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JEL classification: Q56, R11

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The rich, the clean, and the kind - a comprehensive wealth index for cities applied to the case of Germany ☆

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Abstract

We develop a comprehensive wealth index for cities that measures their endowment with environmental, energy, social, human, and economic capital stocks. We apply this index to the 100 largest autonomous cities in Germany. We find that (i) a good economic performance does not need to come at the cost of environmental degradation; (ii) clear regional differences exist between West and East Germany and between North and South Germany; and (iii) social preferences reflected in the comprehensive wealth index account for roughly half of the variation in housing rents, which reflect individual willingness to pay for living in a certain city.

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1. Introduction

Sustainable development has become a key term in the political and public debate on assessing wealth, indicating in particular the increasing awareness of environmental issues. A reflection of this is an increasing number of indices and measures to assess sustainability at the country level. However, several decisions with relevance for wealth and development are made at a local level (e.g., Camagni, 2002; Tanguay et al., 2010). This holds in particular true if it is acknowledged that wealth – in a comprehensive sense – is not only determined by economic growth or the quality of the environment, but also by aspects of social or human capital like, for instance, the provision of recreational areas or education issues. In this context, cities are particularly important, because the majority of the world's population lives in urban areas. In developed regions like Europe the share is even between 70 and 80 percent (UN, 2011). However, profound indicators to measure wealth in cities are still rare (Mori and Christodoulou, 2012).

In this paper we derive, first, a comprehensive wealth index for cities based on the approach of Arrow et al. (2003), which allows ordinal comparability of cities based on their capital endowments. Second, we apply this index to the 100 largest autonomous cities in Germany to assess their endowments of environmental, energy, social, human, and economic capital. Third, we investigate for the obtained ranking structural and regional patterns across Germany, the sensitivity of the results with respect to the elasticity of substitution, and discuss implications for sustainability policy. Fourth, we empirically investigate to which extend the social preferences reflected by the ranking are consistent with individual preferences, which we measure by rent levels in the cities.

The seminal work by Meadows (1972) has emphasized that in the presence of finite resources a wide concept of growth and wealth is necessary. These thoughts and the following discussion related to the concept of sustainable development have become widely acknowledged–in particular since the Brundtland Report (Brundtland et al., 1987; Schultz et al., 2008).[1] From an economic perspective, sustainable development can be measured by whether

[1]Note that the more general discussion of sustainable development and management reaches even back

the economy's production possibility is maintained or growing so that the wealth of future generations does not decrease (e.g., Smith et al., 2001; Arrow et al., 2003; Alfsen and Greaker, 2007; Dasgupta, 2009; Arrow et al., 2012). The economy's production possibility is determined in the strict sense by its capital endowment (e.g., Pearce and Atkinson, 1993; Smith et al., 2001; Alfsen and Greaker, 2007). Consequently, a sustainable development requires that the capital endowment is sustained. However, the capital approach does not cover all possible linkages between the economic capital and other capital stocks like, e.g., the environmental capital. Therefore, it is necessary to pay attention to the possibilities of substitution between the various capitals stocks (Victor, 1991). Among the first to investigate the role of natural resources for wealth and economic growth, Dasgupta and Heal (1979) show that if manufactured capital is sufficiently substitutable for natural resources, economic growth can be sustained even in the absence of technological progress. Their result was derived under the assumption that the elasticity of substitution between man-made capital and resource inputs in the production of goods is one or higher. However, this model has been criticized for not taking sufficiently into account that a certain amount of natural resources are necessary to produce manufactured capital and also to operate that capital (e.g., Bartelmus, 1989; Daly, 1991; Victor, 1991).

For that reason the differentiation between *strong* and *weak* sustainability has been introduced in the early 1990s: the concept of strong sustainability does not allow for any substitution between different capital stocks and, therefore, requires that all capital stocks have to be maintained at least; on the contrary, the concept of weak sustainability allows for a certain degree of substitution and requires that the aggregate of the various capital stocks (valued with their respective shadow prices) does not decline (Pearce et al., 1989; Hartwick, 1990; Daly and Cobb, 1989; Asheim, 1994; Hamilton, 1994; Pezzey and Withagen, 1995; Ekins et al., 2003; Arrow et al., 2003; Ott and Döring, 2004; Dietz and Neumayer, 2007; Baumgärtner and Quaas, 2009).[2] Ekins et al. (2003) suggest to initially start with a con-

into the 18th century. During that time first concepts for sustainable management in the German forestry sector have been developed (e.g., Hamberger, 2003).

[2]The change in the aggregate of the various capital stocks valued with their shadow prices is known as *genuine saving* (Hamilton and Clemens, 1999).

cept of relative strong sustainability (i.e., assuming a low elasticity of substitution between capital stocks) to investigate the influence of non-market goods and capital stocks and, if appropriate, to gradually move towards a concept of weaker sustainability (i.e., assuming a higher elasticity of substitution between capital stocks).

