for instrumental variable than conventional estimates, robust to the inclusion of local unemployment and particulate pollution, and larger for environmentalists and predicted risk groups. To calculate total willingness-to-pay for clean air, the estimates are supplemented by hedonic housing regressions. (100 words)

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> *As soon as I escaped from the oppressive atmosphere of the city, and from the stink of the smoky chimneys, which, being stirred, pour forth, along with a cloud of ashes, all the poisonous fumes they've accumulated in their interiors, I perceived at once change in my feelings.*
>
> Seneca, epistle CIV

1. Introduction

The introductory quote by Seneca demonstrates that urban air pollution was already a menace in first century Rome. Yet it was the twentieth century that witnessed both, the worst air quality and massive improvements. Air pollution could be literally seen and felt, causing the first manmade climate change (a drop in temperature caused by sulfur particles bouncing back sunlight), occasionally forcing motorists to turn headlights on or leave their cars because of impaired visibility, damaging historic buildings (e.g. Time Magazine 1967; Economist 2006), and, most importantly, increasing morbidity and mortality (see references below). In response, many countries enacted air quality regulations such as the Clean Air Act in the U.S. Characterized by some scholars as the most significant laws aimed at advancing environmental quality, safety and health (Portney 1990), these regulations brought about considerable improvements in air quality. However, not in all countries and not for all pollutants the situation looks bright. This raises the questions of how important air quality is for the affected population and, consequently, about realized and potential benefits of air quality regulations.

Traditionally, the benefits of clean air have been assessed with the hedonic method (see Smith, V. K. and Huang 1995 for a meta-analysis). The hedonic method can be applied if the public good is weakly complementary to private goods such as housing and jobs. In this situation, information on public good demand is embedded in the prices and consumption levels of the private goods. However, the hedonic method is afflicted by two well-known problems: First, if migration is costly, the benefits of clean air are only incompletely capitalized in house prices and wages. Second, individuals' behavior in private markets is governed by perceived rather than objective risk. To the extent that they are ignorant about (health) effects of exposure to air pollution, these effects are not reflected in private markets. Moreover, both reasons for incomplete capitalization can be simultaneously present. Research suggests that hedonic estimates indeed substantially underestimate the benefits of clean air (e.g. Smith, V. K. and Huang 1995; Bayer, Keohane and Timmins 2006; for a discussion see section 4).

We use the life satisfaction approach to assess the costs of air pollution for the exposed population. The life satisfaction approach builds on the recent development of happiness research in economics (for surveys see Frey and Stutzer 2002; Easterlin 2005; Clark, Frijters and Shields 2006; Di Tella and MacCulloch 2006; Helliwell 2006; Layard 2006). With the life satisfaction approach, life satisfaction is regressed on the public good of interest, income and other covariates. Using the coefficients for the public good and income, it is possible to calculate utility constant trade-off ratios between the public good and income for marginal and inframarginal changes in the public good provision. The life satisfaction approach captures the residual effect of air pollution for which people are not already compensated in the housing market. If all effects of air pollution are correctly perceived and the equilibrium condition holds, air pollution should not be systematically related to life satisfaction. Thus, the life satisfaction approach also allows to directly test the fundamental assumptions of the hedonic method and to assess the importance of deviations from these assumptions (see appendix A.1. for a discussion of what effects can be identified by the hedonic method and the life satisfaction approach). This approach has been used to value (the residual effects of) climate (Frijters and Van Praag 1998; Rehdanz and Maddison 2005), urban air pollution (Welsch 2002; 2006) and sulfur emissions (Di Tella and MacCulloch 2005), airport noise nuisance (Van Praag and Baarsma 2005), political violence and terrorism (Frey, Luechinger and Stutzer 2004), and flood hazards (Luechinger and Raschky 2007). On a conceptual level, the life satisfaction approach is compared to the standard non-market valuation techniques in Frey, Luechinger and Stutzer (2004), Kahneman and Sugden (2005), and Dolan and Peasgood (2006).

This paper has two major objectives. First, we estimate the effect of SO_2 concentration on life satisfaction and housing rents using high-resolution pollution data and a large panel survey (stretching over 19 years) for Germany, a country with a large variation in pollution, both across space and over time. Second, using the results of the hedonic housing regression and the life satisfaction regressions, we calculate the total willingness-to-pay (*WTP*) for improvements in air quality as the sum of the estimates based on the two different methods. A comparison of the estimates based on the two different methods also reveals what part of the total effect is capitalized in private markets.

Estimating the effect of SO_2 concentration on life satisfaction and housing rents is associated with potentially serious simultaneity problems (Chay and Greenstone 2005; Bayer, Keohane and Timmins 2006). While technical progress and air quality regulations are important reasons for improvements in air quality, local economic downturns and declining industrial production are other likely candidates. These simultaneous and spatially coincident developments have a countervailing effect on life satisfaction and rents. To avoid this potential source of bias, we use the estimated improvement in air quality caused by the mandated installation of scrubbers at power plants as a novel instrument for air pollution. We estimate the effect of scrubbers with a difference-in-difference analysis. The retrofitting of power plants constitutes the treatment and the geography of plants and prevailing wind direction divide locations into treatment and control groups.

The most important finding is that SO_2 concentration negatively affects life satisfaction. This indicates that the effects of SO_2 are incompletely capitalized in private markets. The magnitude of the effect of SO_2 is larger for the instrumental variable estimates compared to the conventional estimates. This difference suggests that improved air quality is indeed accompanied by factors with a countervailing effect on life satisfaction. The effect of SO_2 concentration is robust to the inclusion of the local unemployment rate and particulates concentration. Further, the effect is increasing in the degree to which individuals are concerned about the environment and in the degree they are predicted to suffer adverse health consequences from pollution exposure. The effect of pollution on life satisfaction translates into considerable implicit *WTP*. The marginal *WTP* (*MWTP*) for a reduction of SO_2 concentration by 1 $\mu g/m^3$ is in the range between € 195 and € 458 annually. In our hedonic housing regressions as well, we find a negative effect of SO_2 concentration on rents. The *MWTP* estimates are between € 10 and € 38 annually. Total *MWTP* estimates range from € 230 to € 496 annually. Thus the estimates based on the life satisfaction approach are larger than the estimates based on the hedonic method and only a small proportion of the overall effects of air pollution seems to be capitalized in the housing market.

In contrast to previous papers on the relationship between life satisfaction and pollution, the current setting allows to deal with critical empirical challenges of the life satisfaction approach. While the earlier papers provide suggestive evidence, the estimates are afflicted with serious problems associated with the structure of the data (cross-section) and/or the unit of analysis (country level). Differences in air pollution reflect either different natural or economic conditions or different policy choices. A failure to control for the differences in conditions may bias the estimates in either direction. The notion of choice implies that a failure to include all dimensions of the relevant trade-off biases the estimates downwards. Improvements in air quality often come at costs, which are difficult hold constant (such as inconveniencies in daily life); if these costs cannot be controlled for, only the net benefit of clean air can be recovered. Of course, the problem of omitted variables is particularly severe in cross-section analyses (Welsch 2002). In repeated cross-sections, time invariant factors can be captured by country fixed effects (Di Tella and MacCulloch 2005; Welsch 2006). However, the change in pollution itself indicates that either the conditions or policies have changed as well. By focusing on one country, we can avoid these problems. From the point of view of individual regions, the installation of scrubbers at large power plants (the single most important reason for the improvement in air quality) amounts to a natural experiment. Although the statutory provisions are the result of a choice at the national level, they disproportionately benefit downwind regions compared to upwind regions.[1] A further problem of the earlier papers is that there is a huge variation in the air quality within countries. Therefore, country level data are a very imprecise measure of individuals' exposure to air pollution. In addition, the pollution variable in Di Tella and MacCulloch (2005) is SO_2 emissions. However, at the country level, emissions and pollution concentration are only weakly correlated. For example, only 14% of the Danish sulfur emissions remain in Denmark. For larger countries the fraction is higher, but it is below 50% for all European countries (Eliassen and Saltbones 1983). All these problems can be interpreted as measurement errors which bias the pollution coefficient towards zero. By focusing on one country and by using high-resolution pollution data, we minimize these measurement errors. Further, by using panel data at the individual level, we can control for individual heterogeneity.

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[1] It is worth noting that the costs of the regulation such as increased electricity prices and secondary benefits such as jobs created in the environmental industry are equally spatially distributed (or at least orthogonal to wind directions). Further, the statutory provisions were enacted before the period considered. Therefore, the actual installation of scrubbers does not reflect a shift in political power from upwind to downwind regions.

The remainder of the paper is organized as follows. In section 2, we introduce the pollution data and our strategy to instrument SO_2 concentration. Section 3 presents the panel data and the empirical strategy, the life satisfaction regressions along with various robustness tests as well as our hedonic housing regressions. In section 4, we monetize the effect of air pollution and calculate utility constant trade-offs for marginal and inframarginal changes in air quality. Further, we calculate the total *WTP* with the results of the hedonic housing regressions and compare the results based on the two different methods. Section 5 concludes.

2. Pollution: Data, evolution and instrument

We concentrate on SO_2 pollution for three reasons. First, for a long time, SO_2 was one of the major pollutants in industrialized countries and the primary focus of many regulations. Second, the main emitters of SO_2 are large stationary sources. Taken together, these characteristics give rise to a large variation in SO_2 concentrations, both, across regions and across time. Third, SO_2 contributes to the formation of acid rain, impairs visibility and, most importantly, causes adverse health effects. Consequences of SO_2 exposure found in controlled laboratory studies are bronchoconstriction, decrements in respiratory functions, mucus secretion, alterations in pulmonary defenses and airway inflammation with consequent coughing, wheezing, shortness of breath and chest tightness (Sheppard et al. 1980; Sandstrom et al. 1989; Smith, E. G., Haines and Stone 1994). According to epidemiological studies, high SO_2 concentrations result in increased morbidity and premature mortality due to cardiovascular and respiratory diseases (Schwartz, J. and Dockery 1992; Wong et al. 1999).

The *Umweltbundesamt* (German federal environmental agency; hereafter UBA for short) provides data on the annual mean SO_2 concentration measured at the monitors belonging to the monitoring networks of the 16 *Landesumweltämter* (state environmental agencies) and the UBA for the years 1985 to 2003. We have SO_2 data from 553 monitors or, in individual years, between 196 monitors in 1985 and 416 monitors in 1994. Panel A in Figure 1 depicts the location of the monitors used for 1985. In order to estimate the SO_2 concentration at all other locations, we use GIS to interpolate the monitor readings on a grid with cell size of 1 km^2 covering the whole area of Germany. We estimate the value of cell i of the grid as the weighted average over the readings at the 9 nearest monitors j using the inverse cubed distance

(D_{ij}^{-3}) as weights (method of inverse distance weighting). Specifically, grid values are estimated according to equation 1:

$$(1) \qquad grid\ value_i = \sum_{j=1}^{9} monitor\ reading_j \cdot D_{ij}^{-3} \Big/ \sum_{j=1}^{9} D_{ij}^{-3} .$$

The parameters have been suggested by the UBA, but interpolated values are similar for slightly different parameters. The interpolated mean SO_2 concentration for 1985 is shown in panel B of Figure 1. In order to match the pollution data with the survey data, we aggregate the interpolated values on the level of German *Kreise* and *kreisfreie Städte* (roughly corresponding to U.S. counties); annual mean SO_2 concentrations are estimated using polygon data describing the boundaries of these administrative units.[2] The mean SO_2 concentration per county is depicted in panel C of Figure 1 for the year 1985 and in panel A of Figure 3 for the years 1985, 1990, 1995 and 2000.

[Figure 1 about here]

The pattern and evolution of SO_2 pollution reveals two striking features. First, in the mid-1980s, pollution was highly concentrated at three hotspots. The three hotspots are the Ruhrgebiet in the west, Nordhessen in the centre and the area around Leipzig in the east, by then all important industrial centers and coal mining areas. Second, air quality improved dramatically between 1985 and 1990 in the FRG and after 1990 in the former GDR. In large part, these improvements reflect the effect of air quality regulations. As a result of an amendment to the *Grossfeuerungsanlagenverordnung* (large combustion plant ordinance) enacted in 1983, fossil fuel fired power plants had to be retrofitted with flue gas desulfurization, switch to low sulfur fuel or were subjected to early closure. Time limits were in the range between three and nine years from 1986 on and differed according to the capacity of a power plant and its actual emissions. With the *Einigungsvertrag* (unification treaty) signed in 1990, power plants in the former GDR were subjected to the same regulations. However, the pattern and evolution of SO_2 pollution also points at the potential simultaneity of local economic activity and pollution. Since 1980, the Ruhrgebiet undergoes structural change.

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[2] In 1994, population per county was between 31,800 in Klingenthal and 2,170,000 in West Berlin with a median of 131,400. Following reunification, several counties in the former GDR were merged. Therefore, the number of counties fell from 543 in 1993 to 439 in 2001. The polygon data used for aggregation describe the boundaries of the 445 counties existing in 1996.

New jobs in the service sector compensate only partially for job losses in the industrial sector. Similarly, the area around Leipzig is still recovering from the collapse of industrial production after reunifications.

Failure to control for this simultaneity would bias the pollution coefficients in the life satisfaction and hedonic rent regression towards zero or may even lead to perverse results. To address this potential source of bias, we develop a novel instrument that exploits the facts that SO_2 is primarily emitted by large stationary sources and that regulations required retrofitting of power plants, coupled with information on the geography of power plants and wind directions.

