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 controls for local unemployment, particulate pollution, reunification effects and rural/urban trends, and larger for environmentalists and predicted risk groups. To calculate total willingness-to-pay, 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 shows 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, and, most importantly, increasing morbidity and mortality. In response, many countries enacted air quality regulations such as the Clean Air Act in the US 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 benefits of air quality regulations.

Traditionally, the benefits of clean air have been assessed with the hedonic method (see Smith 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. Information on public good demand is then embedded in the prices of the private goods. But 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. Second, individuals' behavior in private markets is governed by perceived rather than objective risk. To the extent that they are ignorant about pollution levels and effects, 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 and Huang 1995; Bayer et al. 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 approach builds on the recent development of happiness research in economics (for surveys see Frey and Stutzer 2002; Di Tella and MacCulloch 2006; Clark et al. 2008). With the life satisfaction approach, self-reported 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.

The life satisfaction approach captures the residual effect of air pollution for which people are not already compensated in the housing market. Air pollution affects individuals' life satisfaction directly and indirectly through reduced costs of housing. Since the indirect effect is a countervailing, compensating effect, the willingness-to-pay (*WTP*) estimates from the life satisfaction approach have to be combined with *WTP* estimates from the hedonic method to recover the full *WTP* for clean air (van Praag and Baarsma 2005; see also appendix A.1.). 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.

The approach has been used to value (the residual effects of) climate (Frijters and van Praag 1998; Rehdanz and Maddison 2005; Becchetti et al. 2007), urban air pollution (Welsch 2002; 2006) and sulfur emissions (Di Tella and MacCulloch 2005), airport noise nuisance (van Praag and Baarsma 2005), urban regeneration schemes (Dolan and Metcalfe 2008), terrorism (Frey et al. 2007), and flood hazards (Luechinger and Raschky 2008). On a conceptual level, the life satisfaction approach is compared to the standard non-market valuation techniques in Frey et al. (2007) and Kahneman and Sugden (2005) and Dolan and Metcalfe (2008).

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 for Germany, a country with a large variation in pollution, both across space and over time. In our sample, mean SO_2 concentration fell from 43 $\mu g/m^3$ in the years 1985/1986 to 5 $\mu g/m^3$ in the years 2002/2003. Second, using the results of the life satisfaction and hedonic housing regressions, we calculate the total *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 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 rents is associated with potentially serious simultaneity problems (Chay and Greenstone 2005; Bayer et al. 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 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. The instrument is a difference-in-difference term with the retrofitting of power plants as treatment and with prevailing wind direction dividing 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 than the conventional estimates. This 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 controls for local unemployment, particulate pollution, reunification effects and rural/urban trends. Further, the effect is larger for individuals that are concerned about the environment and that 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 is in the range between €183 and €313 annually. In our hedonic housing regressions as well, we find a negative effect of SO_2 concentration on rents. The *MWTP* estimates are between €6 and €34 annually. Total *MWTP* estimates range from €217 to €319 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. 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; 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 statutory provisions are the result of a choice at the national level, they disproportionately benefit downwind regions compared to upwind regions.[1] Another important problem of the earlier papers is that there is a huge variation in the air quality within countries. Country level data, i.e. data on country-wide mean concentrations, cannot capture this huge within-country variation and 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. All these problems can be interpreted as measurement errors that 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.

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

[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.

well as our hedonic housing regressions. In section 4, we monetize the effect of air pollution 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 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 across regions and over 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 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. According to epidemiological studies, high SO_2 concentrations result in increased morbidity and premature mortality due to cardiovascular and respiratory diseases (e.g., Schwartz and Dockery 1992; Smith et al. 1994).

The German federal environmental agency (*Umweltbundesamt*; 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 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. In order to estimate the SO_2 concentration at all other locations, we 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):

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

The parameters have been suggested by the UBA, but interpolated values are similar for slightly different parameters.

In order to match the pollution data with the survey data, we aggregate the interpolated values on the level of German counties (*Kreise* and *kreisfreie Städte*) and estimate annual mean SO_2 concentrations.[2] The mean SO_2 concentration per county for the years 1985, 1990, 1995 and 2000 is depicted in Figure 1.

[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 Ruhr area in the west, Northern Hesse 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 large combustion plant ordinance (*Grossfeuerungsanlagenverordnung*) 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. It is important to note that time limits were statutorily fixed and depended on the capacity of a power plant and its actual emissions but that they were not in the discretion of the operating companies or regulatory bodies. With the 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. 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 mandated retrofitting of power plants, coupled with information on the geography of power plants and wind directions.

[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. The number of counties fell from 543 in 1993 to 439 in 2001 as several counties in the former GDR merged. The polygon data used for aggregation describe the boundaries of the 445 counties existing in 1996.

We use the changes in SO_2 concentration caused by the large combustion plant ordinance and consequent retrofitting of power plants as an instrument for SO_2 pollution. Our instrument in later stages of the analysis is the difference-in-difference term with desulfurization at power plants as the treatment and with counties assigned to control and treatment groups according to prevailing wind directions at power plants. In a standard difference-in-difference setting, this term would simply be the interaction of a dummy variable with value one if power plant j has installed a scrubber at time t, $1(scrubber)_{jt}$, and a dummy variable and with value one if county c lies downwind of power plant j, $1(downwind)_{cj}$. Hence, we would explain the SO_2 concentration in county c at time t, P_{ct}, as follows:

(2) $$P_{ct} = \alpha_0 + \alpha_2 1(scrubber)_{jt} \cdot 1(downwind)_{cj} + \chi_c + \tau_t + \varepsilon_{ct},$$

where χ_c and τ_t are county and time specific effects respectively.

We depart from this idealized setting in three respects. First, treatment and control group status is a matter of degree rather than one of kind. Although there is everywhere a predominant wind direction distinguishing counties into windward and leeward counties, wind directions can change. Therefore, the treatment group variable, $f(R_{cj})$, is the frequency that county c lies downwind of power plant j and the difference-in-difference term becomes $1(scrubber)_{jt} \cdot f(R_{cj})$.

Second, since we consider simultaneously all power plants j and all counties c, the treatment variable is a weighted sum of desulfurization at all power plants. The weights are the uncleaned, pre-desulfurization, emissions of the plants, E_j, and a distance decay function, $g(D_{cj})$. The new difference-in-difference term thus is $\sum_j E_j \cdot 1(scrubber)_{jt} \cdot g(D_{cj}) \cdot f(R_{cj})$.

The distance decay is modeled as an exponential curve with an implied characteristic decay distance of 480 km, $g(D_{cj}) = \exp(-2.1E\text{-}6 \cdot D_{cj})$, as suggested by field studies (Schwartz 1989; Summers and Fricke 1989). The decrease in concentration with distance captures both removal of material by deposition and dilution or dispersion caused by lateral or vertical mixing of air.