Measuring wealth and sustainable development of cities is still in its infancy, in particular when it comes to the challenge of assessing natural capital on that level (Oliwiler, 2006; Mori and Christodoulou, 2012). Even though there exist already many profound case studies, like for example on the sustainability of Taipei (Lee, 2007) or Santiago de Chile (Kopfmüller et al., 2012), comparative indices for a large number of cities are still rare. Existing indices with urban application often cover only some aspects of wealth and sustainable development, like the Water Footprint index focusing on freshwater consumption or the application of *emergy* and *exergy* indices focusing on energy efficiency (Mori and Christodoulou, 2012).

One popular exemption is the *City Development Index*, which measures the performance in the categories infrastructure, waste, health, education, and city product (e.g., UN-Habitat, 2001). However, the various categories are aggregated by using a simple weighted mean implying perfect substitution (an infinite elasticity of substitution) between the different spheres of capital endowments. Tanguay et al. (2010) review 17 indices measuring sustainability on the city level in developed western countries, including 6 case studies. They conclude that the approaches for constructing such indices are varying a lot. They report, for instance, that indices under investigation used between 10 and 86 indicators and that 72 percent of the indicators were only used in one or two studies. Furthermore, according to Tanguay et al. (2010) there is no public information about the methods of aggregation used for these 17 indices and how it is dealt with the issue of substitution in each of these cases.

It should also be noted that there exists a large body of grey literature on the subject, like for example the sustainable city index for Britain or the German Green City Index (Ross and Underwood (2010) and Friederich and Langer (2011), respectively), which often provide a relatively good coverage of available indicators but lack a profound foundation of the measurement concept. In summary, a profound index that ensures both, a comprehensive coverage of the various determinants of wealth and consideration of the leakage effects outside the city area, does currently not exist (Mori and Christodoulou, 2012).

The paper is structured as follows. Section 2 explains the derivation of the comprehensive wealth index for cities. Section 3 presents the selection of indicators to measure the environmental, energy, human, social, and economic capital stock of German cities. It also presents the derivation of a weighting scheme from an expert assessment. Section 4 presents the results of the comprehensive wealth index for the 100 largest autonomous cities in Germany. First structural and regional patterns in Germany are analyzed (Section 4.1), second the influence of the elasticity of substitution is analyzed (Section 4.2), and third the potential for sustainable development is discussed (Section 4.3). Section 5 provides empirical results on the relation between comprehensive wealth components and rent levels. Section 6 concludes.

2. A comprehensive wealth index for cities: Theoretical background

In order to derive a comprehensive wealth index for cities, we build on the concept of Arrow et al. (2003). The concept is based on the idea that social wealth is determined by the production possibilities of the economy under investigation which in turn are determined by the capital endowment of the economy. Clearly, the capital endowment is not only determined by the stock of manufactured capital (economic capital) but does also include other capital stocks, such as environmental or social capital. We denote by $k_i(t)$ the quantity of capital stock i at time t and by $c_i(t)$ a corresponding resource flow or consumption variable. We assume that there are n relevant capital stocks for each city. We denote the vector of capital stocks as $\mathbf{k(t)} \equiv (k_1(t), k_2(t), \ldots, k_i(t), \ldots, k_n(t))$ and the vector of corresponding consumption quantities as $\mathbf{c(t)} \equiv (c_1(t), c_2(t), \ldots, c_i(t), \ldots, c_n(t))$. In the following we simplify notation by omitting the time argument for the variables.

Intertemporal social welfare of each city is measured by the social welfare function

$$W = \int_0^\infty U(\mathbf{c})\, e^{-\delta\, t}\, dt, \tag{1}$$

where δ is the social rate of pure time preference, and $U(\mathbf{c})$ is the instantaneous utility function (also referred to as felicity function), which is assumed to be increasing in all arguments and strictly concave. By assuming a welfare function like (1), we extend the approach of Arrow et al. (2003) by allowing welfare to depend on more than one consumption good. We assume that the welfare function (1) is ordinally measurable and fully comparable across cities. The comprehensive wealth index which we derive below will have the same properties.

According to Arrow et al. (2003), a *resource allocation mechanism*, M, is a one-to-one mapping that relates the current vector of capital stocks, $\mathbf{k}(t)$ to the future time paths of capital stocks, $\mathbf{k}(t')$ and consumption quantities $\mathbf{c}(t')$ for all $t' > t$. These time paths may be optimal according to the welfare function (1), but M may also describe a sub-optimal or inefficient future development of the city.