We use the changes in SO_2 concentration caused by the large combustion plant ordinance and the consequent retrofitting of power plants as an instrument for SO_2 pollution. The changes in SO_2 concentration are estimated using a kind of difference-in-difference analysis. Thereby, desulfurization at power plants constitutes the treatment and counties are assigned to control and treatment groups according to prevailing wind directions at power plants. The improvement in air quality caused by flue gas desulfurization is estimated as the difference in the pre- and post-desulfurization difference in pollution concentrations between upwind and downwind counties or, alternatively, as the pre- and post-desulfurization difference in the difference between upwind and downwind concentrations. The identifying assumption in later stages of the analysis is that there exists no systematic difference in the effect of retrofitting of power plants on reported life satisfaction and rents between upwind and downwind counties *except* through the effect on pollution.

The actual analysis departs from this idealized difference-in-difference setting in two respects. First, as we consider simultaneously all power plants and all counties, the treatment is a weighted average of desulfurization at all plants with pre-desulfurization emissions of the plants and a function of the distance between particular plants and counties as weights. Second, counties are not either in the control group or the treatment group. Depending on the frequency distribution of wind directions, they lie more or less often upwind or downwind of a power plant. In what follows, we explain more precisely the construction of the instrument. For details about data and data sources, we refer to the appendix A.2.

A key role in our analysis play estimates of annual SO_2 emissions (before desulfurization) for the largest power plants, information on when plants installed scrubbers, wind directions at the plants as well as direction and distance vectors between counties and plants. For 303 fossil fuel fired generating units, i.e. all units active between 1985 and 2003 with an electricity capacity of 100 MW and more, we have information on the launching year, the refit (desulfurization) year, the year the unit was shut down, capacity, fuel and fuel efficiency. The data are from the UBA, information published by the operating companies and the technical literature, a survey mailed to operating companies and statutory provisions. We georeference power plants using a route planer. The locations of the power plants are depicted in panel A of Figure 2. With emission factors published in the literature and the plants characteristics, annual SO_2 emissions can be estimated. Frequencies of wind directions in 12 30-degree sectors measured at 43 wind stations describe the wind situation at the power plants. From an originally larger sample of wind stations, we use for each plant the closest wind station. The stations are shown in panel B of Figure 2. The predominant wind direction is west-southwest. At all power plants, some wind directions clearly prevail, thus distinguishing counties into windward and leeward counties. In order to relate the data at the plant level with the pollution data at the county level, we calculate the Euclidean distance and direction between every power plant and every county.

[Figure 2 about here]

We can use these data to explain SO_2 concentrations at the county level and calculate fitted values and counterfactual pollution levels of a hypothetical situation without retrofitting of power plants. The difference between the counterfactual and the fitted values measures the improvement in air quality caused by the installation of scrubbers at power plants. The difference is our instrument for SO_2 pollution in later stages of the analysis.

The SO_2 concentration in county c at time t, P_{ct}, can be explained by the product of a dummy variable indicating whether power plant j is active at time t, $1(active)_{jt}$, estimated annual emissions at plant j before desulfurization, E_j, the average separation efficiency of scrubber that is to be estimated, β_2, a dummy variable indicating whether plant j has a scrubber installed at time t, $1(scrubber)_{jt}$, a distance decay function, $f(D_{cj})$, and the frequency the county c lies downwind of plant j, $g(R_{cj})$, summed over all power plants as well as county and time specific fixed effects, χ_c and τ_t, respectively. Equations 2a and 2b summarize the specification:

$$\text{(2a)} \quad P_{ct} = \beta_0 + \beta_1 \sum_j 1(active)_{jt} \cdot E_j \cdot (1 - \beta_2 \cdot 1(scrubber)_{jt}) \cdot f(D_{cj}) \cdot g(R_{cj}) + \chi_c + \tau_t + \varepsilon_{ct},$$

or,

$$\text{(2b)} \quad P_{ct} = \beta_0 + \beta_1 \sum_j 1(active)_{jt} \cdot E_j \cdot f(D_{cj}) \cdot g(R_{cj})$$

$$- \beta_1 \beta_2 \sum_j 1(active)_{jt} \cdot E_j \cdot 1(scrubber)_{jt} \cdot f(D_{cj}) \cdot g(R_{cj}) + \chi_c + \tau_t + \varepsilon_{ct}$$

In equation 2b, the second term on the right hand side denotes the sum of uncleaned SO_2 emissions, i.e. emissions before flue gas desulfurization, from all power plants weighted by a distance decay function and the frequency distribution of wind directions (hereafter 'weighted sum of uncleaned SO_2 emissions' for short), the third term denotes the sum of retained SO_2 emissions. We use two different functions to model the distance decay. In a first and simple variant, the emissions of all power plants within a distance of 450 km get a weight of one, all other emissions get zero weight; 450 km lies in the range of mean transport distances documented in the literature. In a second variant, the distance decay is modeled as an exponential curve with an implied characteristic distance decay distance of 480 km, $f(D_{cj}) = e^{-2.1E\text{-}6 \cdot D_{cj}}$, as suggested by field studies (Schwartz, S. E. 1989; Summers and Fricke 1989). Table 1 presents the results, column I the results for the first distance decay function, column II for the second.

[Table 1 about here]

As expected, the sum of uncleaned SO_2 emissions at power plants increases, and the sum of retained emission decreases, measured air pollution. Using the coefficient for the uncleaned and the retained emissions, we estimate separation efficiencies of 116% and 69%, respectively; standard errors are estimated using the delta method. In a first plausibility test of the results, actual separation efficiencies serve as a benchmark. Statutory provisions in Germany require a separation efficiency of 60% at the smallest units and more efficient scrubbers at larger units; separation efficiency at the largest power plants lies typically in the range of 90% to 99%. While the separation efficiency estimated with the first model is not statistically significantly different from actual values, the separation efficiency estimated with the second model is marginally below actual values. Second, a visual comparison of the actual pollution levels (P_{ct}) and the fitted values ($\hat{P}_{ct}$) based on the first model for the four years shown in panels A and B of Figure 3 as well as the R^2 reveal a satisfactory goodness-of-fit. We are now in a position to estimate counterfactual pollution levels for a hypothetical situation without installation of scrubber at power plants ($\widetilde{P}_{ct}$) and the difference between the counterfactual and predicted pollution levels ($\tilde{P}_{ct} - \hat{P}_{ct}$). This difference is an estimate of the causal effect of flue gas desulfurization and is our instrument for SO_2 pollution. The counterfactual pollution levels and the instrument based on the first model are shown in panel C and D of Figure 3.

[Figure 3 about here]

3. Effects of pollution on life satisfaction and rental prices

3.1 Data

In order to examine the impact of air pollution on life satisfaction and housing rents, we use the German Socio-Economic Panel (GSOEP) containing information on both, individual life satisfaction and rents. The GSOEP is a nationally representative panel that closely follows a large number of households and individuals since 1984. Following the fall of the Berlin wall, the panel was extended to include residents of the former GDR. The baseline life satisfaction regressions are based on a panel for the period 1985-2003 consisting of 33,864 individuals who remain on average for 6.7 years in the panel. Household identifiers and information on moving dates of households allow to build a panel at the dwelling level. The hedonic housing regressions are based on a panel for the period 1985-2003 consisting of 17,291 housing units with an average length in the panel of 3.7 years.

We relate the survey data to the pollution data described in the previous section at the county level. In post-reunification years, county mergers in East Germany reduced the number of counties from 543 in 1993 to 439 in 2001. As our polygon data describe the boundaries of the 445 existing counties in 1996, we assign the same SO_2 concentration to several counties in earlier years and calculate area-weighted averages for later years.

3.2 Effects on life satisfaction

3.2.1 Empirical strategy and explanatory variables

The basic idea of the life satisfaction approach is to estimate a trade-off ratio between the public good and income by regressing reported life satisfaction on the public good, income and other covariates. The main variables of interest are, therefore, individual life satisfaction, a measure of the public good, in this case air pollution, and income. The GSOEP elicits individual life satisfaction with the following question: “How satisfied are you at present with your life, all things considered?” The responses run from 0 (completely dissatisfied) to 10 (completely satisfied). The mean reported life satisfaction in our sample is 7.07 (std. dev. 1.75).

Apart from the pollution data, another important explanatory variable is post-government household income as a measure of disposable income. Its coefficient is later used for monetization. The variable is the sum of total household income from labor earnings (including bonuses etc.), asset flows, private retirement income, public and private transfers and social security pensions minus total household taxes. Except estimates of tax burden, which are based on tax calculation routines, all other components are actually received incomes as declared in the survey of the subsequent year. Thus, income information for households exiting the panel in the following year is not available. Further, the information is missing for East Germany in the year 1990.

Estimating the effect of income on life satisfaction is afflicted with serious endogeneity and omitted variables problems. Happy people earn more and time-varying factors may lead to both greater satisfaction and higher income (e.g. Clark, Frijters and Shields 2006; Gardner and Oswald 2006). A related problem is that costs of income generation such as working hours, stress, health risks etc. are inherently difficult to control for. Omission of such factors induces downward biased estimates. To address these problems, we instrument income with a predictor of household income and with job tenure of the main income earner, or if the respondent is the main income earner, job tenure of the secondary income earner. Our predictor of household income is similar in spirit to the one used by Luttmer (2005). We predict labor earnings for around 5,000 *industry · occupation* cells by regressing log labor earnings on a full set of industry and occupation dummies, for each year, and for West and

East Germany, separately.[3] The exponential of the fitted values of these regressions are the predicted earnings for individuals in each *industry · occupation* in a particular region and year. Summing over all household members, we get a prediction of household income. Therefore, increases in predicted household income reflect industry and/or occupation wide factors but not exceptional personal efforts by one of the household members.

Based on theoretical considerations and convention, we include household income in its natural logarithm (see Layard, Mayaraz and Nickell 2006 for a study on the functional form between income and life satisfaction) and control for the square root of household size in order to capture the effect of household size on equivalence income.

Following the previous literature, we include the most commonly used observable *time-varying* predictors of life satisfaction (Frijters, Haisken-DeNew and Shields 2004; Stutzer and Frey 2004; Ferrer-i-Carbonell 2005). These are age (or rather age squared), disability status, marital and partnership status, labor force status, occupational position, type of employment contract and city or district size. We add own job tenure and average weekly working hours to this list because our instruments for household income might only be valid conditional on these two variables. For example, in bargaining collective work agreements, unions may accept industry wide income reductions in return for a shorter work week thereby reducing both, income and effort cost. Dummies for individuals participating in the survey for the first and second time, respectively, serve as a proxy for interviewing experience and panel learning effects (D'Ambrosio and Frick 2004). In order to control for the secular upward trend in life satisfaction in post-reunification years in East Germany documented by Frijters, Haisken-DeNew and Shields (2004), we include state specific time trends along with a full set of state and year fixed effects.[4] Finally, a fixed effect model is appropriate as fixed personality traits are important predictors of life satisfaction (Ferrer-i-Carbonell and Frijters 2004). The equation to be estimated in the second stage thus is

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[3] We exclude self-employed people both in predicting household income and in the life satisfaction regressions because self-employed people are more reluctant to state their income and tend to underreport their incomes (e.g. Joulfaian and Rider 1998 for the U.S.).

[4] Due to German data protection laws, we are not allowed to have the regional data on our local computer but are obliged to use the remote access to the GSOEP, SOEPremote. Because of memory restrictions at the DIW, the host of SOEPremote, we cannot estimate models with county specific effects. However, we observe only around 10% of respondents in more than one county. If we restrict our sample to the individuals that do not move across county boundaries, the results are very similar. For all individuals who remain within the county boundaries, county specific effects are captured by the individual specific fixed effects. Therefore, the results are not driven by unobserved county characteristics. The results are available upon request from the authors.

$$LS_{icst} = \beta_0 + \beta_1 P_{cst} + \beta_2 \ln(m_{icst}) + \beta_3 Z_{icst} + \beta_4 trend_s + \sigma_s + \tau_t + \iota_i + \varepsilon_{icst}, \tag{3}$$

where LS_{icst} is the life satisfaction of respondent i living in county c in state s at time t, P_{cst} pollution at county level, m_{icst} respondent's household income, Z_{icst} a vector of personal characteristics, $trend_s$ state specific time trends, σ_s, τ_t and ι_i state, year and individual fixed effects, respectively, and ε_{icst} an error term. Generally, we estimate equation 3 by instrumental variables, using the estimated effect of flue gas desulfurization as an instrument for SO_2 pollution and job tenure of the main or secondary income earner and the predictor of household income as instruments for income. Robust standard errors are adjusted for clustering on county and year level.

Although scores of life satisfaction are reported on an ordinal scale, we treat them cardinally. However, assuming ordinality or cardinality of life satisfaction scores makes little difference (Ferrer-i-Carbonell and Frijters 2004). In earlier studies, compensating surpluses estimated on the basis of OLS and ordered probit models differ by less than 3% on average (Frey, Luechinger and Stutzer 2004; Luechinger and Raschky 2006).

3.2.2 Basic results

Table 2 reports the basic life satisfaction regressions in full with the results for all control variables. The effects of the control variables contain no surprises and correspond to results documented in the literature (Frijters, Haisken-DeNew and Shields 2004; Stutzer and Frey 2004; Ferrer-i-Carbonell 2005). Being unemployed exerts the largest (negative) effect on life satisfaction of all personal characteristics. This is a well-documented finding in the previous literature (see e.g. Clark and Oswald 1994; Winkelmann and Winkelmann 1998). The control variables are included in all regressions but, for the sake of brevity, we do not report the estimates in subsequent tables.

[Table 2 about here]

The variables of interest are SO_2 concentration and household income. Both have the expected sign and are statistically significant. We will discuss the size of the effect extensively in the next section in which we monetize the effect. The raw coefficients are difficult to interpret and cannot be readily compared to earlier estimates of pollution on life satisfaction, except with respect to sign and significance. Welsch (2002) finds essentially no effect of SO_2 concentration on happiness in a cross-section of 54 countries, both in terms of size and significance. Di Tella and MacCulloch (2005) find a negative and statistically significant effect of SO_2 emissions in a repeated cross-section of 12 countries and 23 years but there is no general method to convert emissions into pollution levels. Finally, Welsch (2006) only considers other pollutants.