Third, some power plants shut down, others are newly built. Therefore, it is necessary to control for changes in the power plant population by introducing an additional term in equation 2 for the weighted sum of uncleaned emissions, $\sum_j E_j \cdot 1(active)_{jt} \cdot g(D_{cj}) \cdot f(R_{cj})$, where $1(active)_{jt}$ is a dummy variable indicating whether power plant j is active at time t. Taking all three departures into account, our difference-in-difference setting thus becomes:

$$(3) \quad P_{ct} = \alpha_0 + \alpha_1 \sum_j 1(active)_{jt} \cdot E_j \cdot g(D_{cj}) \cdot f(R_{cj}) - \alpha_1 \alpha_2 \sum_j 1(active)_{jt} \cdot E_j \cdot 1(scrubber)_{jt} \cdot g(D_{cj}) \cdot f(R_{cj}) + \chi_c + \tau_t + \varepsilon_{ct}.$$

In equation 3, the second term on the right hand side denotes the weighted sum of uncleaned SO_2 emissions, the third term denotes the weighted sum of retained SO_2 emissions. In later stages of the analysis, the weighted sum of retained SO_2 emissions – conditional on the weighted sum of uncleaned SO_2 emissions, county and time specific effects as well as on all the control variables introduced in section 3 – will be our instrument for air pollution. The identifying assumption 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.

We would also get to the specification in equation 3, if we start with the simple pollution model in equation 4 and then re-arrange terms:

$$(4) \quad P_{ct} = \alpha_0 + \alpha_1 \sum_j 1(active)_{jt} \cdot E_j \cdot (1 - \alpha_2 \cdot 1(scrubber)_{jt}) \cdot g(D_{cj}) \cdot f(R_{cj}) + \chi_c + \tau_t + \varepsilon_{ct}.$$

The formulation in equation 4 shows that we can estimate the average separation efficiency of scrubbers, α_2, by dividing the coefficient for the weighted sum of retained SO_2 emissions by the coefficient for the weighted sum of uncleaned SO_2 emissions.

As can be seen from equation 3, we require information on the pre-desulfurization SO_2 emissions of the 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, year of desulfurization, 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 (for details we refer to the appendix A.2.). 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. 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]

Table 1 presents the results of the regression in equation 3. 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 coefficients for the uncleaned and the retained emissions, we estimate a separation efficiency of 69%. We can compare the estimated separation efficiency with actual separation efficiencies. 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%. Hence, the estimated separation is close to, but marginally below, actual separation efficiencies.

[Table 1 about here]

The reason for instrumenting SO_2 concentration is its potential correlation with local economic activity. In order to assess the importance of this issue and in order to provide support for our instrumenting strategy, Table 2 presents the results from ‘pseudo first stage’ regressions, i.e. from regressions of important economic outcome variables on SO_2 concentration and on our instrument as well as on the full set of control variables introduced in section 3. The economic outcomes on the left hand side are the natural log of a respondent’s household labor income, household pre-government income (including asset flows, private retirement income and private transfers) and the respondent’s unemployment status.

[Table 2 about here]

Although the ultimate source of concern is a correlation between air pollution and *unobserved* economic outcomes, Table 2 confirms the conjecture that pollution and local economic activity are correlated and supports our instrumenting approach: While SO_2 concentration is correlated with unemployment and labor income, our instrument is not. Pre-government income is neither correlated with SO_2 concentration nor with the instrument. The actual first stage regressions in section 3 will show that the instrument is also uncorrelated with post-government income.

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 individual life satisfaction and rents. The baseline life satisfaction regressions are based on a panel for the period 1985-2003 consisting of 29,246 individuals who remain on average for 6.4 years in the panel. By combining household identifiers and the date the household moved to the current dwelling, we can construct unique dwelling identifiers and thus a panel at the dwelling level. Since the information is gathered at the level of households and not at the level of dwellings, the same dwelling can have different dwelling numbers if it is occupied by different GSOEP-households. However, it is important for the identification of pollution effects that it is not possible for two different dwellings to have the same dwelling identifier. The hedonic housing regressions are based on a panel for the period 1985-2003 consisting of 17,294 housing units with an average length in the panel of 3.7 years.

We relate the survey data to the pollution data at the county level. 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 main variables are individual life satisfaction, SO_2 concentration and income. Summary statistics for these variables are provided in Table 3, panel A. The GSOEP elicits individual life satisfaction with the following question: "How satisfied are you at present with your life, all things considered?" Responses run from 0 (completely dissatisfied) to 10 (completely satisfied).

[Table 3 about here]

Since we have no a priori reason to adopt a specific functional form for the pollution variable, we follow an approach proposed by Layard et al. (2008) for finding the correct functional form of the income variable. The functional form is determined by using a grid search over a range of parameter values of the following constant relative risk aversion (CRRA) function:

(5) $$f(P_{cst}) = \begin{cases} (P_{cst}^{1-\rho}) \cdot (1-\rho)^{-1} & \text{if } \rho \neq 1 \\ \ln(P_{cst}) & \text{if } \rho = 1 \end{cases}$$

This flexible form embeds convex, linear and concave functions. We compute the log likelihood for different values of the coefficient of risk aversion over the range from -2.0 to 2.0 in steps of 0.1. The log likelihood is maximized at ρ = -0.2. Thus, the functional form is slightly convex but remarkably close to linear. A log likelihood ratio test cannot reject the null of a linear relationship (see Table 3, panel B). Similarly, a log likelihood ratio test does not reject the model with only a linear term in favor of a model with an additional quadratic term. Therefore, we will model pollution linearly but also report how benefit estimates change if a CRRA function with ρ = -0.2 is used instead.

The other important explanatory variable is post-government household 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 (Gardner and Oswald 2007; Clark et al. 2008). 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, 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. By purging the estimates of biases related to unobserved costs of income generation, the instrument addresses one of the most pressing endogeneity problems. However, the instrument is not perfect: Occupational choice is endogenous to individual preferences (though individual specific fixed effects go some way in addressing this problem) and predicted income may also be interpreted as comparison income. Lacking better instruments, we follow 'best practice', acknowledge this issue and discuss the implications for the benefit estimates (see section 4).

Based on existing results regarding the functional form of income (Layard et al. 2008), we include household income in its natural logarithm; we 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 commonly used observable *time-varying* predictors of life satisfaction (Frijters et al. 2004; Ferrer-i-Carbonell 2005). These are age, 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

[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.

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 et al. (2004), we include state specific time trends along with a full set of state and year fixed effects. Our sample only includes individuals that stay put in their county, i.e. we exclude all individuals moving across county boundaries. Therefore, all county specific effects are absorbed by the individual specific fixed effects. A fixed effect model is appropriate as fixed personality traits are important predictors of life satisfaction and correlated with various variable of interest. Failure to control for this source of heterogeneity with individual specific fixed effects would lead to biased estimates of the corresponding coefficients (Ferrer-i-Carbonell and Frijters 2004).