Within this framework, the *value function*, $V(\mathbf{k}(t), M, t)$, reflects social welfare (1) as a function of initial capital stocks and the resource allocation mechanism (Arrow et al., 2003). If the resource allocation mechanism is autonomous, the value function does not explicitly depend on time. We assume that this is the case. The resulting value function for the city under consideration is the comprehensive wealth index we are aiming at.

The aim of deriving a quantitatively measurable comprehensive wealth index for cities requires giving the problem more structure. In the following we derive a functional form for $V(\mathbf{k}(t), M)$ from specific assumptions on the instantaneous utility function and the resource allocation mechanism.

Regarding the instantaneous utility function, a flexible, simple, and yet economically meaningful specification is to assume a constant elasticity of substitution between the different consumption goods. This means that we specify

$$U(\mathbf{c}) = \sum_{i=1}^{n} \frac{\zeta_i}{1-\eta} c_i^{1-\eta} \tag{2}$$

where $\zeta_i > 0$ is the welfare weight of utility drawn from consumption good i. Furthermore, $\sigma \equiv 1/\eta > 0$ is the (constant) elasticity of substitution between any two consumption goods

i and j, and also the elasticity of intertemporal substitution between consumption at different instances in time. Specification (2) is flexible in allowing different welfare weights for the different consumption goods, but it is also flexible in allowing different elasticities of substitution. In particular, it allows to consider low substitution elasticities, which means that all goods have to be consumed in relatively equal quantities to generate high welfare, or high elasticities, which means that it is easy to substitute one good (for example, environmental quality) by another one (for example, consumption of manufactured goods).

The dynamics of the capital stock i are described by the differential equation

$$\dot{k}_i = f_i(k_i) - c_i. \tag{3a}$$

Net investment into capital stock i, $\dot{k}_i$, is given by production, described by the production function $f(k_i)$, which uses only capital stock k_i as input, net of consumption of good i.

We further specify

$$f_i(k_i) = \frac{\beta_i}{1-\epsilon_i}\, k_i^{\epsilon_i} - \frac{\alpha_i}{1-\epsilon_i}\, k_i, \tag{3b}$$

with $\epsilon_i > 0$, $\beta_i > 0$, and $\alpha_i > 0$. This specification allows for several meaningful applications. For example, for $\epsilon_i < 1$, specification (3b) corresponds to the standard specification in a Ramsey-type growth model, where $\beta_i/(1-\epsilon_i)\, k_i^{\epsilon_i}$ is the (gross) production function with decreasing returns on capital, and $\alpha_i/(1-\epsilon_i)$ is the constant rate of capital depreciation (Barro and Sala-I-Martin, 1995; Acemoglu, 2008). For $\epsilon_i = 2$, specification (3b) corresponds to the logistic growth function commonly used in natural resource economics (Clark, 1990). The following propositions establish assumptions that lead to particularly tractable functional forms of the value function. We first focus on the case of optimally managed economies.

Proposition 1. *Assume that $U(\mathbf{c})$ is given by (2), and that the resource allocation mechanism is such that consumption quantities c_i maximize (1) subject to the capital dynamics*

(3) *with* $\epsilon_i = \eta$ *for all* i. *Then the comprehensive wealth index has the form*

$$V(\mathbf{k}, M) = \Phi + \sum_{i=1}^{n} \frac{\gamma_i}{1-\eta} \, k_i^{1-\eta} \tag{4}$$

with some constant Φ *and*

$$\gamma_i = \frac{\eta^\eta}{(\alpha_i + \delta)^\eta} \, \zeta_i . \tag{5}$$

Proof. For a proof see Appendix A. □

Hence, under the assumptions given in Proposition 1, the comprehensive wealth index is simply given by a constant elasticity of substitution function of the capital stocks. The elasticity of substitution is equal to the elasticity of substitution between different consumption goods in utility, and also equal to the output elasticities of capital in the production functions, which are assumed to be identical and equal to η.

The weight corresponding to capital stock i in the wealth index (4) does not only depend on the welfare weight for the respective consumption good, ζ_i, but also on the social rate of discount, δ, the elasticity of substitution, η, and the productivity parameter, α_i. The productivity parameters α_i could be measured by using market data. However, the welfare weights attached to utility drawn from the different consumption goods are parameters that depend on societal value judgements, and can not in general be derived from market observations.

We would like to emphasize that the assumptions stated in Proposition 1 are sufficient, but not necessary, to derive a value function of type (4). In particular, a similar type of value function can be obtained for a city that develops in a sub-optimal, perhaps even inefficient, way. This is stated in the following proposition.