The conventional estimates of SO_2 on life satisfaction (columns I and IV of Table 2), i.e. the estimates not based on pollution instruments, are smaller in absolute terms compared to the estimates in which pollution is instrumented. If we use estimates of the causal effect of flue gas desulfurization based on an indicator distance decay function as an instrument (columns II and V), the effect of SO_2 on life satisfaction more than doubles; if we use estimates based on the exponential distance decay function as an instrument, the effect increases by approximately one third. The finding that the instrumental variables estimates are larger in absolute terms than the conventional estimate suggests that improvements in air quality are accompanied by negative developments. While the conventional estimate captures only the net effect between changes in pollution and the countervailing factors, the instrumental variable estimates capture the whole effect of changes in pollution. However, given the (generically) large standard errors of instrumental variable estimates, the difference between the instrumental variable estimates and the conventional estimate is not significant in a statistical sense. The difference becomes more pronounced for the estimates in which income is instrumented (columns IV to VI) because, in absolute terms, the conventional estimate of the effect of SO_2 slightly decreases and the estimates based on instrumental variables slightly increases (all changes are around 7%). These changes are difficult to interpret in terms of omitted variable biases and none of the changes is statistically significant.

Regarding the effect of log household income on life satisfaction, the conventional estimates (columns I to III) are slightly above the results reported by Ferrer-i-Carbonell and Frijters (2004) and, as far as different econometric models allow for a comparison, below the results reported in Ferrer-i-Carbonell (2005). The effect of instrumenting household income (columns IV to VI) suggests that the OLS estimates are indeed biased. The estimated effect of log household income on life satisfaction more than triples, a change of similar magnitude as the one reported by Luttmer (2005). The coefficients for income are stable across specifications.

Turning to the first stage regressions, we see that the instruments have the expected effect on the endogenous variables they are intended for: the estimated effect of flue gas desulfurization negatively affects SO_2 concentration. Predicted household income and job tenure of the main or secondary income earner both have a positive impact on household income. Our pollution instruments have no effect on income (conditional on the other variables), which is reassuring that the instrument is orthogonal to local economic activity. For unknown reasons, job tenure is weakly negatively associated with SO_2 concentration.

It is important to sound a note of caution regarding the interpretation of the statistical significance in the first stage regressions. Two instruments, the estimated effect of flue gas desulfurization and predicted household income, are estimated regressors in the first stage regressions and, thus, standard errors are underestimated and t-statistics inflated. However, under general conditions, the parameters in the first stage regressions are consistently estimated (Murphy and Topel 1985). Therefore, the second stage regressions are not afflicted by the problem of estimated regressors.

In all cases, the statistical tests suggest that the instruments are relevant. Shea's (1997) partial R^2s are nearly identical to standard R^2s (Bound, Jaeger and Baker 1995), Anderson canonical correlations likelihood-ratio tests reject the null of underidentification and F-tests indicate joint significance of the excluded instruments. Further, none of the Hansen's (1982) J-statistics rejects the null that the instruments are satisfying the orthogonality condition.

3.2.3 Robustness tests

Despite our efforts to instrument pollution, one might worry that levels of SO_2 concentration reflect local economic activity or air quality more generally. In a second set of regressions we include therefore annual unemployment rates at county level and annual mean concentration of total suspended particulates (TSP) as additional controls. Table 3 presents the results; the models presented in particular columns are identical to the models in the corresponding column of Table 2, except for the two additional control variables.

[Table 3 about here]

Overall, the results are robust to the inclusion of local unemployment rate and TSP concentration. The coefficient of SO_2 instrumented with the effect of flue gas desulfurization estimated based on an indicator distance decay function slightly increases. In all models, standard errors of the coefficients of SO_2 increase, pushing the coefficient of SO_2 instrumented with estimates based on the exponential distance decay function presented in column III below conventional significance levels. The conventional pollution estimates are at least as robust as the instrumental variable estimates. The robustness of the conventional estimates contrasts somewhat with the picture that emerges from the difference in the magnitude of conventional and instrumented pollution effects (or rather our interpretation thereof). The ultimate source of concern is a potential correlation between pollution and unobservable characteristics, but local economic activity as captured by local unemployment seems not to bias conventional estimates.

The results in Table 3 imply that TSP concentration is only weakly associated with life satisfaction. However, we do not dwell on these estimates as they may be afflicted by similar simultaneity problems as we conjecture in the case of conventional SO_2 estimates. Local unemployment rates have large negative effects even though we control for respondents' own employment status, a result that is consistent with earlier findings (Di Tella, MacCulloch and Oswald 2001; 2003). The results in the first stage regressions are as expected: TSP and SO_2 concentrations are positively associated, unemployment rates and SO_2 concentrations negatively.

Although unemployment rate and general air pollution drop from the list of potential candidates, there may be other (unobserved) predictors of life satisfaction that are correlated with SO_2 pollution. Therefore, we interact SO_2 with dummy variables for subgroups of the population that are expected to suffer disproportionately from exposure to SO_2 pollution. In this way, the relatively insensitive group controls for other simultaneous and spatially coincident shocks. We consider two such pollution-sensitive groups: environmentally conscious or concerned individuals and individuals that are at risk with regard to adverse health effects from air pollution. The only variable in the GSOEP for environmental attitudes available in all years asks respondents whether they worry about environmental protection. Possible answers are "very concerned", "somewhat concerned" and "not concerned". Table 4 tabulates the number of observations in each category against deciles of SO_2 concentration.

The number of very concerned people increases with pollution levels and the number of unconcerned people decreases. Of course, for environmental concerns to be a channel through which air pollution affects life satisfaction, such a positive relationship between objective and perceived environmental degradation is a necessary condition. Although only a few Germans characterize themselves as unconcerned, there are still 1,561 observations in the least populated cell (10th decile of SO_2 concentration · unconcerned respondents). The distribution of answers and pollution levels thus allows an implementation of the proposed empirical test.

[Table 4 about here]

Hospitalization and disability status are the only health variables in the GSOEP available in all years. These variables are not suitable for capturing pollution related health effects. Further, on a conceptual level, we are interested in identifying individuals belonging to a risk group rather than actually ill ones. In an auxiliary logit regression, we regress a dummy variable indicating persons suffering from chronic illnesses on a set of 24 *sex · age category* dummies and 24 corresponding interaction terms with SO_2 concentration. The dependent variable is the binary response to the question whether respondents suffered at least one year or chronically from specific complaints or illnesses, asked in the early waves of the GSOEP; this variable comes closest to representing respiratory and cardiovascular diseases caused by pollution. Using the estimated coefficients, we predict hypothetical probabilities of illnesses upon exposure to high and low pollution levels. We then classify individuals with a predicted difference in the probability of illness between high and low pollution situations that lies in the highest quartile as belonging to the high risk groups, and individuals with a predicted difference in the probability of illness that lies in the third quartile as belonging to the risk group. Table 5 reports the average effects of SO_2 concentration on the life satisfaction in the various subgroups.

[Table 5 about here]

The effect of air pollution on life satisfaction is monotonically increasing in the degree to which individuals are concerned about the environment and in the degree they are expected to suffer adverse health consequences from pollution exposure (see bottom rows of Table 5). However, the 95% confidence intervals of the point estimates overlap except for unconcerned individuals for which we find no effect of air pollution.

To sum up our results: First and most importantly, we find negative effects of SO_2 concentration on life satisfaction. The magnitude of the effect is larger for the instrumental variables estimates than for the conventional estimates. This difference suggests that pollution is accompanied by factors with a countervailing effect on life satisfaction. Even though an obvious candidate is local economic activity, it is not local unemployment but rather some other unobserved factor. The effects are robust to the inclusion of local unemployment rate and TSP concentration. Finally, differential effects for different groups of respondents imply that it is indeed air pollution that affects life satisfaction and not other simultaneous and spatially coincident shocks.

3.3 Effect on housing rents

3.3.1 Empirical strategy and explanatory variables

In order to calculate the total *WTP* for air quality, we supplement the results of the life satisfaction approach with housing hedonics for the same period and geographical area (see appendix A.1. for a discussion of what effects can be identified by the hedonic method and the life satisfaction approach).[5] In contrast to the majority of hedonic market studies, we use rental prices instead of house prices, a deviation that seems justified in the present case for several reasons, in addition to data availability. First, as the life satisfaction approach, hedonic rent regressions yield *WTP* estimates in the form of (annually) recurring payments. Hence, in summing and comparing estimates based on the two approaches, no assumptions on individuals' discount rates are necessary. Second, expected changes in air quality are capitalized into sales prices but not into current rents. Given that we have a panel with annual data and the major air quality regulation were enacted before our sample period, capitalized expectations would bias our estimates downwards or make it impossible to establish an effect of pollution on house prices. Third, in contrast to other countries, Germany has a well-developed, and relatively loosely regulated, market for rental housing. Nearly 60% of the households live in rented dwellings (compared to around 30% in the U.S.). Rents for vacant dwellings can be freely negotiated between landlords and potential tenants. There are some

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[5] The standard hedonic framework assumes that individuals are compensated in the housing and the labor market for exposure to air pollution. However, as in previous studies, we find no effect of air quality on wages (e.g. Chay and Greenstone 2005; Bayer, Keohane and Timmins 2006). Thus, we only report the hedonic housing regressions.

restrictions on evicting sitting tenants and a ceiling on rent increases for sitting tenants (up to 30% in a three-year period), but this ceiling is generally not binding (Hoffmann and Kurz 2002). An exception are subsidized dwellings, which are subject to comparatively strict regulation.

As a rule, hedonic housing regressions include a large number of time-invariant housing characteristics. With panel data, these characteristics can be captured by dwelling specific fixed effects (see e.g. Mendelsohn 1992; Gayer, Hamilton and Viscusi 2002 for repeat sale models). In accordance with the life satisfaction regressions, we control for state specific time trends and year effects.[6] Economic theory provides no a priori reason to prefer one functional form for the hedonic price function over others (Rosen 1974). However, in general, when variables are omitted or replaced by proxies, simple forms outperform more flexible ones (Cropper, Deck and McConnell 1988). Therefore, we estimate semi-log hedonic rent regressions as specified in equation 4:

$$\ln(R_{icst}) = \beta_0 + \beta_1 P_{cst} + \beta_2 trend_s + \tau_t + o_i + \varepsilon_{icst}, \tag{4}$$

where R_{icst} is the rent of dwelling i in county c and state s at time t, P_{cst} SO_2 pollution, $trend_s$ state specific time trends, τ_t and o_i time and dwelling specific fixed effects, and ε_{icst} the error term. Robust standard errors are adjusted for clustering on county and year level.

We exclude from our sample owner-occupied houses, even though the GSOEP provides owner estimates of rents. It might well be that owners may just convert their estimates of the house price into a rent estimate, with associated problems of capitalized expectations and systematic biases in owners' appraisals (Ihlanfeldt and Martinez-Vazquez 1986). We further exclude subsidized dwellings because of the stricter regulations and, for obvious reasons, institutional households such as nursing homes and barracks as well as dwellings with an unknown ownership status.

3.3.2. Results

Table 6 presents the hedonic housing regressions in the same sequence as the life satisfaction results, i.e. column I presents the conventional estimates, and columns II and III the

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[6] State specific fixed factors are captured by the dwelling fixed effects.

instrumental variable estimates (with the estimated effect of flue gas desulfurization based on an indicator and on an exponential distance decay function, respectively, as instruments); columns IV to VI show the corresponding results with TSP concentration and unemployment as additional control variables.

[Table 6 about here]

Pollution has a negative effect on housing rents. However, the results for the instrumental variable estimates do not allow to draw any firm conclusions. The conventional estimate lies between the instrumental variable estimates. Therefore, it is not clear, whether the conventional estimate is biased in one or the other direction. Further, the instrumental variable estimates are not robust to the inclusion of TSP concentration and local unemployment. The first estimate halves in size, the second completely collapses. Given the difference in the magnitude and the lacking robustness of the instrumental variable estimates, we do not favor one estimate over the others. Thus, the two instrumental variable estimates reported in columns II and III delimit the lower and upper bounds. Of course, one can also see the zero-effect implied by the result in column IV as an alternative upper bound. In the latter case, the conclusion that the housing market inadequately reflects the benefits of clean air is even stronger. According to our results, TSP concentration has a negative effect on housing rents and, contrary to prior expectations, local unemployment a positive effect.

4. Implicit willingness-to-pay

With the estimated coefficients of the micro-econometric life satisfaction functions for air pollution ($\hat{\beta}_1$) and household income ($\hat{\beta}_2$), we can calculate the hypothetical *WTP* for improvements in air quality or implicit utility-constant trade-offs between pollution and income. We measure the *WTP* by the compensating surplus (*CS*). The *CS* is the decrease in income necessary to hold utility constant if air quality improves. Given the specification of the micro-econometric life satisfaction functions expressed in equation 3, the *CS* is defined as follows:

(5) $$CS = m_{i0}(1 - \exp(\hat{\beta}_1 \cdot \hat{\beta}_2^{-1} \cdot \Delta P_i)),$$

where m_{i0} is (initial) household income and ΔP_i the improvement in air quality, P_{i0}-P_{i1}. Based on equation 5, the *WTP* can be calculated for marginal and inframarginal changes in air quality. We will add these estimates to the price gradients in order to calculate the total *WTP* for improvements in air quality.

In order to increase the comparability of the results of the life satisfaction approach and the hedonic method, we calculate the *WTP* for the households contained in the intersection of the two samples with average household income of € 21,462 and average rental costs of € 3,871 (in 2002 €). For both approaches, *MWTP* is expressed as annual household payments and is, therefore, directly comparable. The estimates are based on the coefficients reported in columns IV to VI of Table 2 for the life satisfaction approach and on the coefficients in columns I to III of Table 6 for the hedonic method. Standard errors are bootstrapped based on 1,000 repetitions. Table 7 presents the results. As usual, the conventional estimates are followed by two instrumental variable estimates (with the estimated effect of flue gas desulfurization based on an indicator distance decay function and based on an exponential distance decay function, respectively).