Another source of individual heterogeneity relates to differences in preferences for air quality. If individuals are differently affected by air pollution, a sorting equilibrium may occur with the least sensitive individuals living in the most polluted areas. We would then observe the largest changes in air pollution for the least sensitive individuals. While taste sorting is theoretically plausible and almost certainly affects our *WTP* estimates, our setting does not allow us to address this issue empirically. Empirical evidence on taste sorting in the context of hedonic property studies for the US suggests that heterogeneity at aggregate levels such as counties and the resulting bias in *WTP* estimates is small (Chay and Greenstone 2005).

Following from the previous discussion, the equation to be estimated in the second stage is

$$(6) \qquad LS_{icst} = \beta_0 + \beta_1 P_{cst} + \beta_2 \ln(m_{icst}) + \beta_3 Z_{icst} + \beta_4 trend_{st} + \tau_t + \iota_i + \varepsilon_{icst},$$

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, $trend_{st}$ state specific time trends, τ_t year effects, ι_i individual (and thereby also county) fixed effects, and ε_{icst} an error term. Robust standard errors are adjusted for clustering on county and year level.

Life satisfaction scores are reported on an ordinal scale. However, assuming ordinality or cardinality of life satisfaction scores makes usually little difference (Ferrer-i-Carbonell and Frijters 2004). This is also the case here. For ease of interpretation, we report the full results based on a cardinal interpretation but we also present benefit estimates based on Probit adjusted OLS (Ferrer-i-Carbonell and van Praag 2004). With this method, a linear model is estimated for a transformed dependent variable, namely the expectation of a double truncated standard normal variate where the truncation points are derived from the marginal distribution of the satisfaction variable.

3.2.2 Basic results

Table 4 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.

[Table 4 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 previous estimates, 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 size of the conventional estimate of SO_2 on life satisfaction (column I of Table 4) is only 58% of the size of the instrumental variable estimate (column II). This finding is consistent with the conjecture that improvements in air quality are accompanied by negative developments. 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.

Income has a positive effect on life satisfaction that is highly statistically significant. The estimated effect of log household income on life satisfaction more than triples if income is instrumented compared to the conventional estimates.[4] This change is of similar magnitude as the one reported by Luttmer (2005) and suggests that the OLS estimates are indeed biased.

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, 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.

In all cases, the statistical tests suggest that the instruments are relevant. Shea's partial R^2s are nearly identical to standard R^2s, 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 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. As a first robustness test we include therefore annual unemployment rates at county level and annual mean concentration of total suspended particulates (TSP) as additional controls.

From columns I and II of Table 5, we see that the estimates are robust to the inclusion of the local unemployment rate and TSP concentration. The robustness of the conventional estimate contrasts somewhat with the picture that emerges from the difference in the magnitude of

[4] The conventional income estimate lies between 0.150 (std. err.: 0.012) if pollution is instrumented and 0.151 (std. err.: 0.012) if it is not. The results are not shown in Table 4 but are available upon request from the authors.

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 5 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 et al. 2001).

[Table 5 about here]

Another worry might be that our results are largely driven by the development in East Germany. The retrofitting of power plants in the territory of the former GDR and the associated improvement in air quality were a direct result of the German reunification (see section 2). As a second robustness we therefore exclude all East German observations. The results are depicted in columns III and IV of Table 5. The size of the conventional decreases by more than 50% and the statistical significance falls below conventional levels. In contrast, the instrumental variable estimate is largely robust to the exclusion of the East German observations (the size of the coefficient decreases by 14%).

While people living in East Germany are the ones most likely to benefit from reunification effects, people in West German counties close to the East-West German border may benefit as well. Redding and Sturm (2008) show that West German cities located within 75 kilometers of the East-West German border experienced a substantial decline in population growth relative to other West German cities as a consequence of the German division after the Second World War. Similarly, in the aftermath of the German reunification these cities experienced a relative increase in the population growth, although this latter effect is smaller. Following the analysis of Redding and Sturm (2008), we interact a dummy variable with value one for counties within 75 kilometers of the East-West German border with the full set of year effects. In addition, in order to control for possible urban/trends, we include year specific distance-to-city effects.[5] The results are depicted in columns V and VI of Table 5.

In comparison to column III of Table 5, the coefficient of the conventional estimate in column V increases by 18% in absolute terms and is again narrowly statistically significant. The instrumental variable estimate is again more robust. In absolute terms, the coefficient decreases by around 6%. These changes are the net effect of a decrease in the size of the pollution estimates caused by the inclusion of the interaction of year effects with the dummy variable for counties close to the East-West border and an increase of the size of the pollution estimates caused by the inclusion of the year specific distance effects. All changes are much more pronounced for the conventional estimate than for the instrumental variable estimate. Including year specific distance effects in the whole sample slightly increases the size of the pollution estimates (results are available upon request).

Controlling for additional variables and excluding observations is one way to check the robustness and plausibility of the results. Another is to interact the SO_2 concentration with 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 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 6 tabulates row percentages of the number of observations in each category against deciles of SO_2 concentration. Generally, 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 1,344

[5] In our analysis, we consider all cities that had 100,000 or more inhabitants at some point in time over the sample period.

observations in the least populated cell (10^{th} decile of SO_2 concentration · unconcerned respondents). In the analysis bellow, we compare the strongly and moderately concerned individuals against the unconcerned individuals.

[Table 6 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 above the median as belonging to the risk group.

Table 7 reports the average effects of SO_2 concentration on the life satisfaction in the various subgroups. Columns I and III depicts the results for the West German sample, columns II and IV for the whole sample.

[Table 7 about here]

In both samples, environmentally concerned people and people belonging to the risk group are more severely affected by air pollution than the rest of the population. For these subgroups, the effect is negative and statistically significantly in all cases (see bottom rows of Table 7).

To sum up our results: First and most importantly, we find negative effects of SO_2 concentration on life satisfaction. The size of the effect is larger for the instrumental variable estimate than for the conventional estimate. 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. Excluding East German observations and controlling for reunification effects in West German counties close to the East-West German border reduces the size of the effect for the conventional estimate and, conversely, controlling for rural/urban trends increases the size of the effect. The instrumental variable estimate is much more robust to these changes. Finally, differential effects for different groups of respondents imply that it is indeed air pollution that affects life satisfaction and not other simultaneous 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 (see appendix A.1. for a theoretical discussion). 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 the major air quality regulation were enacted before our sample period, capitalized expectations would bias our estimates downwards. 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 US). Rents for vacant dwellings can be freely negotiated between landlords and potential tenants. There are some restrictions on evictions 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).