Proposition 2. *Assume that* $U(\mathbf{c})$ *is given by* (2), *and that the resource allocation mechanism is given by the capital dynamics* (3) *with* $\epsilon_i = \eta$ *for all* i *and feedback control rules* $c_i(k_i) = \xi_i \, k_i$ *with some arbitrary* $\xi_i > 0$. *Then the comprehensive wealth index has the* *form* (4) *with some constant* Φ *and*

$$\gamma_i = \frac{\xi_i^{1-\eta}}{\delta + \alpha_i + (1-\eta)\,\xi_i}\,\zeta_i. \tag{6}$$

Proof. For a proof see Appendix B. □

Assuming that all cities have the same natural, social and technological preconditions, that means the α_i and β_i are the same for all cities, and that all share the same time preference rate δ; and using the assumption of ordinal measurability, we can choose the wealth index as

$$\hat{V}(\mathbf{k}) = \left[\sum_{i=1}^{n} \hat{\gamma}_i\, k_i^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \tag{7}$$

where $\sigma = 1/\eta > 0$ and $\hat{\gamma}_i = \gamma_i / \sum_{i=1}^{n} \gamma_i$.

In the following application, we use further disaggregated measures for the capital stocks k_i (i.e. manufactured capital, environmental capital, social capital etc.), where each of these capital stocks is composed of m_i different sub-stocks x_j^i. Assuming a functional form similar to (7) we can write

$$k_i = \left[\sum_{j=1}^{m_i} \varphi_j^i\, \left[x_j^i\right]^{\frac{\psi-1}{\psi}}\right]^{\frac{\psi}{\psi-1}}, \tag{8}$$

where $\varphi_j^i > 0$ are weighting factors and $\psi > 0$ is again an elasticity of substitution, which is assumed to be the same for all capital stocks k_i.

Note that for $\sigma \to 1$, the wealth index (7) becomes a weighted geometric mean, $\hat{V}(\mathbf{k}) = \Pi_{i=1}^{n} k_i^{\hat{\gamma}_i}$, and similarly the sub-indices (8) also become weighted geometric means.[3] Only in the case $\sigma = 1$ and $\psi = 1$, the scale of measurement for the different capital stocks does not affect the ordering implied by the index (Ebert and Welsch, 2004). For $\sigma \neq 1$ or $\psi \neq 1$, the welfare weights ζ_i and φ_j^i have to be adjusted when changing the scale of measurement for

[3] This is straightforward to show by applying l'Hospital's rule.

the capital stocks. The next section describes how we quantify the index (7) with (8) by specifying σ, ψ, the weighting factors γ_i and φ^i_j, and measures for the capital sub-stocks x^i_j.

3. Indicator selection and weighting for Germany's 100 largest cities

To apply the comprehensive wealth index (7), the different capital stocks for the German cities needed to be quantified. Ekins et al. (2003) suggest to consider environmental, human, social, and economic capital to measure the capital basis of a society. Furthermore, they divide the environmental capital into four categories: i) provision of resources for production, ii) absorption and regeneration of pollutants, iii) provision of vital services like the climate, and iv) provision of environmental amenities like recreational services. In contrast, Smith et al. (2001) further distinguish the provision of resources and the provision of land in the first category, but summarize the other three categories as ecosystem services. Similar division for the other capital stocks can be discussed.[4]

An accurate quantification of the capital stocks would required a comprehensive accounting system. The System of Environmental-Economic Accounting (SEEA) of the United Nations provide internally agreed concepts, definitions, classifications and accounting rules to achieve comparable statistics (e.g., United Nations et al., 2012). The SEEA accounts in particular for changes in the environmental capital in addition to the economic capital stocks. Changes in human or social capital are not accounted for. Moreover, such systems aggregate capital stocks at the country level and do not provide information at urban levels.

For that reason the various capital stocks at the city level need to be approximated by various indicators which contain both stock and flow variables. With respect to the latter, we assume that they monotonically change in response to changes in capital stocks. For example, we assume that the current number of school degrees qualifying for higher education influences human capital, or that current electricity consumption influences energy capital. Flow variables associated with an improvement of the corresponding capital stock

[4]Following another theoretical approach than the capital stock approach the German government summarizes the single indicators into the categories generational fairness, quality of life, social cohesion, international justice (Die Bundesregierung, 2002, 2012).

are positively assessed (e.g., the number of school degrees); flow variables associated with a deterioration of the corresponding capital stocks (e.g., energy consumption) are negatively assessed. Mapping flow values with stock values is not always straightforward. For example, fossil-fuel based electricity generation implies both a reduction of energy capital and a reduction of environmental capital due to the corresponding increase in atmospheric carbon concentration. However, much more important than the exact demarcation of the various capital stocks and the matching of the stock and flow variables is the selection of appropriate indicators to account for the wealth implications of the capital stocks (Alfsen and Greaker, 2007).