[Table 7 about here]

We start the discussion with the *MWTP* for a reduction in SO_2 concentration of 1 $\mu g/m^3$. The results for the life satisfaction approach lie in the range of € 195 to € 458 or, in percent of household income, in the range of 0.9% to 2.1%. The implicit prices for clean air reflected in the housing market are much smaller and lie between € 10 and € 35 (or between 0.05% and 0.2% of household income). By summing the estimates from the two methods, we get total *MWTP* estimates in the range of € 230 and € 496 (1.1% and 2.3% of household income, respectively). Further, the results in table 7 suggest that only between 3.5% and 15.2% of the total effects of air quality are capitalized in the housing market. This seems to be a very low proportion. At the same time, *MWTP* estimates based on the life satisfaction approach seem rather high. Potential reasons for these related findings are discussed below.

In order to asses the validity of our own hedonic price estimates, Table 8 presents 34 estimates of *MWTP* for 6 cities reported in 5 different studies. In light of the large literature using the hedonic method to value air quality, the number of studies may seem relatively small.

However, none of the other studies we could locate can be considered because they either investigate the effect of TSP concentration (see Smith, V. K. and Huang 1995 for a meta-analysis) and other pollutants or because SO_2 pollution is measured in units for which no generally accepted conversion factor to μg/m^3 exists (see e.g. Ridker and Henning 1967).

[Table 8 about here]

Table 8 reveals a large variation in *MWTP* estimates. The median of all estimates is € 201, the mean € 483. If we concentrate our attention on the positive and statistically significant implicit marginal prices, median and mean coincide at € 487. With a real interest rate of around 2% per annum, a lump-sum payment of € 487 equals an annual *CS* of € 10 paid in perpetuity, i.e. the lowest *MWTP* based on the hedonic method in Table 7. With a real interest rate of around 8% per annum, it equals an annual *CS* of € 38, the highest *MWTP* in Table 7. Hence, our *MWTP* estimates based on the hedonic method are broadly comparable to the estimates published in the literature.

We also calculate the *WTP* for an inframarginal improvement in air quality of 48 μg/m^3, corresponding to the average total decrease in SO_2 concentration between 1985 and 2003 for the households in the West German sample and between 1991 and 2003 for the households in East German sample. Estimates based on the life satisfaction approach are between € 7,590 and € 13,828 or between 34.4% and 64.4% of annual household income. Implicit prices for clean air in the housing market are between € 471 and € 1,830 or between 2.2% and 7.9%. Total *WTP* estimates amount to between €9,283 and € 15,658 (43.3% and 73.0% of annual household income, respectively). These results would imply that only between 4.5% and 18.2% of the effect of air pollution are reflected in the housing rents.

The comparably low implicit price for clean air in the housing market (relative to the overall effect) and the large absolute size of the life satisfaction approach estimates warrant discussion. We have already mentioned two potential reasons for the low implicit price in the housing markets: migration costs and incomplete perception of the effects air pollution by individuals. If mobility is costly, the true value of a change in air quality is greater than the effects on the housing rents would imply. If air quality improves in a particular county, new residents will be attracted and, as a consequence, rents rise until a new equilibrium is reached.

Without mobility costs, the change in the costs of housing fully reflect the value of cleaner air. But if migration is costly, a person will only move to the county with improved air quality if the cleaner air compensates her or him for both, higher rents and the costs of moving. This reason for incomplete capitalization is especially important in the short run and, thus, in panel analyses in which the effect of air quality is identified on the basis of intraregional fluctuations. In a recent study, Bayer, Keohane and Timmins (2006) take these mobility costs seriously and estimate a discrete choice model of residential sorting. Their *MWTP* estimates that allow for mobility costs are 3.5 times higher than the normal hedonic prices (*MWTP* for a decrease in 1 $\mu g/m^3$ PM10 increases from \$55 to \$185). Further, individuals base their moving decisions on the perceived effects and levels of air pollution rather than objective effects and levels. Smith and Huang (1995) provide evidence that is consistent with the hypothesis that individuals only partially perceive the effects of air pollution. Benefit estimates for improvement in air quality in selected U.S. cities based on dose-response functions and on Viscusi's (1993) summary value of mortality risk (mostly based on hedonic wage studies) are around 4 times higher than benefit estimates based on hedonic studies. Of course, a mis-perception of the effects of air pollution may not be the only reason for this discrepancy. But the estimate also understates the actual degree of "under-capitalization". Reduced mortality risk is only one benefit of clean air. Reduced risk of morbidity, both chronic diseases and minor symptomatic discomforts, reduced material damages and improved visibility are other benefits. It is important to note that both reasons may be simultaneously present and contribute to an incomplete reflection of the benefits of clean air in private markets. The life satisfaction approach is not afflicted by these problems. For example, it can capture the utility consequences of health effects even if individuals are ignorant about the causes. The difference between perceived and objective effects of air quality also points to a third substantive explanation for the comparatively low implicit price. The explanation is based on the notion of two different concepts of utility, decision and experienced utility (Kahneman and Thaler 1991; Kahneman, Wakker and Sarin 1997). Decision utility is a representation of preferences as derived from choices – today's standard concept of utility. Experience utility follows an interpretation of utility in hedonistic terms broadly understood and is similar to the original interpretation of utility going back to Bentham (1789). There is evidence indicating that in some situations the two concepts of utility systematically diverge (e.g Kahneman and Thaler 2006). Welfare measures based on the life satisfaction approach relate to experienced utility. In contrast, welfare measures based on the hedonic method relate to decision utility. Thus, they may be biased estimates of the hedonic experience of the decision as evaluated ex post by the individuals themselves. Decisions in markets for private goods may not accurately reveal people's hedonic experience from the consumption of public goods (Rabin 1998). For example, when buying a house, other housing characteristics may be more salient than regional air quality. If people underestimate future utility streams derived from intangible goods such as good health relative to utility streams derived from disposable income (Frey and Stutzer 2004), we would expect that the experienced utility losses from air pollution are inadequately reflected in housing rents.

A more prosaic reason for the low implicit price relative to the residual shadow benefit estimated with the life satisfaction approach is related to a crucial element of the life satisfaction approach, the estimation of the marginal utility of income. Instrumenting income is inherently difficult and our efforts may fall short of completely resolving the problems of endogeneity of income and omitted costs of income generation. Further, a growing body of literature demonstrates that relative motives play an important role. Individuals evaluate their income situation relative to the income of reference groups (Clark and Oswald 1996; Blanchflower and Oswald 2004; Helliwell and Huang 2004; Senik 2004; Ferrer-i-Carbonell 2005; Luttmer 2005), own past income (Clark 1999; Di Tella, Haisken-De New and MacCulloch 2005; Easterlin 2005) and income aspirations (Easterlin 2001; Stutzer 2004). If people adapt to changes in income, the long-run marginal utility of income understates the short-run utility consequences of income changes. This could also explain the high absolute estimates based on the life satisfaction approach. Investigating the relationship between income and life satisfaction is a fast growing area of research (see Clark, Frijters and Shields 2006 for a review). Therefore, better estimates of marginal utility of income will come forward. However, the importance of these issues is not confined to technical problems associated with estimating the marginal utility of income. Rather it raises conceptual questions, which are beyond the scope of this paper. The realization of the importance of relative concerns has implications for all non-market valuation methods and may well speak in favor of the use of the life satisfaction approach instead of standard approaches. For example, Frank (2000) shows that positional concerns bias hedonic market estimates downward.

The problems associated with estimating the effect of income makes it difficult to give precise benefit estimates in monetary terms and to exactly establish the degree of incompleteness in the capitalization of the benefits in the housing market. Better estimates on the effect of income will make precise estimates possible. However, in the meantime, at least two unambiguous conclusions can be drawn in the present case. First, the negative relationship between air pollution and life satisfaction indicates that individuals are not fully compensated in markets. Thus, while the life satisfaction approach may overstate benefits of clean air, the hedonic method clearly understates these benefits. Our results suggest, that the difference may be large. Second, the evaluation of the large combustion plant ordinance in Germany is unambiguous. Whatever *WTP* estimate is chosen, the costs of flue gas desulfurization are dwarfed. Rough estimates of the private compliance costs (not social costs; see Hazilla and Kopp 1990) for Western Germany range between €35 and €180 per year and household.[7]

5. Conclusion

In the Western hemisphere, air quality has improved significantly in the last decades, at least partly, because of air quality regulations. According to our results, these impressive improvements imply substantial benefits of pollution abatement and large increases in human welfare. Even though most of the first generation regulations were heavy-handed and costly command-and-control regulations and no reliable estimates of the social costs of these regulations are available, they had probably a positive effect on balance. In developing countries, the pollution situation looks less bright and is often getting worse. In the mid-nineties, Russia and China had SO_2 concentrations in urban areas of around 100 $\mu g/m^3$. This suggests that there are large potential welfare gains from pollution abatement in these countries. Of course the size of the benefits tells us nothing about the means by which air quality should be improved. By relying on incentive based approaches with lower compliance costs (see e.g. Schmalensee 1998), the net effect of air quality regulations may well exceed the one experienced by Western countries. Regarding the benefits of air quality, this paper

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[7] Schaerer and Haug (1990) put the cost of installation of scrubbers at West German power plants at DM 14.2 billion (1988 DM). Doubling this value to account for operation costs, assuming a real long-term interest rate of 5% and dividing by 27,793,000 households (living in Germany in 1989), gives an estimate of € 36 per household and year. Another estimate of desulfurization at power plants provided by Schaerer and Haug (1990) is DM 0.0075 per kWh of electricity produced. In 1989, West German power plants produced 452.39 billion kWh of electricity. The costs per household and year are therefore € 87. Finally, Schulz' (1985) most pessimistic cost estimate is DM 9 per household and month (1985 DM assumed) or € 179 per household and year. It is important to note, that these estimates say nothing on the distribution of the costs.

contributes to the growing evidence that pollution has larger consequences for the affected population than has previously been recognized. In contrast to other papers that address problems of the hedonic method (Chay and Greenstone 2005; Bayer, Keohane and Timmins 2006), our evidence is based on a new approach, the life satisfaction approach. Even though our evidence is based on German data, the finding is of more general relevance. This is demonstrated by the close correspondence between our own hedonic market estimates and published results for the U.S. and South Korea. Therefore, one may well transfer our life satisfaction approach estimates to other countries as well.

Our analysis corroborates the finding that life satisfaction data contain useful information on individuals' preferences and hedonic experience of public goods. Therefore, the life satisfaction approach expands economists' toolbox in the area of non-market valuation. Advances in estimating the effect of income on life satisfaction will base the monetary benefit estimates on firmer grounds. At present, the life satisfaction approach may overstate the benefits of clean air. At the same time, our results indicate that the hedonic method understates the benefits of clean air. We regard additional and systematic comparisons of the life satisfaction approach to the hedonic method as a priority for future research. Two related questions are (i) for which goods and under what conditions is capitalization more or less complete (ii) how can these differences be explained. Answers to these questions will have important implications beyond the area of non-market valuation and will, for example, shed light on the validity of the equilibrium assumption in important private markets, on individuals' risk perceptions, on systematic errors of individuals in predicting utility consequences of their decisions and on the difference between various utility concepts. These latter issues also raise difficult questions as to which measure is appropriate for policy evaluation.

References

Atkinson, Scott E. and Thomas D. Crocker (1987). A Bayesian Approach to Assessing the Robustness of Hedonic Property. *Journal of Applied Econometrics* 2(1): 27-45.

Bakkum, A., H. Bartelds, J. A. Duiser and C. Veldt (1987). *Handbook of Emission Factors, Part 3. Stationary Combustion Sources.* The Hague, NL: Ministry of Housing, Physical Planning and Environment.

Bayer, Patrick, Nathaniel O. Keohane and Christopher Timmins (2006). Migration and Hedonic Valuation: The Case of Air Quality. NBER Working Paper No. w12106, Cambridge, MA: National Bureau of Economics.

Bentham, Jeremy (1789). *An Introduction to the Principles of Morals and Legislation.* Reprinted 1948. Oxford: Blackwell.

Blanchflower, David G. and Andrew J. Oswald (2004). Well-Being over Time in Britain and the USA. *Journal of Public Economics* 88(7-8): 1359-1386.

Bound, John, David A. Jaeger and Regina M. Baker (1995). Problems with Instrumental Variables Estimation When the Correlation between the Instruments and the Endogenous Explanatory Variable Is Weak. *Journal of the American Statistical Association* 90(430): 443-450.

Chattopadhyay, Sudip (1999). Estimating the Demand for Air Quality: New Evidence Based on the Chicago Housing Market. *Land Economics* 75(1): 22-38.

Chay, Kenneth Y. and Michael Greenstone (2005). Does Air Quality Matter? Evidence from the Housing Market. *Journal of Political Economy* 113(2): 376-424.

Clark, Andrew E. (1999). Are Wages Habit-Forming? Evidence from Micro Data. *Journal of Economic Behavior and Organization* 39(2): 179-200.

Clark, Andrew E., Paul Frijters and Michael A. Shields (2006). Income and Happiness: Evidence, Explanations and Economic Implications. Mimeo, Paris-Jourdan Sciences Economiques.

Clark, Andrew E. and Andrew J. Oswald (1994). Unhappiness and Unemployment. *Economic Journal* 104(424): 648-659.

Clark, Andrew E. and Andrew J. Oswald (1996). Satisfaction and Comparison Income. *Journal of Public Economics* 61(3): 359-381.

Cropper, Maureen L., Leland B. Deck and Kenneth E. McConnell (1988). On the Choice of Functional Form for Hedonic Price Functions. *Review of Economics and Statistics* 70(4): 668-75.