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 (e.g., Mendelsohn 1992 for repeat sale models). In accordance with the life satisfaction regressions, we control for state specific time trends and year effects; state and county specific effects are absorbed by the dwelling effects. Economic theory provides no a priori reason to prefer one functional form for the hedonic price function over others (Rosen 1974) but, in general, simple forms have proven to outperform more flexible ones (Cropper et al. 1988). Therefore, we estimate semi-log hedonic rent regressions as specified in equation 7:

$$\ln(R_{icst}) = \gamma_0 + \gamma_1 P_{cst} + \gamma_2 trend_{st} + \tau_t + o_i + \varepsilon_{icst}, \qquad (7)$$

where R_{icst} is the rent of dwelling i in county c and state s at time t, P_{cst} SO_2 pollution, $trend_{st}$ 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. 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, which are subject to comparatively strict regulation, and institutional households such as nursing homes and barracks.

3.3.2. Results

Table 8 presents the hedonic housing regressions, column I the conventional estimate and column II the instrumental variable estimate.

[Table 8 about here]

Pollution has a negative effect on housing rents. However, the instrumental variable estimate is smaller (in absolute terms) compared to the conventional estimate and it is not statistically significant. The relative size of the effect of the conventional and instrumental variable estimates is contrary to prior expectations: As with the life satisfaction regressions, we would expect the instrumental variable estimate to be larger than the conventional estimate.

4. Implicit willingness-to-pay

With the estimated coefficients of the life satisfaction regressions 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 6, the *CS* is defined as follows:

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

where m_{i0} is initial household income and ΔP_i the improvement in air quality, P_{i0}-P_{i1}. Based on equation 8, we estimate the *WTP* for marginal changes in air quality. In order to calculate the total *WTP* for improvements in air quality, we add these estimates to the hedonic rent gradients.

We calculate the *WTP* for households that are contained in both samples, i.e. the sample for the life satisfaction regressions and the sample for the hedonic housing regressions. These household have an average household income of €21,462 and average rental costs of €3,871 (in 2002 €). The estimates are based on the coefficients reported in Table 4 for the life satisfaction approach and on the coefficients in Table 8 for the hedonic method. For the life satisfaction approach, we will also report estimates based on other specifications.

[Table 9 about here]

According to the results in Table 9, the *MWTP* estimates based on the life satisfaction approach are €183 for the conventional estimate and €313 for the instrumental variable estimate or, in percent of household income, 0.9% and 1.5%. If we give up the cardinal interpretation of satisfaction scores and use the coefficients based on Probit adjusted OLS estimates (complete results are available upon request), the *MWTP* estimates increase by between 6% and 8% to €193 (std. err.: €43) and €339 (std. err.: €146) or to 0.9% (std. err.: 0.2%) and 1.6% (std. err.: 0.7%) of household income, respectively. If the effect of pollution on life satisfaction is modeled with the CRRA function in equation 5 and a risk aversion coefficient of -0.2, the *MWTP* estimates decrease by between 15% and 22% to €143 (std. err.: €32) and €264 (std. err.: €114) or to 0.7% (std. err.: 0.1%) and 1.2% (std. err.: 0.5%) of household income. Finally, if we use the coefficients for the West German sample reported in columns III and IV of Table 5, the *MWTP* estimates are between 53% and 94% of the *MWTP* estimates for the whole sample: €98 (std. err.: €69) or 0.5% (std. err.: 0.3%) of household income for the conventional estimate and €294 (std. err.: €145) or 1.4% (std. err.: 0.7%) of household income for the instrumental variable estimate.

The implicit prices for clean air reflected in the housing market are much smaller and lie between €6 and €34 or between 0.03% and 0.2% of household income (with only the latter estimate being statistically significant). As reported in appendix A.3., the average *MWTP* estimate for a reduction in SO_2 published in the literature is between €483 (if all estimates are considered) and €487 (if only positive and significant estimates are considered). With a real interest rate of around 1.2% per annum, a lump-sum payment of €483 to €487 equals an annual *CS* of €6 paid in perpetuity, i.e. the lower *MWTP* based on the hedonic method in Table 9. With a real interest rate of around 7.0% per annum, it equals an annual *CS* of €34, the higher *MWTP* in Table 9. Hence, our *MWTP* estimates based on the hedonic method are broadly comparable to the estimates published in the literature.

By summing the estimates in Table 9 from the two methods, we get total *MWTP* estimates in the range of €218 and €318 (1.0% and 1.5% of household income, respectively). Further, the results in Table 9 suggest that at most around 16% 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. In the following, we discuss three potential reasons for these interrelated findings: (i) Migration costs and (ii) incomplete information on pollution levels and risks can both explain the low implicit price in the housing markets; (iii) problems associated with estimating the marginal effect of income can explain why the life satisfaction approach estimates are large in absolute terms as well as relative to the hedonic housing estimates.

Mobility costs imply that changes in rents understate the true value of a change in air quality. If in a county air quality improves, 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 reflects 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 et al. (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).

As with mobility costs, the fact that individuals base their moving decisions on the perceived rather than objective effects and levels of air pollution is likely to bias the hedonic estimates downwards. To correctly anticipate the effect of air pollution at a particular location, a prospective house buyer or renter requires adequate knowledge of pollution risks or dose-response relationships *and* adequate information about prevailing pollution levels. Distorted risk perceptions may bias hedonic estimates in either direction since people may underestimate or exaggerate the risk of pollution. In contrast, incomplete information about prevailing pollution levels invariably attenuates price gradients towards zero (e.g., Pope 2006 for a theoretical discussion). Several studies suggest that individuals' information void on location specific amenity levels and the resulting downward bias in hedonic estimates may be large. Brookshire et al. (1985) and Troy and Romm (2004) find no price discounts for properties in areas with elevated risks of earthquakes and flooding before laws have been passed that require sellers of property to disclose information on earthquake and flood risks, but large and significant price discounts thereafter. Similarly, Pope (2006) finds the introduction of mandatory disclosure requirements to increase the marginal valuation of airport noise by 36%.

Distorted perceptions are of particular importance for the capitalization of health effects. Smith and Huang (1995) provide evidence consistent with the notion of incomplete capitalization of health effects. Benefit estimates for improvements in air quality in selected US cities based on dose-response functions and value of statistical life estimates are around 4 times higher than benefit estimates based on hedonic studies. Of course, incomplete information 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.

The life satisfaction approach is less afflicted by distorted risk perceptions. Most importantly, it can capture indirect effects of externalities that affect individuals' life satisfaction through a process unnoticed by the individuals themselves. For example, it can capture the utility consequences of health effects even if individuals are ignorant about the causes. Further, long-term residents of a county are arguably better informed about prevailing pollution levels than prospective house buyers and renters who consider moving to that county. This is not to say that perceptions are completely unimportant for the life satisfaction approach. To the extent that perceptions of local pollution levels have direct effects on life satisfaction, distorted risk perceptions affect life satisfaction estimates as well. However, the above discussion suggests distorted perceptions are much more important for the hedonic method than for the life satisfaction approach.