The selection of appropriate indicators is restricted by data availability and is always a normative choice with important implications for the results of the index (e.g., Krellenberg et al., 2010). In order to keep our selection of indicators transparent and traceable we start by collecting and classifying indicators from a broad collection of wealth and sustainable development assessments and indexes, namely the sustainable development assessment of Santiago de Chile (Kopfmüller et al., 2012), the City Development Index (UN - Habitat, 2002), the German Green City Index (Friederich and Langer, 2011), the indicator set "Zukunftsfähige Kommune" (Spreter et al., 2004), the indicator report for the National Sustainable Strategy of Germany (Statistisches Bundesamt (Destatis), 2012), and the progress report for the National Sustainability Strategy of Germany (Die Bundesregierung, 2012).

In a second step, we select those indicators with both relevance for wealth and sustainable development in cities and under the sphere of influence of cities. For example, the share of organic farming is obviously not relevant in the context of urban development, and the quality of rivers is not under the single responsible of a city. Additionally, we exclude indicators which measure components of capital stocks which are not scare. For example, fresh water is abundant in Germany, and SO_2 air concentration is already below official thresholds. Consequently, the associated shadow values of these components of the capital stock would be zero implying that we do not need to account for those indicators. For certain indicators data is not available at the city level. In such cases we approximate those indicators with similar indicators. A detailed description of the indicator selection can be found in Table C.1 in the Appendix.

Following Smith et al. (2001) and Ekins et al. (2003) we use the selected indicators to measure environmental, energy, human, social, and economic capital. For environmental capital we select indicators in the categories air quality, land use, and waste management, for energy capital in the categories energy and traffic, for human capital in the categories labor market, eduction, and child-care, for social capital in the categories demography, security, and health, recreation, and community, and for economic capital in the categories productivity, public debt, and taxes.

To make the meaning of the welfare weights ζ_i and φ_j^i in equations (7) and (8) transparent, we transform the indicators so that all of them are between zero and one, where one is the best value to achieve and corresponds to the best value observed in our sample (e.g., Zhou et al., 2006). The transformation yields indicators standardized with respect to range, but not with respect to average or variance. The indicators assigned to the various capital stocks are aggregated by (8) to measure the level of the capital stocks, which are then aggregated again by (7) to provide the comprehensive wealth index. Consequently, the index is based on a two-stage nested CES aggregation of indicators.

Furthermore, as already explained in the previous section, the welfare weights can not be derived from market data or other data, but have to be put in. Following existing wealth or sustainability indices (see for example Eboli (2012) for the Fondazione Eni Enrico Mattei (FEEM) sustainable index) we derive the weights from an expert questioning. We ask 30 experts across Germany, representing the fields of research, business, NGOs, politics, and media, to adjust the weights so that the influence of the various indicators on wealth is adequately represented. For that task, the experts were provided with the data and, as a prior, a uniform weighting scheme.[5] The selected indicators, their assignment to capital stocks, and the associated weights from the expert questioning are summarized in Table

[5]The uniform weighting scheme assigned the same weight to each capital stock and within each capital stock the same weight to each indicator. Due to the fact that the number of indicators for each capital stock varies, the initial weights for the indicators also vary. The experts then chose if a particular weight should be doubled, be halved, or should stay the same. The derivation of the weights is based on a geometric average of the resulting posteriors for the indicator weights.

1. The overview shows that the experts assign the highest weight to human capital in determining the wealth of cities and the lowest weight to social capital. On the level of single indicators the highest weight is assigned to the share of natural area in the city area.

Table 1: Indicator selection, source, weighting and assignment to capital stocks

Category	Indicator	Measurement unit	Source	Year	Target	Weight
Environmental capital						0.2070
Air quality	Particulate concentration	No. of days above threshold	UBA	2011	low	0.024
	Ozone concentration	No. of days above threshold	UBA	2011	low	0.022
	Nitrogen dioxide concentration	Average concentration in $\mu g/m^3$	UBA	2011	low	0.023
Land use	Human settlements and transport infrastructure area	Share of city area (%)	StBA	2009	low	0.030
	Natural area	Share of city area (%)	StBA	2009	High	0.041
Waste management	Household waste	kg/year/resident	StBA	2010	Low	0.030
	Recycling quote	Share of separately collected organic waste and recyclable materials	StBA	2010	High	0.037
Energy capital						0.1902
Energy	Private electricity consumption	kWh/year/resident	green-computing-portal.de	2011	Low	0.037
	Utilization of KfW-ERP program	Loan commitment in Euro/resident	BBR	2009	High	0.023
	Utilization of KfW-CO_2 program	Loan commitment in Euro/resident	BBR	2009	High	0.025
	Solar thermal power	m^2/100,000 residents	solaratlas.de	2012	High	0.023
Traffic	Number of cars	cars/100 residents	StBA	2011	Low	0.025
	Reachability of railway stations (EC/IC/ICE)	Distance from focal settlement point (car minutes)	BBR	2010	Low	0.031
	Electricity mobility	No. of charging stations/ha traffic area	Own research	2012	High	0.025
Human capital						0.2297
Job market	Unemployment	Quote by Federal Agency of Employment	StBA	2011	Low	0.020
	Youth unemployment	Quote by Federal Agency of Employment	StBA	2011	Low	0.025
	Employment rate	No. employees with mandatory social insurance/100 residents (20-65 years)	BBR	2009	High	0.017