D'Ambrosio, Conchita and Joachim R. Frick (2004). Subjective Well-Being and Relative Deprivation: An Empirical Link. IZA Discussion Paper Series No. 1351, IZA, Bonn.

Di Tella, Rafael, John Haisken-De New and Robert J. MacCulloch (2005). Adaptation to Income and to Status in an Individual Panel. Mimeo, Harvard Business School.

Di Tella, Rafael and Robert J. MacCulloch (2005). Gross National Happiness as an Answer to the Easterlin Paradox? Mimeo, Harvard Business School.

Di Tella, Rafael and Robert J. MacCulloch (2006). Some Uses of Happiness Data in Economics. *Journal of Economic Perspectives* 20(1): 25-46.

Di Tella, Rafael, Robert J. MacCulloch and Andrew J. Oswald (2001). Preferences over Inflation and Unemployment: Evidence from Surveys of Happiness. *American Economic Review* 91(1): 335-341.

Di Tella, Rafael, Robert J. MacCulloch and Andrew J. Oswald (2003). The Macroeconomics of Happiness. *Review of Economics and Statistics* 85(4): 809-827.

Dolan, Paul and Tessa Peasgood (2006). Valuing Non-Market Goods: Does Subjective Well-Being Offer a Viable Alternative to Contingent Valuation? Mimeo, Tanaka Business School.

Easterlin, Richard A. (2001). Income and Happiness: Towards an Unified Theory. *Economic Journal* 111(473): 465-484.

Easterlin, Richard A. (2005). Building a Better Theory of Well-Being. In: Luigino Bruni and Pier Luigi Porta (eds). *Economics and Happiness. Framing the Analysis*. Oxford: Oxford University Press: 29-64.

Economist (2006). The Heat Is On. *Economist*, September 9, 2006: 3-4.

Eliassen, Anton and Jørgen Saltbones (1983). Modelling of Long-Range Transport of Sulphur over Europe: A Two-Year Model Run and Some Model Experiments. *Atmospheric Environment* 17(8): 1457-1473.

Ferrer-i-Carbonell, Ada (2005). Income and Well-Being: An Empirical Analysis of the Comparison Income Effect. *Journal of Public Economics* 89(5-6): 997-1019.

Ferrer-i-Carbonell, Ada and Paul Frijters (2004). How Important Is Methodology for the Estimates of the Determinants of Happiness? *Economic Journal* 114(497): 641-659.

Frank, Robert H. (2000). Why Is Cost-Benefit Analysis So Controversial? *Journal of Legal Studies* 29(2): 913-930.

Frey, Bruno S., Simon Luechinger and Alois Stutzer (2004). Valuing Public Goods: The Life Satisfaction Approach. CESifo Working Paper No. 1158, Munich: CESifo.

Frey, Bruno S. and Alois Stutzer (2002). What Can Economists Learn from Happiness Research? *Journal of Economic Literature* 40(2): 402-35.

Frey, Bruno S. and Alois Stutzer (2004). Economic Consequences of Mispredicting Utility. IEW Working Paper No. 218, University of Zurich.

Frijters, Paul, John P. Haisken-DeNew and Michael A. Shields (2004). Money Does Matter! Evidence from Increasing Real Income and Life Satisfaction in East Germany Following Reunification. *American Economic Review* 94(3): 730-740.

Frijters, Paul and Bernard M. S. Van Praag (1998). The Effects of Climate on Welfare and Well-Being in Russia. *Climatic Change* 39(1): 61-81.

Gardner, Jonathan and Andrew Oswald (2006). Money and Mental Wellbeing: A Longitudinal Study of Medium-Sized Lottery Wins. *Journal of Health Economics*, forthcoming.

Gayer, Ted, James T. Hamilton and W. Kip Viscusi (2002). The Market Value of Reducing Cancer Risk: Hedonic Housing Prices with Changing Information. *Southern Economic Journal* 69(2): 266-289.

Hansen, Lars Peter (1982). Large Sample Properties of Generalized Method of Moments Estimators. *Econometrica* 50(4): 1029-1054.

Hazilla, Michael and Raymond J. Kopp (1990). Social Cost of Environmental Quality Regulations: A General Equilibrium Analysis. *Journal of Political Economy* 98(4): 853-873.

Helliwell, John F. (2006). Well-Being, Social Capital and Public Policy: What's New? *Economic Journal* 116(510): C34-C45.

Helliwell, John F. and Haifang Huang (2004). How's the Job? Well-Being and Social Capital in the Workplace. NBER Working Paper No. 11759, Cambridge, MA: National Bureau of Economic Research.

Hoffmann, Johannes and Claudia Kurz (2002). Rent Indices for Housing in West Germany, 1985 to 1998. ECB Working Paper Series No. 116, European Central Bank.

Ihlanfeldt, Keith R. and Jorge Martinez-Vazquez (1986). Alternative Value Estimates of Owner-Occupied Housing: Evidence on Sample Selection Bias and Systematic Errors. *Journal of Urban Economics* 20(3): 356-369.

Joulfaian, David and Mark Rider (1998). Differential Taxation and Tax Evasion by Small Business. *National Tax Journal* 51(4): 675-687.

Kahneman, Daniel and Robert Sugden (2005). Experienced Utility as a Standard of Policy Evaluation. *Environmental and Resource Economics* 32(1): 161-181.

Kahneman, Daniel and Richard H. Thaler (1991). Economic Analysis and the Psychology of Utility: Applications to Compensation Policy. *American Economic Review. Paper and Proceedings* 81(2): 341-346.

Kahneman, Daniel and Richard H. Thaler (2006). Anomalies: Utility Maximization and Experienced Utility. *Journal of Economic Perspectives* 20(1): 221-234.

Kahneman, Daniel, Peter P. Wakker and Rakesh Sarin (1997). Back to Bentham? Explorations of Experienced Utility. *Quarterly Journal of Economics* 112(2): 375-405.

Kim, Chong Won, Tim T. Phipps and Luc Anselin (2003). Measuring the Benefits of Air Quality Improvement: A Spatial Hedonic Approach. *Journal of Environmental Economics and Management* 45(1): 24-39.

Layard, Richard (2006). Happiness and Public Policy: A Challenge to the Profession. *Economic Journal* 116(510): C24-C33.

Layard, Richard, Guy Mayaraz and Stephen Nickell (2006). The Marginal Utility of Income. Mimeo, London School of Economics.

Li, Mingche M. and H. James Brown (1980). Micro-Neighborhood Externalities and Hedonic Housing Prices. *Land Economics* 56(2): 125-141.

Luechinger, Simon and Paul Raschky (2006). Valuing Flood Disasters with the Life Satisfaction Approach. Mimeo, University of Zurich.

Luechinger, Simon and Paul Raschky (2007). Valuing Flood Disasters Using the Life Satisfaction Approach. Mimeo, University of Zurich.

Luttmer, Erzo F. P. (2005). Neighbors as Negatives: Relative Earnings and Well-Being. *Quarterly Journal of Economics* 120(3): 963-1002.

Mendelsohn, Robert (1992). Measuring Hazardous Waste Damages with Panel Models. *Journal of Environmental Economics and Management* 22 3: 259-71.

Murphy, Kevin M. and Robert H. Topel (1985). Estimation and Inference in Two-Step Econometric Models. *Journal of Business and Economic Statistics* 3(4): 370-379.

Portney, Paul R. (1990). Economics and the Clean Air Act. *Journal of Economic Perspectives* 4(4): 173-181.

Rabin, Matthew (1998). Psychology and Economics. *Journal of Economic Literature* 36(1): 11-46.

Rehdanz, Katrin and David Maddison (2005). Climate and Happiness. *Ecological Economics* 52(1): 111-125.

Ridker, Ronald G. and John A. Henning (1967). The Determinants of Residential Property Values with Special Reference to Air Pollution. *Review of Economics and Statistics* 49(2): 246-257.

Roback, Jennifer (1982). Wages, Rents, and the Quality of Life. *Journal of Political Economy* 90(6): 1257-1278.

Rosen, Sherwin (1974). Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition. *Journal of Political Economy* 82(1): 34-55.

Roy, René (1947). La Distribution Du Revenu Entre Les Divers Biens. *Econometrica* 15(3): 205-225.

Sandstrom, T., N. Stjernberg, M. C. Andersson, B. Kolmodinhedman, R. Lundgren, L. Rosenhall and T. Angstrom (1989). Cell Response in Bronchoalveolar Lavage Fluid after Exposure to Sulfur-Dioxide: A Time-Response Study. *American Review of Respiratory Disease* 140(6): 1828-1831.

Schärer, Bernd and Norbert Haug (1990). Bilanz der Großfeuerungsanlagen-Verordnung. *Staub. Reinhaltung der Luft* 50: 139-144.

Schmalensee, Richard (1998). An Interim Evaluation of Sulfur Dioxide Emissions Trading. *Journal of Economic Perspectives* 12(3): 53-68.

Schulz, Werner (1985). *Der monetäre Wert besserer Luft: Eine empirische Analyse individueller Zahlungsbereitschaft und Ihrer Determinanten Auf der Basis Von Repräsentativumfragen*. Frankfurt a.M., Bern and New York: Lang.

Schwartz, Joel and Douglas W. Dockery (1992). Increased Mortality in Philadelphia Associated with Daily Air-Pollution Concentrations. *American Review of Respiratory Disease* 145(3): 600-604.

Schwartz, Stephen E. (1989). Acid Deposition: Unraveling a Regional Phenomenon. *Science* 243(4892): 753-763.

Senik, Claudia (2004). When Information Dominates Comparison: Learning from Russian Subjective Panel Data. *Journal of Public Economics* 88(9-10): 2099-2123.

Shea, John (1997). Instrument Relevance in Multivariate Linear Models: A Simple Measure. *Review of Economics and Statistics* 79(2): 348-352.

Sheppard, Dean, W. S. Wong, C. F. Uehara, Jay A. Nadel and Homer A. Boushey (1980). Lower Threshold and Greater Bronchomotor Responsiveness of Asthmatic Subjects to Sulfur-Dioxide. *American Review of Respiratory Disease* 122(6): 873-878.

Smith, Eric G., John H. Haines and Susan Lyon Stone (1994). Review of the Naional Ambient Air Quality Standards for Sulfur Oxides. Assessment of Scientific and Technical Information. EPA-452R-94-013, Resaerch Triangle Park, NC: Air Quality Management Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency.

Smith, V. Kerry and Ju-Chin Huang (1995). Can Markets Value Air Quality? A Meta-Analysis of Hedonic Property Value Models. *Journal of Political Economy* 103(1): 209-227.

Stutzer, Alois (2004). The Role of Income Aspirations in Individual Happiness. *Journal of Economic Behavior and Organization* 54(1): 89-109.

Stutzer, Alois and Bruno S. Frey (2004). Reported Subjective Well-Being: A Challenge for Economic Theory and Economic Policy. *Schmollers Jahrbuch: Zeitschrift fur Wirtschafts- und Sozialwissenschaften* 124(2): 191-231.

Summers, Peter W. and Wolfgang Fricke (1989). Atmospheric Decay Distances and Times for Sulphur and Nitrogen Oxides Estimated from Air and Precipitation Monitoring in Eastern Canada. *Tellus* 41B(3): 286-295.

Taylor, Laura O. (2003). The Hedonic Method. In: Patricia A. Champ, Kevin J. Boyle and Thomas C. Brown (eds). *A Primer on Nonmarket Valuation*. Dordrecht, NL: Kluwer Academic Publishers: 331-393.

Time Magazine (1967). Menace in the Skies. *Time Magazine*, January 27, 2007.

Traup, Stephan and Burkhard Kruse (1996). *Wind und Windenergiepotentiale in Deutschland. Winddaten für Windenergienutzer*. Offenbach am Main, DE: Deutscher Wetterdienst.

Van Praag, Bernard M. S. and Barbara E. Baarsma (2005). Using Happiness Surveys to Value Intangibles: The Case of Airport Noise. *Economic Journal* 115(500): 224-246.

Viscusi, W. Kip (1993). The Value of Risks to Life and Health. *Journal of Economic Literature* 31(4): 1912-1946.

Welsch, Heinz (2002). Preferences over Prosperity and Pollution: Environmental Valuation Based on Happiness Surveys. *Kyklos* 55(4): 473-494.

Welsch, Heinz (2006). Environment and Happiness: Valuation of Air Pollution Using Life Satisfaction Data. *Ecological Economics* 58(4): 801-813.

Winkelmann, Liliana and Rainer Winkelmann (1998). Why Are the Unemployed So Unhappy? Evidence from Panel Data. *Economica* 65(257): 1-15.

Wong, Tze Wai, Tai Shing Lau, Tak Sun Yu, Anne Neller, Siu Lan Wong, Wilson Tam and Sik Wing Pang (1999). Air Pollution and Hospital Admissions for Respiratory and Cardiovascular Diseases in Hong Kong. *Occupational and Environmental Medicine* 56(10): 679-683.

Zabel, Jeffrey E. and Katherine A. Kiel (2000). Estimating the Demand for Air Quality in Four U.S. Cities. *Land Economics* 76(2): 174-194.

Appendix

A. 1 Relationship between hedonic method and life satisfaction approach

This appendix provides a discussion of what effects can be identified by the hedonic method and the life satisfaction approach and of the relationship between the two methods.