A related aspect is the notion of two different concepts of utility, decision and experienced utility (Kahneman et al. 1997). 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.

The third explanation concerns a crucial element of the life satisfaction approach, the estimation of the marginal utility of income. Instrumenting income is inherently difficult and – as discussed in section 3.2.1 – our efforts may fall short of completely resolving all endogeneity and omitted variable problems. Two pieces of evidence suggest that an underestimation of the effect of income on life satisfaction contributes the large *MWTP* estimates. First, large implicit monetary valuations of intangibles are a prevalent finding in the life satisfaction literature, not only in the case of the valuation of public goods (see references in section 1) but also in the case of the valuation of life events such as unemployment and divorce (e.g., Blanchflower and Oswald 2004). Second, the trade-off ratios between air pollution and other personal characteristics are not particularly large. To illustrate this point, we look at the effect of changes in air pollution relative to the psychological costs of changes in the local unemployment rate.

For an employed individual, the negative effect of an increase in the local unemployment rate is the sum of the general negative effect of high unemployment rates on society shown in

Table 5 plus the increase in the likelihood of falling unemployed themselves (Di Tella et al. 2001). In the case of a full-time employed individual and an increase of the unemployment rate by 1 percentage point, the latter effect is approximately -0.0055 (-0.55 · 0.01). Thus a decrease in SO_2 concentration by 1 $\mu g/m^3$ is offset by an increase in the local unemployment rate by between 0.24 percentage points (conventional estimate) and 0.34 percentage points (instrumental variable estimate). Alternatively, the effect on life satisfaction of a decrease in pollution by its mean (16.68 $\mu g/m^3$) would be between 39% and 56% of the effect of a reduction in the local unemployment rate by its mean (10.16%), the effect of a decrease in pollution by one standard deviation (17.67 $\mu g/m^3$) would be between 92% and 130% of the effect of a reduction in the local unemployment rate by one standard deviation (4.64%). In interpreting these figures, it is important to note that we only capture the psychological costs of unemployment because German employees are protected by a relatively generous unemployment insurance, because we hold income constant and because fiscal effects cannot be identified in the current empirical setting. Arguably, taking all monetary and fiscal consequences of unemployment into account would make changes in the local unemployment rate much more important than changes in local air pollution.

Investigating the relationship between income and life satisfaction is a fast growing area of research (see Clark et al. 2008 for a review). Therefore, better estimates of the marginal utility of income will come forward. However, the question about the effect of income on life satisfaction 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. 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; Senik 2004; Ferrer-i-Carbonell 2005; Luttmer 2005), own past income (Clark 1999; Di Tella et al. 2005) and income aspirations (Easterlin 2001; Stutzer 2004). Such relative concerns have important implications for the valuation of public goods. If people adapt to income levels, short-run utility consequences will differ from the long-run marginal utility of income and, consequently, the short-run evaluation of public goods will differ from the long-run evaluation. 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 private 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 for Western Germany range between €35 and €180 per year and household (Schulz 1985; Schärer and Haug 1990).

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, the net effect of air quality regulations may well exceed the one experienced by Western countries.

Regarding the benefits of air quality, this paper 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 et al. 2006), our evidence is based on a new approach, the life satisfaction approach.

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 and on the difference between various utility concepts. These latter issues also raise difficult questions as to which measure is appropriate for policy evaluation.

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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 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 equilibrium, wages and rents must adjust to equalize utility across locations. Otherwise, some individuals would have an incentive to move (e.g., Roback 1982). Hence we have $v(a, m(a), r(a)) = k$ in all locations. By totally differentiating and rearranging we obtain:

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

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

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

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 information on pollution levels and risks is complete and the equilibrium condition holds, individuals' *MWTP* for clean air can be inferred from rent and wage gradients. However, because of migration costs and incomplete information, the effects of air pollution will 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*:

(11) $$p_a = h \cdot \mathrm{d}r/\mathrm{d}a - \mathrm{d}m/\mathrm{d}a = (\delta v/\delta a)/(\delta v/\delta m) - (\mathrm{d}v/\mathrm{d}a)/(\delta v/\delta m) < (\delta v/\delta a)/(\delta v/\delta m).$$

The life satisfaction approach does not rely on observed behavior but regresses life satisfaction, as a proxy for the underlying latent variable utility, on air quality and income. The estimated coefficient for air quality corresponds to the term $\mathrm{d}v/\mathrm{d}a$ in equation 9. Hence, 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 $\mathrm{d}m/\mathrm{d}a = \mathrm{d}r/\mathrm{d}a = 0$. 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 $E(\tilde{\beta}_1) = \beta_1 + \beta_2 \sum((a_i - \bar{a})m_i) / \sum(a_i - \bar{a})^2 + \beta_3 \sum((a_i - \bar{a})r_i) / \sum(a_i - \bar{a})^2$, which corresponds to d$v$/d$a$ in equation 9.

Theoretically, housing costs and wages could be included in the set of explanatory variables in life satisfaction regressions and, thus, the full effect could be recovered. However, even if housing rents are available, it may not be advisable to include them in life satisfaction regression if it is not possible to control for all relevant observed and unobserved housing characteristics. This is also the case here. In order to control for unobserved housing characteristics, we would have to include the full set of dwelling specific effects. Even if these effects are absorbed by individual specific effects for individuals that stay put in their dwelling, we would need to include 10,703 dwelling specific effects for movers. Such a model is beyond the memory capacity of the host of a remote access to the GSEOP data (SOEPremote at DIW) that we have to use because German data protection laws do not allows us to have the regional data on our local computer. (Including rents without dwelling specific effects, leaves the coefficient for air pollution virtually unaffected; results are available upon request). Similarly, since we use instrumental variables for household income, the endogenous part of income is excluded. Thus, the coefficient for air quality captures only the residual effect that is not capitalized in private markets, i.e. dv/da (< $\delta v / \delta a$). The residual effect can be monetized with the marginal utility of income as shown in equation 12:

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

The sum of the implicit hedonic price in equation 11 plus the residual shadow benefit in equation 12 yields the correct *MWTP* for clean air. As in previous studies (e.g., Chay and Greenstone 2005; Bayer et al. 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.

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, the technical literature or a route planner. Otherwise, the centroid of the zip code is assumed as 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):

$$\eta_j = \underset{(3.76)}{9.6\text{E-}4} \cdot \mathit{start\ year}_j + \underset{(6.98)}{9.9\text{E-}5} \cdot \mathit{capacity}_j \underset{(-1.25)}{-0.035} \cdot 1(\mathit{lignite})_j + \underset{(0.27)}{0.008} \cdot 1(\mathit{sub\text{-}bituminous\ coal})_j +$$

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

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

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

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

$R^2 = 0.727$, Prob > 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

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

This calculation overstates emissions because the assumption of constant full utilization is not plausible but we lack data on utilization rates. Moreover, the procedure allows us 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 (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 and 1995.