Category	Indicator	Measurement unit	Source	Year	Target	Weight
	Trainee positions	Company trainee positions/100 candidates	BBR	2009	High	0.020
Education	Research institutes	No. of Frauenhofer, Max Planck, Leibniz, and Helmholtz institutes/100,000 residents	Own research	2012	High	0.012
	Students	Students/1,000 residents	BBR	2009	High	0.012
	Adult education	No. of adult evening courses/10,000 residents	BBR	2009	High	0.009
	Migrants in higher educatin	Difference between share of migrants in secondary school and other schools (%)	BBR	2009	Low	0.012
	School leavers without certification	Share of all school leavers (%)	BBR	2009	Low	0.015
	School leavers with admission to university	Share of all school leavers (%)	BBR	2009	High	0.013
Child care	Children aged below 3	Share of children in care center (%)	BBR	2009	High	0.026
	Pre-school children	Share of children in care center (%)	BBR	2009	High	0.025
	Quality of child care	No. children/care-giver	BBR	2009	Low	0.024
		Social capital				0.1780
Demographics	Age structur	Relation of residents aged above 65 to residents aged between 18 and 65 (%)	StBA	2010	Low	0.03
	Gender balance	Excess share of men or women (percentage points)	StBA	2010	Low	0.023
Crime	Criminal acts	No. of acts/100,000 residents	BKA	2010	Low	0.035
	Clearance rate	Share of solved acts (%)	BKA	2010	High	0.029
Health/ Recreation/ Polity	Physician supply	Residents/physician	BBR	2009	Low	0.013
	Hospital care	hospital beds/100,000 residents	BBR	2009	High	0.012
	Life expectancy	Average life expectancy (years)	BBR	2009	High	0.015
	Recreational area	Share of city area (%)	StBA	2009	High	0.015
	Competitive sport	No. of teams in upper leagues (soccer, basketball, ice hockey, handball, volleyball, tennis)/100,000 residents	Own research	2012	High	0.007
		Economic capital				0.1952
Economic performance	Output	GDP/resident (Euro)	StBA	2009	High	0.022
	Income	Available income/resident (Euro)	StBA	2009	High	0.024

Category	Indicator	Measurement unit	Source	Year	Target	Weight
Public finances	Productivity	Gross value added/workers (Euro)	StBA	2009	High	0.022
	Public debt	Debt/resident (Euro)	StBA	2009	Low	0.033
	Tax revenues	Tax revenue/resident (Euro)	BBR	2009	High	0.024
Innovation capability	Start-ups	No. of new firms/10,000 residents	BBR	2007	High	0.016
	Internet affinity	No. of registered de-domains/residents	BBR	2009	High	0.008
	R&D	No. Workers in R&D/1,000 workers (%)	BBR	2009	High	0.015
	Knowledge-intensive industries	Share of workers in knowledge-intensive industries (%)	BBR	2009	High	0.017
	Creative industries	Share of workers in creative industries (%)	BBR	2009	High	0.013
UBA: Federal Environmental Agency BBR: Federal Office for Building and Regional Planning StBA: Federal Statistic Office BKA: Federal Criminal Police Office						

4. Results

4.1. Structural and regional patterns of the ranking

By calculating the sustainable wealth index (7) with (8) for the 100 largest autonomous cities in Germany we obtain an ordinal ranking, reflecting the social preferences among the cities based on each single capital stock and on the aggregated capital stocks. For the aggregation of indicators to describe the various capital stocks we choose an elasticity of substitution of $\psi = 10$ and for the aggregation of capital stocks to obtain the comprehensive wealth index we choose an elasticity of substitution of $\sigma = 2$. Thus, we assume that there are better substitution possibilities within the capital stocks than between the capital stocks. Furthermore, a higher elasticity on the first aggregation level reduces the influence of measurement errors and imperfect proxies on the estimated level of the capital stock. A sensitivity analysis regarding the elasticity of substitution is carried out in Section 4.2.