In the standard hedonic method framework, individuals are assumed to have an indirect utility function, $v(\cdot)$, with clean air, a, household income, $m(a)$, and rental costs, $r(a)$, per unit of housing, h, as arguments (with $\delta v/\delta a > 0$, $\delta v/\delta m > 0$ and $\delta v/\delta r < 0$). In the market equilibrium, wages and rents must adjust to equalize utility across locations. Otherwise, some individuals would have an incentive to move (see e.g. Roback 1982). Hence we have $v(a, m(a), r(a)) = k$ in all locations. By totally differentiating and rearranging we obtain:

$$\text{(6)} \qquad \mathrm{d}v/\mathrm{d}a = \delta v/\delta a + \delta v/\delta m \cdot \mathrm{d}m/\mathrm{d}a + \delta v/\delta r \cdot \mathrm{d}r/\mathrm{d}a = 0.$$

Defining the implicit price for clean air reflected in the labor and housing markets, $\mathrm{p_a}$, as $\mathrm{p_a} = h \cdot \mathrm{d}r/\mathrm{d}a - \mathrm{d}m/\mathrm{d}a$ and using Roy's (1947) identity, $h = -(\delta v/\delta r)/(\delta v/\delta m)$, one can write:

$$\text{(7)} \qquad \mathrm{p_a}^* = h \cdot \mathrm{d}r/\mathrm{d}a - \mathrm{d}m/\mathrm{d}a = (\delta v/\delta a)/(\delta v/\delta m).$$

Thus, in equilibrium, the implicit price for clean air equals the marginal willingness-to-pay (*MWTP*). This is the underlying assumption of the hedonic method. If all effects of air quality are anticipated and if the equilibrium condition holds, individuals' *MWTP* for clean air can be inferred from the observable demand for residential housing as well as from rent and wage gradients. However, because of moving and transaction costs and because of partial ignorance regarding the effects of air pollution, these effects are likely to be incompletely capitalized in wages and rents. In this situation, utility is not equalized across locations with different air quality, i.e. $\mathrm{d}v/\mathrm{d}a > 0$, and the observed implicit price falls short of individuals' *MWTP*:

$$\text{(8)} \qquad \mathrm{p_a} = h \cdot \mathrm{d}r/\mathrm{d}a - \mathrm{d}m/\mathrm{d}a = (\delta v/\delta a)/(\delta v/\delta m) - (\mathrm{dv/da})/(\delta v/\delta m) < (\delta v/\delta a)/(\delta v/\delta m).$$

The life satisfaction approach does not rely on observed behavior but regresses life satisfaction, as an empirical approximation for the underlying latent variable utility, on air quality, income and other covariates. In a regression of life satisfaction on air quality, the coefficient for air quality corresponds to the term dv/da in equation 6. As can be seen, the coefficient equals the marginal utility of air quality if and only if either wages and rents are held constant or if air quality is not capitalized in private markets, i.e. if dm/da = dr/da = 0. If air quality is capitalized and life satisfaction is regressed only on air quality but neither wages nor rents, a mis-specified model of the form $v = \tilde{\beta}_0 + \tilde{\beta}_1 a + \varepsilon$ instead of the true population model $v = \beta_0 + \beta_1 a + \beta_2 m + \beta_3 r + \varepsilon$ is estimated. The coefficient $\tilde{\beta}_1$ is a biased estimate of β_1 and amounts to $E(\tilde{\beta}_1) = \beta_1 + \beta_2 \sum((a_i - \overline{a})m_i) / \sum(a_i - \overline{a})^2 + \beta_3 \sum((a_i - \overline{a})r_i) / \sum(a_i - \overline{a})^2$, which corresponds to d$v$/d$a$ in equation 6. Theoretically, housing costs and wages could be included in the set of explanatory variables in micro-econometric life satisfaction functions and, thus, the full effect could be recovered. However, even if housing rents are available in the data, it may not be advisable to include them in life satisfaction regression because it is not possible to control for all relevant observed and unobserved housing characteristics. Similarly, in order to address endogeneity and simultaneity problems associated with estimating the effect of income, household income is instrumented and, hence, the endogenous part of income is excluded. Thus, the coefficient for air quality captures only the residual effect that is not capitalized in the housing market, i.e. dv/da (< $\delta v/\delta a$). The residual effect can be monetized with the marginal utility of income as shown in equation 9:

$$(9)\qquad (\mathrm{d}v/\mathrm{d}a)/(\delta v/\delta m) = [\delta v/\delta a + \delta v/\delta m \cdot \mathrm{d}m/\mathrm{d}a + \delta v/\delta r \cdot \mathrm{d}r/\mathrm{d}a]/(\delta v/\delta m).$$

The sum of the implicit hedonic price in equation 8 plus the residual shadow benefit in equation 9 yields the correct *MWTP* for clean air. Hence, the two methods are *complements*. As in previous studies (e.g. Chay and Greenstone 2005; Bayer, Keohane and Timmins 2006), we find no statistically significant effect of air quality on wages. Thus, total *WTP* is the sum of the estimates based on the hedonic housing regressions and the life satisfaction approach.

So far, the analysis refers to cross-section analyses. However, the same conclusions apply to panel analyses. Assuming that not all future changes in air quality are expected and capitalized in the housing market, utility will be equalized across regions at every point in time but not necessarily across time. (It is important to note that while future changes in amenities may be capitalized into sales prices, they are not expected to be capitalized into current rents; see Taylor 2003.) The changes over time, however, are captured in the year fixed effects. Thus, even with panel data, only the residual effect can be captured. Of course, compensation is most likely to be minor in a panel setting in which annual intra- and interregional fluctuations are studied. In this context, the residual effect may capture a great part of the overall effect. Nevertheless, conceptually, it is still a residual effect and the two methods remain complements.

A. 2 Power plants and wind directions: Data and data sources

This appendix provides a detailed description of the data on German power plants and wind directions used to estimate the causal effect of flue gas desulfurization on annual mean SO_2 concentrations at county level.

Power plants

The data for fossil fuel fired generating units with an electricity capacity of 100 MW and more are from the UBA, information published by the operating companies and the technical literature, a survey mailed to operating companies and statutory provisions. To a list of 396 generating units provided by the UBA, we add 56 units and then reduce the number of units to 390 by combining all units with identical location and characteristics. Of theses 390 units, 7 units have a capacity of less than 100 MW, 351 were active in the period 1985 to 2003 and 303 units were active and are neither nuclear or hydroelectric power plants. The UBA list contains information on the plant name, operator and/or owner, zip code of contact address (which does not necessarily correspond to the plant's location), the launching year, the year the plant was shut down, capacity and fuel. We complement the data with the location, the year of refit (desulfurization), fuel efficiency and estimates of annual SO_2 emissions.

Location: If possible, we establish the exact address using information published by the operating companies and in the technical literature, or a route planner. Otherwise, the centroid of the zip-code is assumed to be a plant's location. We georeference the addresses with a route planner.

Year of refit: Published information and responses to our survey of operating companies allows us to determine the year scrubbers were installed for 224 units (61%). For the other units the year can be approximated on the basis of statutory provisions, the launching year, the year the plant was shut down and the capacity.

Fuel efficiency (η_j): Published information and survey responses provide information on the fuel efficiency of 196 units (54%). For the other units fuel efficiency is predicted based on the following regression (t-values in parentheses):

$$\eta_j = 9.6\text{E-}4\cdot \textit{start year}_j + 9.9\text{E-}5\cdot \textit{capacity}_j - 0.035\cdot 1(\textit{lignite})_j + 0.008\cdot 1(\textit{sub-bituminous coal})_j +$$

(3.76) (6.98) (-1.25) (0.27)

$$0.054\cdot 1(\textit{natural gas})_j - 0.042\cdot 1(\textit{HEL})_j + 0.079\cdot 1(\textit{HS})_j - 0.103\cdot 1(\textit{uranium})_j + 0.185\cdot 1(\textit{hydro})_j -$$

(1.98) (-1.56) (2.32) (-2.73) (4.03)

$$-0.053\cdot 1(\textit{mixed fuel})_j - 0.027\cdot 1(\textit{desox})_j + 0.056\cdot 1(\textit{denox})_j - 1.589$$

(-1.72) (-3.37) (5.39) (-3.13)

$R^2 = 0.727$, Prof > F = 0.000

Emissions: In order to estimate annual SO_2 emissions, we use emission factors, *EF*, from a time shortly before scrubbers were installed (Bakkum et al. 1987). Emission factors are defined as the industry wide average ratio between the emission rate and the actual load differentiated according to fuel and capacity. Assuming full utilization of capacities, the annual emission at plant *j*, E_j, can be estimated as

$$E_j = EF(\textit{fuel}, \textit{capacity})\cdot \textit{capacity}_j\cdot \eta_j^{-1}\cdot \textit{time period} \text{ (31,536,000 seconds).}$$

This calculation overstates emissions because the assumption of constant full utilization is not plausible but we lack data on utilization rates. Moreover, the procesure allows to capture the important differences in emissions between fuels and plant sizes.

Wind stations

Frequencies of wind directions in 12 30-degree sectors measured wind stations are published in Traup and Kruse (Traup and Kruse 1996). The wind atlas contains data on 107 wind stations of which 12 are not representative for a larger area. For each power plant the wind station closest to the plant is used to describe the wind situation at the plant, restricting the number of wind stations to 43. The frequency distributions are based on measurement series of at least 5 years, in most cases 15 years and in some cases more than 15 years in the period between 1976-1995.

Table 1. Effect of fossil fuel fired power plants and flue gas desulfurization on SO_2 concentration

Dependent Variable	I		II	
SO_2 ($\mu g/m^3$) concentration	Coefficient	t-value	Coefficient	t-value
Emissions from power plants				
Weighted sum of uncleaned SO_2 emissions	3.7E-06**	9.10	1.4E-05**	17.64
Weighted sum of retained SO_2 emissions	-4.2E-06**	-35.90	-9.9E-06**	-36.46
County specific effects	Yes		Yes	
Year specific effects	Yes		Yes	
Constant	Yes		Yes	
Number of observations		8,455		8,455
Prob > F		0.000		0.000
R^2		0.663		0.672
	Coefficient	St. Err.	Coefficient	St. Err.
Estimated separation efficiency	-1.156**	0.128	-0.686**	0.042

Notes: (1) OLS estimates; (2) ** is significant at the 99% level; (3) standard errors for the separation efficiency are estimates using the delta method.

Table 2. Basic results: Effect of SO_2 pollution on life satisfaction, Germany 1985-2003

A. Second stage regression

Dependent Variable	I		II		III		IV		V		VI	
Life satisfaction	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value
Pollution												
SO_2 (μg/m^3)	-0.005 **	-6.95	-0.010 *	-2.38	-0.006 $^{(*)}$	-1.80	-0.004 **	-6.45	-0.010 **	-2.56	-0.006 $^{(*)}$	-1.91
HH income												
ln(post govt. income)	0.140 **	14.94	0.138 **	14.62	0.139 **	14.81	0.484 **	8.94	0.482 **	8.90	0.484 **	8.93
HH size$^{1/2}$	-0.167 **	-7.82	-0.168 **	-7.85	-0.167 **	-7.82	-0.379 **	-9.69	-0.380 **	-9.69	-0.379 **	-9.68
Personal characteristics												
Age^2	-9E-5 **	-2.67	-9E-5 **	-2.77	-9E-5 **	-2.70	-8E-5 *	-2.55	-9E-5 **	-2.68	-8E-5 **	-2.59
Not disabled	Reference group		Reference group		Reference group		Reference group		Reference group		Reference group	
Disabled	-0.225 **	-11.03	-0.227 **	-11.13	-0.226 **	-11.08	-0.228 **	-11.14	-0.231 **	-11.25	-0.229 **	-11.20
Single, no partner	Reference group		Reference group		Reference group		Reference group		Reference group		Reference group	
Single, with partner	0.163 **	7.19	0.162 **	7.14	0.163 **	7.19	0.168 **	7.37	0.166 **	7.31	0.167 **	7.36
Married	0.245 **	9.99	0.246 **	10.01	0.245 **	9.98	0.236 **	9.59	0.237 **	9.62	0.236 **	9.59
Separated, no partner	-0.319 **	-6.55	-0.319 **	-6.54	-0.319 **	-6.55	-0.282 **	-5.72	-0.282 **	-5.72	-0.282 **	-5.72
Separated, with partner	0.098	1.24	0.097	1.23	0.098	1.24	0.103	1.30	0.101	1.29	0.102	1.30
Divorced, no partner	-0.032	-0.81	-0.032	-0.82	-0.032	-0.81	-0.006	-0.16	-0.007	-0.17	-0.006	-0.16
Divorced, with partner	0.318 **	7.47	0.318 **	7.48	0.318 **	7.47	0.311 **	7.31	0.311 **	7.33	0.311 **	7.31
Widowed, no partner	-0.230 **	-4.95	-0.228 **	-4.90	-0.230 **	-4.93	0.252 **	5.40	-0.250 **	-5.34	-0.251 **	-5.37
Widowed, with partner	0.338 **	3.78	0.338 **	3.77	0.338 **	3.78	-0.283 **	-3.17	0.283 **	3.17	0.283 **	3.17
Spouse in home country	-0.110	-1.23	-0.112	-1.25	-0.110	-1.24	-0.098	-1.07	-0.100	-1.10	-0.098	-1.08
No children in HH	Reference group		Reference group		Reference group		Reference group		Reference group		Reference group	
Children in HH	0.053 **	3.94	0.053 **	3.96	0.053 **	3.94	0.094 **	6.34	0.095 **	6.35	0.094 **	6.34
German citizen	Reference group		Reference group		Reference group		Reference group		Reference group		Reference group	
EU citizen	-0.184 *	-2.03	-0.182 *	-2.02	-0.183 *	-2.03	-0.185 *	-2.03	-0.182 *	-2.01	-0.184 *	-2.03
Non EU foreigner	-0.049	-0.94	-0.045	-0.87	-0.048	-0.92	-0.052	-0.99	-0.048	-0.91	-0.050	-0.97

To be continued.