A.3 *MWTP* estimates reported in the literature

This appendix presents 34 estimates of *MWTP* for a reduction in SO_2 concentrations by 1 $\mu g/m^3$ for 6 cities reported in 5 different studies. These are all benefit estimates in the literature that can be expressed as *MWTP* for a reduction in SO_2 concentrations by 1 $\mu g/m^3$.

[Table A.3. about here]

Table 1. Effect of power plant emissions and flue gas desulfurization on SO_2 concentration

Dependent variable SO_2 ($\mu g/m^3$) concentration	Coef.	t-value
Emissions from power plants		
Weighted sum of uncleaned SO_2 emissions	1.4E-5**	17.64
Weighted sum of retained SO_2 emissions	-9.9E-6**	-36.46
County specific effects	Yes	
Year specific effects	Yes	
Number of observations		8,455
Prob > F		0.000
R^2		0.672
ΔR^2 due to inclusion of emission terms		0.065
	Coef.	St. Err.
Estimated separation efficiency	-0.686**	0.042

Notes: (1) OLS estimates; (2) ** is significant at the 99% level. (3) Standard error for the effect of flue gas desulfurization is estimated using the delta method.

Table 2. Partial correlations between economic outcomes and SO_2 and predicted ΔSO_2

Dependent variable	Unemployed		ln(labor income)		ln(pre govt. income)	
	Coef.	t-value	Coef.	t-value	Coef.	t-value
SO_2 ($\mu g/m^3$)	-4.9E-20$^{(*)}$	-1.74	0.002 *	2.12	0.001	1.57
Control variables	Yes (see Table 4)		Yes (see Table 4)		Yes (see Table 4)	
Predicted ΔSO_2	2.2E-20	0.53	-2.8E-4	-0.39	-0.001	-0.82
Control variables	Yes (see Table 4)		Yes (see Table 4)		Yes (see Table 4)	

Notes: (1) Coefficients and t-values are from 'pseudo first stage' regressions analogous to the ones in Table 4. (2) OLS estimates. (3) * is significant at the 95% level, and $^{(*)}$ at the 90% level.

Table 3. Summary statistics of main variables and functional form of SO_2 variable

A. Summary statistics			
Individual panel (186,628 observations)	Mean	Median	Std. Dev.
Life satisfaction	7.07	7.00	1.75
SO_2 (μg/m^3)	16.68	9.71	17.67
ln(post govt. income)	10.20	10.25	0.59
Housing panel (64,672 observations)			
ln(rent)	5.75	5.83	0.65
SO_2 (μg/m^3)	17.70	9.55	19.85

B. Functional form of SO_2 variable			
Functional form	M.E. at mean	LR statistics	P > χ^2
CRRA function with ρ = -0.2	-0.004	2.17	0.140
2nd order polynomial	-0.005	0.58	0.446
Linear	-0.005	-	-

Notes: (1) 'M.E. at mean' is the marginal effect of SO_2 on life satisfaction at its sample mean of 16.68 μg/m^3. (2) The likelihood ratio (LR) statistics is asymptotically distributed as χ^2 with one degree of freedom.

Table 4. Basic results: effect of SO_2 pollution on life satisfaction

A. Second stage regression				
Dependent variable	I		II	
Life satisfaction	Coef.	z-value	Coef.	z-value
Pollution				
SO_2 (μg/m^3)	-0.005**	-5.86	-0.008*	-2.46
HH income				
ln(post govt. income)	0.548**	8.36	0.548**	8.36
HH size$^{1/2}$	-0.445**	-9.67	-0.448**	-9.73
Personal characteristics				
Age below 21	Reference group		Reference group	
Age 21-30	-0.076**	-3.03	-0.073**	-2.91
Age 31-40	-0.051	-1.57	-0.050	-1.53
Age 41-50	-0.055	-1.38	-0.053	-1.32
Age 51-60	5.E-4	0.01	0.002	0.04
Age 61-70	0.233**	4.18	0.234**	4.19
Age above 70	0.146*	2.23	0.146*	2.24
Not disabled	Reference group		Reference group	
Disabled	-0.232**	-10.62	-0.233**	-10.68
Single, no partner	Reference group		Reference group	
Single, with partner	0.212**	7.20	0.210**	7.13
Married	0.255**	8.46	0.255**	8.44
Separated, no partner	-0.218**	-3.60	-0.220**	-3.64
Separated, with partner	0.120	1.24	0.120	1.24
Divorced, no partner	0.012	0.26	0.011	0.22
Divorced, with partner	0.339**	6.41	0.340**	6.43
Widowed, no partner	-0.260**	-5.01	-0.261**	-5.03
Widowed, with partner	0.299**	3.08	0.297**	3.05
Spouse in home country	-0.066	-0.65	-0.069	-0.68
No children in HH	Reference group		Reference group	
Children in HH	0.126**	7.19	0.127**	7.22
German citizen	Reference group		Reference group	
EU citizen	-0.211*	-2.11	-0.212*	-2.12
Non-EU foreigner	-0.085	-1.46	-0.084	-1.42
Not working	Reference group		Reference group	
Retired	0.097**	3.95	0.097**	3.92
In education	0.229**	6.87	0.228**	6.86
Maternity leave	0.142**	4.08	0.144**	4.13
Military, community service	-0.004	-0.07	-0.004	-0.08
Unemployed	-0.418**	-16.73	-0.418**	-16.72
Sometimes working	0.005	0.12	0.007	0.16
Full-time employment	0.140**	4.79	0.142**	4.84
Part-time employment	0.003	0.10	0.003	0.13
Vocational training	0.070	1.05	0.073	1.08
Other employment	-0.042	-1.07	-0.041	-1.05

To be continued.

Table 4, part 2

	I		II	
	Coef.	z-value	Coef.	z-value
Blue collar worker	Reference group		Reference group	
Trainee	0.147*	2.44	0.146*	2.43
Public service employee	-0.054	-1.33	-0.052	-1.28
White collar worker	0.012	0.76	0.012	0.77
Managerial position	0.078**	3.12	0.080**	3.17
Temporary employment	-0.028	-1.29	-0.028	-1.31
Permanent employment	0.042**	3.31	0.043**	3.38
Job tenure	-0.004**	-5.26	-0.004**	-5.33
Actual working hours	1.E-4*	2.26	9.E-5*	2.20
First interview	0.172**	9.89	0.179**	9.62
Second interview	0.045**	2.83	0.055**	2.88
Third and later interviews	Reference group		Reference group	
City, district size				
Less than 2,000	Reference group		Reference group	
Less than 20,000	0.016	0.48	0.016	0.47
Less than 100,000	0.047	1.12	0.047	1.12
Less than 500,000	-0.004	-0.07	-0.004	-0.05
Over 500,000	0.026	0.34	0.027	0.36
Predicted uncleaned emissions				
Predicted uncleaned emissions			-0.004*	-2.49
State specific time trends	Yes		Yes	
Year specific effects	Yes		Yes	
Individual specific effects	Yes		Yes	
Prob > F		0.000		0.000
R^2 within		0.029		0.029
R^2 between		0.025		0.050
R^2 overall		0.029		0.044
B. First stage regressions				
	Coef.	t-value	Coef.	t-value
Dependent variable				
SO_2 ($\mu g/m^3$)				
Excluded instruments				
Predicted ΔSO_2			-0.291**	-16.87
Predicted income			0.019	1.44
Tenure income earner			-0.011*	-2.38
Predicted uncleaned emissions				
Predicted uncleaned emissions			0.080(*)	1.68
Included instruments			Yes	
Dependent variable				
ln(post govt. income)				
Excluded instruments				
Predicted ΔSO_2			2.E-4	1.07

To be continued.