The complete ranking can be found in Table D.1 in the Appendix. Table 2 shows the correlations in ranks between the different capital stocks as well as with the overall rank and with the population size. The correlation coefficients show that the environmental and energy capital stocks are not correlated with other capital stocks, except for the correlation between environmental and human capital. This indicates that a high endowment with economic capital does not necessarily come at the costs of poor endowment with environmental capital. The correlation analysis also shows that there is a positive correlation between the social, human, and economic capital stocks. However, none of those correlations is so high that a separation of these three capital stocks would be redundant. Due to the higher correlation among the human, social, and economic capital, those capital stocks have a higher correlation with the aggregated capital stock. The high correlation between human capital and overall capital stock reflects the fact that this capital stock has the highest weight in the construction of the wealth index (see Table 1). The correlation between the population size and the overall ranking is low. This shows that our approach and the selection of indicators do not systematically give advantage to either large or small cities. The highest correlation between population size and a single capital stock is observed for the environmental capital stock, indicating that smaller cities tend to have above-average endowments with this capital stock.

Table 2: Correlation between ranking in various capital stocks

	Environment	Energy	Human	Social	Economy	Total	Pop.
Environment	1	0.07	0.47	0.19	0.03	0.55	0.37
Energy		1	0.26	0.02	-0.11	0.32	-0.13
Human			1	0.55	0.40	0.87	0.15
Social				1	0.53	0.71	0.05
Economy					1	0.62	-0.10
Total						1	0.12
Pop.							1

The ranking also reflects regional differences in Germany. First, there still exist structural differences between West and East Germany. While cities in East Germany on average have a higher endowment with environmental and energy capital (average rank 44.00 versus 51.58 and 27.26 versus 56.45, respectively), they tend to be poorly endowed with social and economic capital (average rank 64.05 versus 41.09 and 81.68 versus 42.73, respectively). Second, there exist a structural difference between the northern and southern part of Germany. Aggregating the covered cities from Lower Saxony, Schleswig-Holstein, Mecklenburg-West Pomerania with Hamburg and Bremen to represent the northern part and aggregating the cities from Bavaria and Baden-Wuerttemberg to present the southern part, we observe substantially higher endowments of human, social, and economic capital stocks in the South (28.59, 20.22, and 29.00 versus 62.55, 65.45, and 62.20, respectively).

On the one hand, this shows that the wealth ranking reflects well-known regional differences to some extend. On the other hand, it constitutes indirect evidence against the assumption of equal natural, social, and technological preconditions for all cities that we made in Section 2. The average ranking in terms of environmental capital of the 20 cities in the Rhine-Ruhr metropolitan region (78.95) suggests, for instance, that these cities have poorer preconditions due to the high degree of industrialization in the past than similar cities in other regions.

4.2. Influence of elasticity of substitution

As already discussed in the introduction, the application of the capital concept to measure wealth or sustainable development satisfies only a weak concept of sustainability as long as substitution possibilities among the various capital stocks exists. However, by choosing different values for σ in (7) the sensitivity of the results regarding the substitution possibilities can be investigated. The limit case $\sigma \to 0$ would then satisfy a concept of strong sustainability by excluding any possibility of substitution, while $\sigma \to \infty$ would imply perfect substitution and therefore a very weak sustainability concept. The two extreme cases can easily be derived from the ranking in Table D.1 in the Appendix. A ranking for the former case can be obtained by ranking the cities according to their comparatively worst of the five capital endowments. A ranking for the latter can be obtained by calculating a simple weighted arithmetic mean using the weights from Table 1.[6]

We assume that in any case a minimum degree of substitutability exists among the various capital stocks, in particular at the urban level. In order to analyze the sensitivity of the index on the substitution possibilities we consider $\sigma = 0.5$ and $\sigma = 100$ for the aggregation of the capital stocks. Figure 1 displays the combination of rankings for the cities obtained for this two elasticities. The ranks of all cities would be on the 45° line, were

[6]These results are also available from the authors upon request.