Table 2, part 2

	I		II		III		IV		V		VI	
	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value
Not working	Reference group		Reference group		Reference group		Reference group		Reference group		Reference group	
Retired	0.194 **	8.70	0.193 **	8.62	0.194 **	8.68	0.193 **	8.60	0.191 **	8.52	0.192 **	8.58
In education	0.257 **	9.32	0.254 **	9.21	0.256 **	9.31	0.249 **	8.86	0.246 **	8.74	0.248 **	8.83
Maternity leave	0.164 **	5.58	0.165 **	5.63	0.164 **	5.59	0.158 **	5.36	0.160 **	5.42	0.159 **	5.38
Military, community service	-0.027	-0.56	-0.028	-0.60	-0.027	-0.57	-0.026	-0.54	-0.028	-0.59	-0.027	-0.56
Unemployed	-0.443 **	-19.70	-0.443 **	-16.69	-0.443 **	-19.70	-0.454 **	-20.02	-0.454 **	-20.01	-0.454 **	-20.02
Sometimes working	0.046	1.30	0.048	1.37	0.046	1.32	0.031	0.87	0.034	0.95	0.032	0.89
Full-time employment	0.179 **	7.25	0.182 **	7.32	0.180 **	7.24	0.119 **	4.54	0.122 **	4.65	0.120 **	4.56
Part-time employment	0.037 (*)	1.67	0.039 (*)	1.74	0.038 (*)	1.68	0.001	0.03	0.003	0.12	0.001	0.06
Vocational training	0.134 *	2.37	0.135 *	2.39	0.134 *	2.37	0.070	1.22	0.071	1.25	0.070	1.23
Other employment	0.012	0.34	0.013	0.36	0.012	0.34	-0.003	-0.09	-0.002	-0.06	-0.003	-0.08
Blue collar worker	Reference group		Reference group		Reference group		Reference group		Reference group		Reference group	
Trainee	0.144 **	2.81	0.142 **	2.77	0.144 **	2.80	0.176 **	3.41	0.174 **	3.37	0.175 **	3.40
Public service employee	-0.043	-1.22	-0.040	-1.16	-0.042	-1.21	-0.035	-1.00	-0.032	-0.92	-0.034	-0.97
White collar worker	0.015	1.06	0.015	1.04	0.015	1.06	0.012	0.82	0.011	0.80	0.012	0.81
Managerial position	0.112 **	5.29	0.114 **	5.37	0.112 **	5.31	0.086 **	3.97	0.088 **	4.08	0.087 **	4.00
Temporary employment	-0.063 **	-3.38	-0.063 **	-3.39	-0.063 **	-3.38	-0.051 **	-2.74	-0.052 **	-2.75	-0.051 **	-2.74
Permanent employment	0.056 **	4.95	0.057 **	5.03	0.057 **	4.96	0.056 **	4.87	0.057 **	4.96	0.056 **	4.89
Job tenure	-0.004 **	-5.04	-0.004 **	-5.17	-0.004 **	-5.04	-0.004 **	-5.75	-0.005 **	-5.92	-0.004 **	-5.78
Actual working hours	1E-4 **	2.73	1E-4 **	2.63	1E-4 **	2.70	6E-5	1.61	6E-5	1.49	6E-5	1.57
First interview	0.203 **	12.62	0.212 **	12.01	0.205 **	11.94	0.190 **	11.67	0.201 **	11.30	0.194 **	11.16
Second interview	0.061 **	4.25	0.077 **	3.99	0.065 **	3.66	0.058 **	4.05	0.077 **	4.01	0.064 **	3.63
Third and later interviews	Reference group		Reference group		Reference group		Reference group		Reference group		Reference group	

To be continued.

Table 2, part 3

	I		II		III		IV		V		VI	
	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value
City, district size												
Less than 2,000	Reference group		Reference group		Reference group		Reference group		Reference group		Reference group	
Less than 20,000	-0.006	-0.21	-0.006	-0.21	-0.006	-0.21	-0.008	-0.31	-0.008	-0.31	-0.008	-0.31
Less than 100,000	0.033	1.13	0.035	1.20	0.034	1.15	0.029	0.99	0.032	1.07	0.030	1.01
Less than 500,000	-0.012	-0.38	-0.009	-0.28	-0.011	-0.36	-0.004	-0.13	-4E-4	-0.01	-0.003	-0.09
Over 500,000	-0.051	-1.40	-0.048	-1.31	-0.050	-1.37	-0.047	-1.27	-0.044	-1.18	-0.046	-1.24
State specific effects	Yes		Yes		Yes		Yes		Yes		Yes	
State specific time trends	Yes		Yes		Yes		Yes		Yes		Yes	
Year specific effects	Yes		Yes		Yes		Yes		Yes		Yes	
Individual specific effects	Yes		Yes		Yes		Yes		Yes		Yes	
Prob > F		0.000		0.000		0.000		0.000		0.000		0.000
R^2 within		0.037		0.036		0.037		0.028		0.028		0.029
R^2 between		0.066		0.066		0.066		0.086		0.086		0.086
R^2 overall		0.057		0.056		0.057		0.063		0.062		0.063
B. First stage regressions												
Dependent Variable												
SO_2 (μg/m^3)												
Excluded instruments												
Predicted ΔSO_2			-0.200 **	-13.66	-0.217 **	-19.32			-0.200 **	-13.64	-0.217 **	-19.31
ln(predicted hh income)									0.012	1.08	0.012	1.09
Tenure income earner									-0.012 *	-2.48	-0.011 *	-2.39
Included instruments			Yes		Yes		Yes		Yes		Yes	

To be continued.

Table 2, part 4

	I		II		III		IV		V		VI	
	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value
Dependent Variable												
ln(post govt. income)												
Excluded instruments												
Predicted ΔSO_2									-3E-4	-1.12	-1E-4	-0.67
ln(predicted hh income)							0.026 **	37.09	0.026 **	37.06	0.026 **	37.05
Tenure income earner							0.005 **	27.66	0.005 **	27.75	0.005 **	27.75
Included instruments							Yes		Yes		Yes	
Number of observations		227,789		227,789		227,789		227,789		227,789		227,789
Number of individuals		33,864		33,864		33,864		33,864		33,864		33,864
Avg. no. of obs. per individual		6.7		6.7		6.7		6.7		6.7		6.7
Number of clusters		7,413		7,413				7,413				7,413
Shea's partial R^2 for SO_2				0.025		0.043				0.025		0.043
Bound et al. partial R^2				0.025		0.043				0.025		0.043
F-test exc. instruments (p-value)				0.000		0.000				0.000		0.000
Shea's partial R^2 for log income								0.028		0.028		0.028
Bound et al. partial R^2								0.028		0.028		0.028
F-test exc. instruments (p-value)								0.000		0.000		0.000
Anderson LR statistic (p-value)				0.000		0.000		0.000		0.000		0.000
Hansen's J statistic (p-value)				-		-		0.254		0.311		0.271

Notes: (1) OLS and IV estimates with individual fixed effects; SO_2 concentration is instrumented with the effect of flue gas desulfurization at power plants estimated with a distance decay modeled as an indicator function in specifications II and V and modeled with an exponential function in specifications III and VI; household income is instrumented with the sum of predicted incomes of the household members and job tenure of household of the primary/secondary wage earner in specifications IV, V and VI. (2) Standard errors are adjusted for clustering on county and year level. (3) ** is significant at the 99% level, * at the 95% level, and $^{(*)}$ at the 90% level.

Table 3. Robustness check: Effect of SO_2 pollution on life satisfaction controlling for TSPs and unemployment rate

A. Second stage regression

Dependent Variable	I		II		III		IV		V		VI	
Life satisfaction	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value
Pollution												
SO_2 ($\mu g/m^3$)	-0.005**	-6.87	-0.011*	-2.22	-0.006	-1.54	-0.004**	-6.35	-0.012*	-2.39	-0.006(*)	-1.65
TSP ($\mu g/m^3$)	-0.001(*)	-1.67	1E-5	0.01	-0.001	-0.97	-0.001(*)	-1.68	2E-4	0.21	-0.001	-0.83
Unemployment rate	-0.012**	-3.49	-0.016**	-3.52	-0.013**	-3.18	-0.011**	-3.11	-0.015**	-3.35	-0.012**	-2.94
HH income												
ln(post govt. income)	0.139**	14.90	0.137**	14.47	0.139**	14.75	0.482**	8.90	0.481**	8.87	0.482**	8.90
Personal characteristics	Yes (see Table 2)		Yes (see Table 2)		Yes (see Table 2)		Yes (see Table 2)		Yes (see Table 2)		Yes (see Table 2)	
City, district size	Yes (see Table 2)		Yes (see Table 2)		Yes (see Table 2)		Yes (see Table 2)		Yes (see Table 2)		Yes (see Table 2)	
State specific effects	Yes		Yes		Yes		Yes		Yes		Yes	
State specific time trends	Yes		Yes		Yes		Yes		Yes		Yes	
Year specific effects	Yes		Yes		Yes		Yes		Yes		Yes	
Individual specific effects	Yes		Yes		Yes		Yes		Yes		Yes	
Prob > F		0.000		0.000		0.000		0.000		0.000		0.000
R^2 within		0.037		0.036		0.037		0.029		0.027		0.029
R^2 between		0.066		0.066		0.066		0.086		0.086		0.086
R^2 overall		0.057		0.055		0.057		0.063		0.062		0.063

B. First stage regressions

Dependent Variable	I		II		III		IV		V		VI	
SO_2 ($\mu g/m^3$)												
Excluded instruments												
Predicted ΔSO_2			-0.169**	-11.94	-0.191**	-17.22			-0.169**	11.92	0.191**	17.21
ln(predicted hh income)									0.013	1.19	0.013	1.15
Tenure income earner									-0.010*	-2.21	-0.010*	-2.13
TSP and unemployment rate												
TSP ($\mu g/m^3$)			0.129**	10.52	0.120**	9.66			0.129**	10.53	0.120**	9.67

To be continued.

Table 3, part 2

	I		II		III		IV		V		VI	
	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value
Unemployment rate			-0.489 **	-5.32	-0.487 **	-5.34			-0.487 **	-5.30	-0.485 **	-5.33
Included instruments			Yes		Yes				Yes		Yes	
Dependent Variable												
ln(post govt. income)												
Excluded instruments												
Predicted ΔSO_2									2E-4	0.98	-1E-4	-0.59
ln(predicted hh income)							0.026 **	37.06	0.026 **	37.02	0.026 **	37.01
Tenure income earner							0.005 **	27.71	0.005 **	27.79	0.005 **	27.79
TSP and unemployment rate												
TSP ($\mu g/m^3$)							1E-4	0.79	-6E-5	-0.48	-6E-5	-0.42
Unemployment rate							-0.004 **	-3.72	-0.003 **	-3.04	-0.003 **	-3.10
Included instruments							Yes		Yes		Yes	
Number of observations		227,789		227,789		227,789		227,789		227,789		227,789
Number of individuals		33,864		33,864		33,864		33,864		33,864		33,864
Avg. no. of obs. per individual		6.7		6.7		6.7		6.7		6.7		6.7
Number of clusters		7,413		7,413		7,413		7,413		7,413		7,413
Shea's partial R^2 for SO_2				0.018		0.034				0.018		0.034
Bound et al. partial R^2				0.018		0.034				0.018		0.034
F-test exc. instruments (p-value)				0.000		0.000				0.000		0.000
Shea's partial R^2 for log income								0.027		0.027		0.027
Bound et al. partial R^2								0.027		0.027		0.027
F-test exc. instruments (p-value)				0.000		0.000				0.000		0.000
Anderson LR statistic (p-value)				0.000		0.000		0.000		0.000		0.000
Hansen's J statistic (p-value)				-		-		0.192		0.254		0.207

Notes: (1) OLS and IV estimates with individual fixed effects; SO_2 concentration is instrumented with the effect of flue gas desulfurization at power plants estimated with a distance decay modeled as an indicator function in specifications II and V and modeled with an exponential function in specifications III and VI; household income is instrumented with the sum of predicted incomes of the household members and job tenure of household of the primary/secondary wage earner in specifications IV, V and VI. (2) Standard errors are adjusted for clustering on county and year level. (3) ** is significant at the 99% level, * at the 95% level, and $^{(*)}$ at the 90% level.

Table 4. SO_2 pollution and environmental concerns, Germany 1985-2003

SO_2 deciles	Environmental concerns			
	Very concerned	Somewhat concerned	Not Concerned	Total
1st	5,261	13,864	3,464	22,589
2nd	5,338	13,590	3,240	22,168
3rd	6,074	14,146	2,909	23,129
4th	6,593	13,734	2,717	23,044
5th	7,765	12,452	2,199	22,416
6th	9,187	11,698	1,652	22,537
7th	10,765	10,567	1,471	22,803
8th	11,617	9,629	1,566	22,812
9th	11,387	9,592	1,548	22,527
10th	10,834	10,194	1,561	22,589
Total	84,821	119,466	22,327	226,614

Table 5. Interaction effects: Effect of SO_2 pollution on life satisfaction for different groups

Dependent Variable	I		II	
Life satisfaction	Coef.	t-value	Coef.	t-value
Pollution and interaction terms				
SO_2 (μg/m^3)	-0.001	-0.61	-0.004**	-5.28
SO_2 x somewhat concerned	-0.004**	-5.74		
SO_2 x very concerned	-0.005**	-5.89		
SO_2 x risk group			-0.002**	-3.00
SO_2 x high risk group			-0.002**	-3.62
Environmentally concerned people and risk groups				
Not concerned at all	Reference group			
Somewhat concerned	-0.053**	-3.38		
Very concerned	-0.085**	-4.85		
Not in risk group			Reference group	
Risk group			0.017	1.37
High risk group			0.071**	4.82
HH income				
ln(post govt. income)	0.139**	16.78	0.140**	14.94
HH size$^{1/2}$	-0.172**	-9.28	-0.165**	-7.74
Personal characteristics	Yes (see Table 2)		Yes (see Table 2)	
City, district size	Yes (see Table 2)		Yes (see Table 2)	
State specific effects	Yes		Yes	
State specific time trends	Yes		Yes	
Year specific effects	Yes		Yes	
Individual specific effects	Yes		Yes	
Number of observations		226,614		227,789
Number of individuals		33,807		33,864
Avg. no. of obs. per individual		6.7		6.7
Number of clusters		7,410		7,413
Prob > F		0.000		0.000
R^2 within		0.038		0.037
R^2 between		0.008		0.065
R^2 overall		0.004		0.055
Marginal Effect of SO_2 for	M.E.	St. Err.	M.E.	St. Err.
Not concerned at all	-0.0005	0.0008		
Somewhat concerned	-0.0048**	0.0007		
Very concerned	-0.0050**	0.0007		
Not in risk group			-0.0039**	0.0007
Risk group			-0.0054**	0.0008
High risk group			-0.0061**	0.0008

Notes: (1) OLS with individual fixed effects. (2) Standard errors are adjusted for clustering on county and year level. (3) ** is significant at the 99% level, * at the 95% level, and $^{(*)}$ at the 90% level.