Table 4, part 3

	I		II	
	Coef.	z-value	Coef.	z-value
Predicted income	0.023 **	34.09	0.023 **	34.06
Tenure income earner	0.005 **	24.99	0.005 **	25.09
Included instruments	Yes		Yes	
Number of observations		186,628		186,628
Number of individuals		29,246		29,246
Avg. no. of obs. per individual		6.4		6.4
Number of clusters		7,118		7,118
Shea's partial R^2 for SO_2				0.061
Bound et al. partial R^2				0.061
F-statistics of excluded instruments				99.54
Shea's partial R^2 for ln(post govt. income)		0.028		0.028
Bound et al. partial R^2		0.028		0.028
F-statistics of excluded instruments		1074.69		718.01
Anderson LR statistic (p-value)		0.000		0.000
Hansen's J statistic (p-value)		0.195		0.214

Notes: (1) IV estimates with individual fixed effects; SO_2 concentration is instrumented with the effect of flue gas desulfurization at power plants estimated; 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. (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 5. Robustness checks

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**	-5.78	-0.008*	-2.14	-0.002	-1.47	-0.007*	-2.10	-0.003(*)	-1.74	-0.007(*)	-1.70
TSP ($\mu g/m^3$)	-0.001(*)	-1.95	-0.001	-0.93								
Unemployment rate												
Unemployment rate	-0.014**	-2.95	-0.018**	-3.12								
Year spec. distance to city	No		No		No		No		Yes		Yes	
Year spec. close to East Germ.	No		No		No		No		Yes		Yes	
HH income												
ln(post govt. income)	0.547**	8.35	0.548**	8.36	0.500**	7.34	0.502**	7.36	0.501**	7.35	0.503**	7.37
Personal characteristics	Yes		Yes		Yes		Yes		Yes		Yes	
City, district size	Yes		Yes		Yes		Yes		Yes		Yes	
Predicted uncleaned emissions	No		Yes		No		Yes		No		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		0.029		0.029		0.033		0.033		0.033		0.033
R^2 between		0.030		0.051		0.048		0.039		0.048		0.033
R^2 overall		0.032		0.045		0.047		0.038		0.047		0.033
B. First stage regressions												
Dependent variable												
SO_2 ($\mu g/m^3$)												
Excluded instruments												
Predicted ΔSO_2			-0.259**	-15.49			-0.306**	-17.13			-0.283**	-13.66
Predicted income			0.019	1.45			0.012	1.30			0.004	0.48
Tenure income earner			-0.011*	-2.22			0.001	0.24			0.002	0.90

To be continued.

Table 5, 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
Predicted uncleaned emissions			Yes				Yes				Yes	
Predicted uncleaned			0.054	1.14			0.306**	6.12			0.128**	3.84
Included instruments			Yes				Yes				Yes	
Dependent variable												
ln(post govt. income)												
Excluded instruments												
Predicted ΔSO_2			1.8E-4	0.92			1.8E-4	0.88			-1.0E-6	0.00
Predicted income	0.023**	34.09	0.023**	34.04	0.024**	30.26	0.024**	30.25	0.024**	30.35	0.024**	30.36
Tenure income earner	0.005**	25.01	0.005**	25.10	0.005**	24.10	0.005**	24.09	0.005**	24.08	0.005**	24.08
Included instruments			Yes				Yes				Yes	
Number of observations		186,628		186,628		147,781		147,781		147,781		147,781
Number of individuals		29,246		29,246		22,881		22,881		22,881		22,881
Avg. no. of obs. per individual		6.4		6.4		6.5		6.5		6.5		6.5
Number of clusters		7,118		7,118		5,540		5,540		5,540		5,540
Shea's partial R^2 for SO_2				0.048				0.190				0.169
Bound et al. partial R^2				0.048				0.190				0.169
F-statistics of excluded instruments				85.22				98.64				62.86
Shea's partial R^2 for ln(post govt. inc.)		0.028		0.028		0.030		0.030		0.030		0.031
Bound et al. partial R^2		0.028		0.028		0.030		0.030		0.030		0.031
F-statistics of excluded instruments		1075.23		718.05		918.04		612.72		919.43		613.32
Anderson LR statistic (p-value)		0.000		0.000		0.000		0.000		0.000		0.000
Hansen's J statistic (p-value)		0.172		0.183		0.377		0.391		0.373		0.369

Notes: (1) IV estimates with individual fixed effects; SO_2 concentration is instrumented with the effect of flue gas desulfurization at power plants; 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. (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. SO_2 pollution and environmental concerns (row percentages)

SO_2 deciles	Environmental concerns		
	Very concerned	Somewhat concerned	Not Concerned
1st	23%	62%	15%
2nd	24%	61%	15%
3rd	26%	61%	13%
4th	28%	60%	12%
5th	33%	56%	10%
6th	40%	52%	8%
7th	47%	46%	7%
8th	49%	44%	7%
9th	49%	43%	7%
10th	47%	46%	7%
Total	37%	53%	10%

Notes: N = 185,605.