Table 6. Hedonic housing regression: Effect of SO_2 pollution on monthly rents, Germany 1985-2003

A. Second stage regression												
Dependent Variable	I		II		III		IV		V		VI	
ln(monthly rent), 2002 euro	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value
Pollution												
SO_2 ($\mu g/m^3$)	-0.009 **	-9.36	-0.010 **	-4.98	-0.003 $^{(*)}$	-1.80	-0.008 **	-8.71	-0.005 *	-2.09	0.002	1.36
TSP ($\mu g/m^3$)							-0.002 **	-5.49	-0.003 **	-5.66	-0.004 **	-7.57
Unemployment rate							0.058 **	15.01	0.060 **	15.10	0.065 **	15.69
State specific time trends	Yes		Yes		Yes		Yes		Yes		Yes	
Year specific effects	Yes		Yes		Yes		Yes		Yes		Yes	
Dwelling specific effects	Yes		Yes		Yes		Yes		Yes		Yes	
Prob > F		0.000		0.000		0.000		0.000		0.000		0.000
R^2 within		0.527		0.527		0.514		0.546		0.542		0.512
R^2 between		0.000		0.000		0.016		0.005		0.015		0.037
R^2 overall		0.001		0.002		0.008		0.001		0.007		0.026
B. First stage regressions												
Dependent Variable												
SO_2 ($\mu g/m^3$)												
Excluded instrument												
Predicted ΔSO_2			-0.322 **	-12.81	-0.283 **	-16.56			-0.278 **	-11.48	-0.251 **	-15.17
Included instruments			Yes		Yes		Yes		Yes		Yes	
Number of observations		64,651		64,651		64,651		64,651		64,651		64,651
Number of dwellings		17,291		17,291		17,291		17,291		17,291		17,291
Avg. no. of obs. per individual		3.7		3.7		3.7		3.7		3.7		3.7
Number of clusters		7,109		7,109		7,109		7,109		7,109		7,109
Shea's partial R^2 for SO_2				0.032		0.040				0.024		0.032
Bound et al. partial R^2				0.032		0.040				0.024		0.032
F-test exc. instruments (p-value)				0.000		0.000				0.000		0.000
Anderson LR statistic (p-value)				0.000		0.000				0.000		0.000

Notes: (1) OLS and IV estimates with individual fixed effects; SO_2 concentration is instrumented with the effect of flue gas desulfurization at power plants estimated with a distance decay modeled as an indicator function in specifications II and V and modeled with an exponential function in specifications III and VI. (2) Standard errors are adjusted for clustering on county and year level. (3) ** is significant at the 99% level, * at the 95% level, and $^{(*)}$ at the 90% level.

Table 7. WTP estimates

Average household income: € 21,462
Average housing rent: € 3,871

Compensating surplus	Life satisfaction approach estimates			Hedonic method estimates		
	Conventional	Instrumental variable		Conventional	Instrumental variable	
-1 $\mu g/m^3$ SO_2						
In euro	€ 195**	€ 458**	€ 275*	€ 35**	€ 38**	€ 10**
	(€ 21)	(€ 157)	(€ 115)	(€ 1)	(€ 4)	(€ 3)
In percent of income	0.9%**	2.1%**	1.3%*	0.2%**	0.2%**	0.05%**
	(0.1%)	(0.7%)	(0.5%)	(0.005%)	(0.02%)	(0.02%)
-48 $\mu g/m^3$ SO_2						
In euro	€ 7,590**	€ 13,828*	€ 9,893**	€ 1,693**	€ 1,830	€ 471**
	(€ 966)	(€ 2,741)	(€ 3,057)	(€ 49)	(€ 176)	(€ 151)
In percent of income	35.4%**	64.5%**	46.2%**	7.9%**	8.5%	2.2%**
	(4.5%)	(12.8%)	(14.2%)	(0.2%)	(0.8%)	(0.7%)

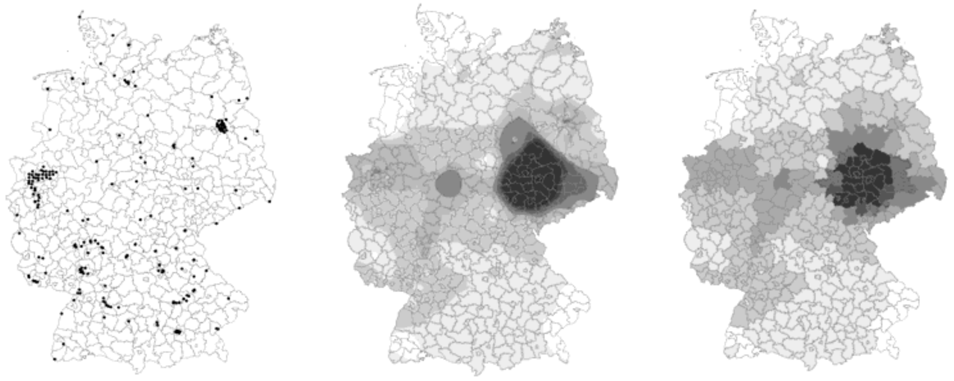
Notes: (1) Standard errors are bootstrapped based on 1,000 repetitions. (2) ** is significant at the 99% level, and * at the 95% level.
Sources: Own estimates (see text for details).

Table 8. MWTP estimates reported in the literature

City	Period	*MWTP* for decrease of 1 $\mu g/m^3$ SO_2		Source
		Reported	In 2002€	
Boston, MA, US	1971	-$39 (n.s.)	-$184	Li and Brown (1980)
		$109 (n.s.)	$514	
		$121 (n.s.)	$570	
Chicago, IL, US	1964-1967	-$22	-$131	Atkinson and Crocker (1987)
	1974-1976	$27 (n.s.)	$39	Zabel and Kiel (2000)
	1977-1979	$12	$18	
	1981-1983	$51 (n.s.)	$75	
	1985-1987	$139	$203	
	1989-1991	$51 (n.s.)	$74	
	1989-1990	$327	$490	Chattopadhyay (1999)
		$325	$487	
		$384	$575	
		$203	$304	
		$369	$554	
		$204 (n.s.)	$305	
Denver, CO, US	1974-1976	$9 (n.s.)	$13	Zabel and Kiel (2000)
	1977-1979	$339 (n.s.)	$495	
	1981-1983	-$120 (n.s.)	-$175	
	1985-1987	$4,843 (n.s.)	$7,074	
	1989-1991	$248 (n.s.)	$363	
Philadelphia, PA, US	1974-1976	$15	$22	
	1977-1979	$94 (n.s.)	$137	
	1981-1983	-$8 (n.s.)	-$11	
	1985-1987	-$3 (n.s.)	-$5	
	1989-1991	$63	$92	
Washington, DC, US	1974-1976	-$24 (n.s.)	-$35	
	1977-1979	-$14	-$20	
	1981-1983	$22 (n.s.)	$32	
	1985-1987	$149	$218	
	1989-1991	$136	$198	
Seoul, KR	1993	$901	$1,055	Kim, Phipps and Anselin (2003)
		$892	$1,044	
		$886	$1,037	
		$864	$1,012	
Median of all estimates			$201	
Median of sign. and positive est.			$487	
Average of all estimates			$483	
Average of sign. and positive est.			$487	

Note: (n.s.) is not significant.

Figure 1. Air quality monitors and mean annual SO_2 concentration, interpolated and aggregated at county level, 1985



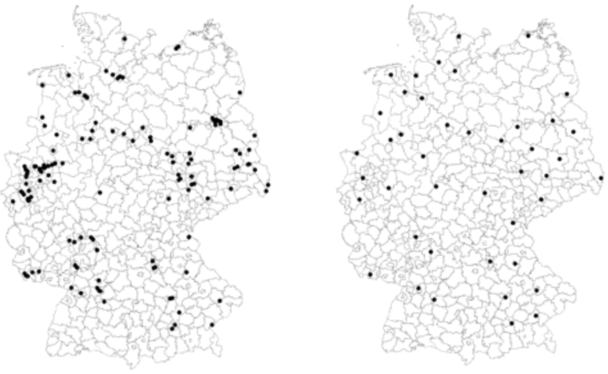
A. Monitors B. Interpolated C. Aggregated

Legend: □ ≤ 20 μg/m³, □ 20 - 40 μg/m³, □ 40 - 60 μg/m³, □ 60 - 80 μg/m³, □ 80 - 100 μg/m³, ■ 100 - 125 μg/m³, ■ 125 - 150 μg/m³ and ■ > 150 μg/m³.

Sources: UBA, own estimates.

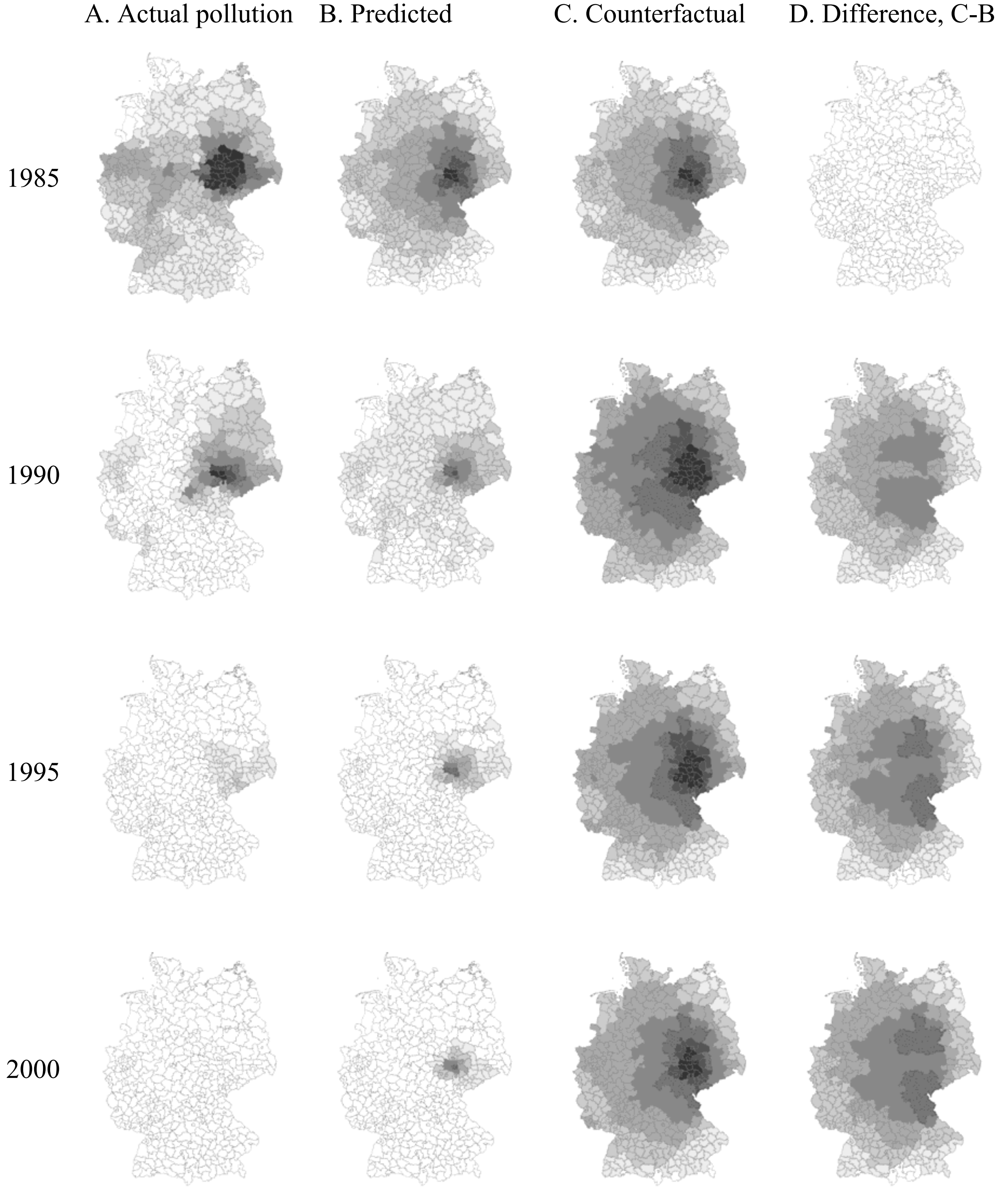
Figure 2. Locations of fossil fuel fired power plants and wind stations

A. Power plants B. Wind stations



Sources: UBA, information published by operating companies, technical literature, route planner and (Traup and Kruse 1996).

Figure 3. Actual, predicted and counterfactual SO_2 concentration and difference between predicted and counterfactual concentration; 1985,1990, 1995 and 2000



Legend: ☐ ≤ 20 μg/m^3, ☐ 20 - 40 μg/m^3, ☐ 40 - 60 μg/m^3, ☐ 60 - 80 μg/m^3, ▨ 80 - 100 μg/m^3, ▨ 100 - 125 μg/m^3, ■ 125 - 150 μg/m^3 and ■ > 150 μg/m^3.

Sources: UBA, own estimates.