Table 7. Interaction effects: effect of SO_2 pollution on life satisfaction for different groups

Dependent Variable	I		II		III		IV	
Life satisfaction	Coef.	z-value	Coef.	z-value	Coef.	z-value	Coef.	z-value
Pollution and interaction terms								
SO_2 ($\mu g/m^3$)	0.002	1.14	-3.6E-4	-0.30	-0.002	-0.94	-0.004**	-4.50
SO_2 · concerned	-0.005**	-4.15	-0.005**	-4.77				
SO_2 · risk group					-0.002*	-2.34	-0.002**	-3.60
Subgroups								
Not concerned at all	Reference group		Reference group					
Concerned	-0.059**	-2.80	-0.051**	-2.79				
Not in risk group					Reference group		Reference group	
Risk group					0.049**	3.03	0.053**	3.98
HH income								
ln(post govt. income)	0.492**	7.17	0.539**	8.18	0.508**	7.46	0.559**	8.54
Personal characteristics	Yes		Yes		Yes		Yes	
City, district size	Yes		Yes		Yes		Yes	
State specific time trends	Yes		Yes		Yes		Yes	
Year specific effects	Yes		Yes		Yes		Yes	
Individual specific effects	Yes		Yes		Yes		Yes	
Number of observations		146,924		185,605		147,781		186,628
Number of individuals		22,881		29,189		22,828		29,246
Avg. no. of obs. per individual		6.5		6.4		6.4		6.4
Number of clusters		5,537		7,115		5,540		7,118
Prob > F		0.000		0.000		0.000		0.000
R^2 within		0.034		0.031		0.032		0.029
R^2 between		0.048		0.026		0.047		0.026
R^2 overall		0.048		0.029		0.047		0.029
Marginal Effect of SO_2 for	M.E.	z-value	M.E.	z-value	M.E.	z-value	M.E.	z-value
Not concerned	0.002	1.14	-3.6E-4	-0.30				
Concerned	-0.003(*)	-1.82	-0.005**	-6.21				
Not in risk group					-0.002	-0.94	-0.004**	-4.50
Risk group					-0.003*	-2.06	-0.006**	-6.81

Notes: (1) IV estimates with individual fixed effects; 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. (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 8. Hedonic housing regression: effect of SO_2 pollution on monthly rents

A. Second stage regression				
Dependent variable	I		II	
ln(monthly rent, excl. heating costs), 2002 euro	Coef.	z-value	Coef.	z-value
Pollution				
SO_2 ($\mu g/m^3$)	-0.009**	-4.20	-0.002	-0.45
Predicted uncleaned emissions				
Predicted uncleaned emissions			0.001	0.55
State specific time trends	Yes		Yes	
Year specific effects	Yes		Yes	
Dwelling specific effects	Yes		Yes	
Prob > F		0.000		0.000
R^2 within		0.527		0.508
R^2 between		0.002		0.028
R^2 overall		0.000		0.019
B. First stage regressions				
Dependent variable				
SO_2 ($\mu g/m^3$)				
Excluded instrument				
Predicted ΔSO_2			-0.303**	-14.55
Predicted uncleaned emissions				
Predicted uncleaned emissions			0.091$^{(*)}$	1.77
Included instruments			Yes	
Number of observations		64,672		64,672
Number of dwellings		17,294		17,294
Avg. no. of obs. per individual		3.7		3.7
Number of clusters		7,111		7,111
Shea's partial R^2 for SO_2				0.040
Bound et al. partial R^2				0.040
F-statistics of excluded instruments				211.65
Anderson LR statistic (p-value)				0.000

Notes: (1) IV estimates with dwelling fixed effects; SO_2 concentration is instrumented with the effect of flue gas desulfurization at power plants. (2) Standard errors are adjusted for clustering on county and year level. (3) ** is significant at the 99% level, and $^{(*)}$ at the 90% level.

Table 9. WTP estimates

Average household income: €21,462

Compensating surplus estimates	Life satisfaction approach		Hedonic method	
	Conventional	IV	Conventional	IV
-1 $\mu g/m^3$ SO_2				
In euro	€183**	€313*	€34**	€6
	(€40)	(€133)	(€8)	(€13)
In percent of income	0.9%**	1.5%**	0.2%**	0.03%**
	(0.2%)	(0.6%)	(0.04%)	(0.06%)

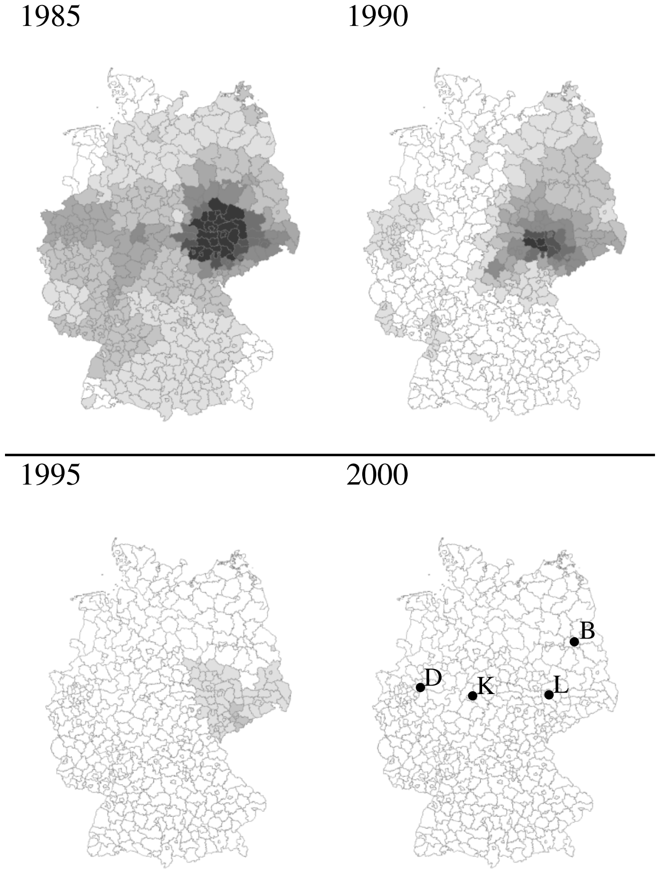
Notes: (1) Standard errors are estimated using the delta method. (2) ** is significant at the 99% level, and * at the 95% level.

Table A.3. MWTP estimates reported in the literature

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

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

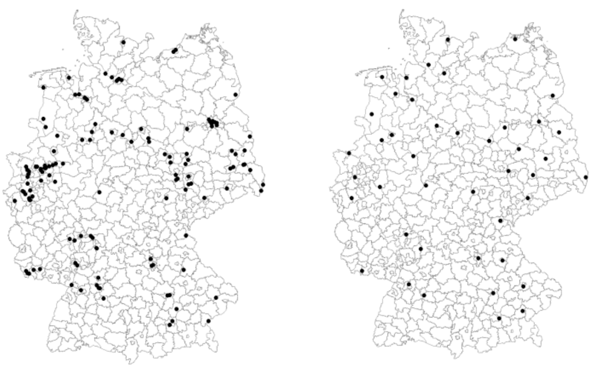
Figure 1. SO_2 concentration in German counties; 1985,1990, 1995 and 2000



Legend: ☐ ≤ 20 $\mu g/m^3$, ☐ 20 - 40 $\mu g/m^3$, ☐ 40 - 60 $\mu g/m^3$, ☐ 60 - 80 $\mu g/m^3$, ☐ 80 - 100 $\mu g/m^3$, ☐ 100 - 125 $\mu g/m^3$, ☐ 125 - 150 $\mu g/m^3$ and ■ > 150 $\mu g/m^3$; cities: D Dortmund in the Ruhr area, K Kassel in Northern Hesse, L Leipzig and B Berlin.
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).