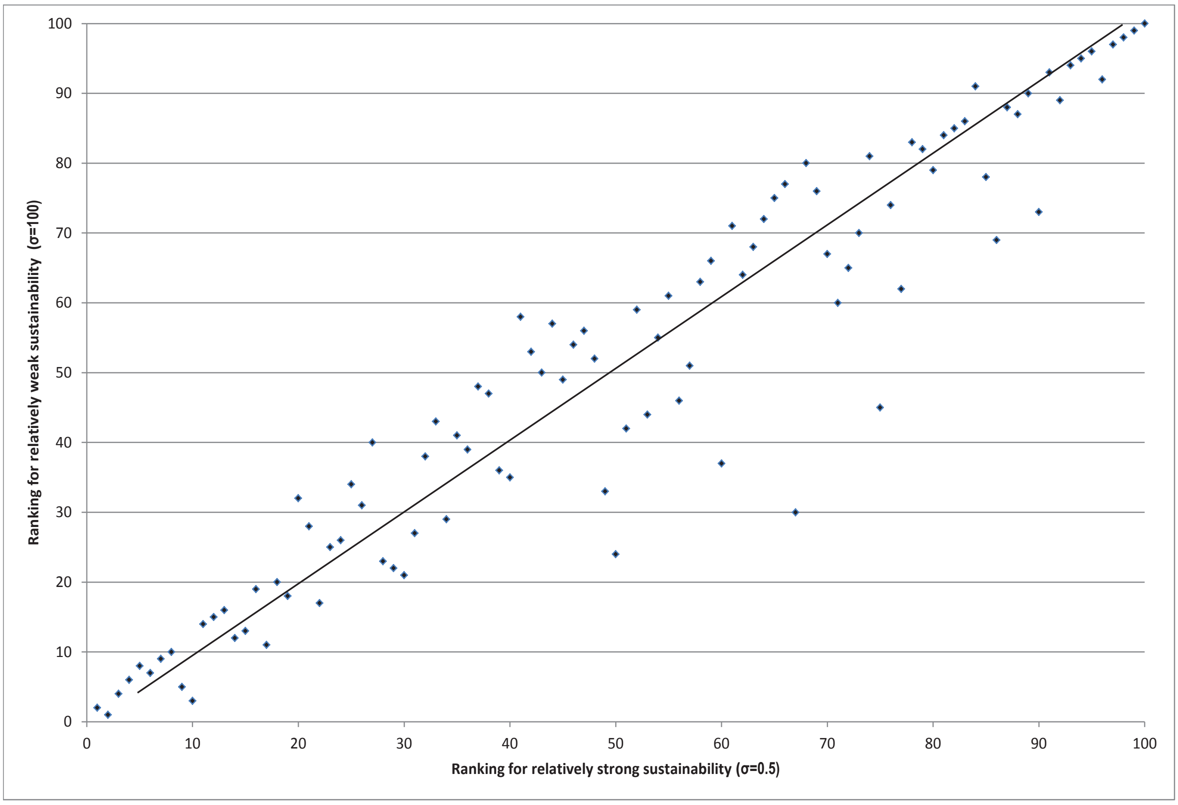

Figure 1: Ranking with high and low elasticity of substitution

there no influence of the elasticity of substitution at all. The figure shows that the majority of cities is rather close to this line, indicating that the German cities have rather balanced endowments among the various capital stocks. However, the figure also displays some cities far below the 45° line. As expected, cities with an unbalanced endowments obtain a much lower wealth level in a situation of low substitution possibilities, implying on the other hand that rather balanced cities improve in the overall ranking. Figure E.1 in the appendix shows two representative cities with rather balanced endowments (Heidelberg and Oberhausen) and two cities with unbalanced endowments (Trier and Greifswald). The numbers at the left of the plots in this figure show the improvement in the ranking when switching from a rather low to a rather high elasticity of substitution. As expected an increase in the elasticity of substitution has little influence on the rank of the cities with balanced endowments (+1 and 0, respectively) while it has a significant influence on the rank of the two other cities (+2 and +16, respectively).

4.3. Potential for sustainable development

So far we have analyzed the wealth of the German cities from a static perspective because the ranking reflects the social preferences at a certain point in time. Sustainable development, however, is a dynamic concept, because it requires that the wealth and therefore the value function of the economy (7) does not decline over time. Following the approach by Arrow et al. (2003) the change of the value function is given by

$$\frac{dV_t}{dt} = \sum_{i}^{n} \frac{\partial V_t}{\partial k_{it}} \frac{dk_{it}}{dt}, \tag{9}$$

given that the resource allocations mechanism is autonomous as assumed in (3b).

As already explained in the introduction, dV/dt provides the amount of genuine savings, meaning the change in the capital stocks assessed with their shadow values. Consequently, from the partial derivatives of the value function one obtains the shadow values for the various capital stocks and therefore also information about their relative scarcity. The relation of the various shadow prices provides the marginal rate of substitution and indicates how a relative change of the capital stocks influences wealth. Accordingly, from calculating the various shadow values for the cities under investigation one obtains information on the most scantiest capital stock for each city. The most scantiest capital stock for each city can be found in column 8 of Table D.1 in the Appendix.

For the majority of cities, the shadow value analysis indicates the economic capital stock to be the most scantiest one (55 cities). Among the remaining cities, 25 should focus on improving the human capital stock, 10 on environmental capital, and also 10 on energy capital. The social capital stock is the scantiest one for none of the cities of the sample. To some degree this result reflects the low weight assigned to the social capital stock. But it can also be partly explained by the limitations of the Max-Min transformation applied in Section 3. Due to the fact that this transformation does not correct for the variation in average and variance among the various indicators, potential negative (positive) outliners increase (reduce) the average level of an indicator and therefore capital stock, implying that this capital stock is one average less (more) scarce. The problem is illustrated in Figure

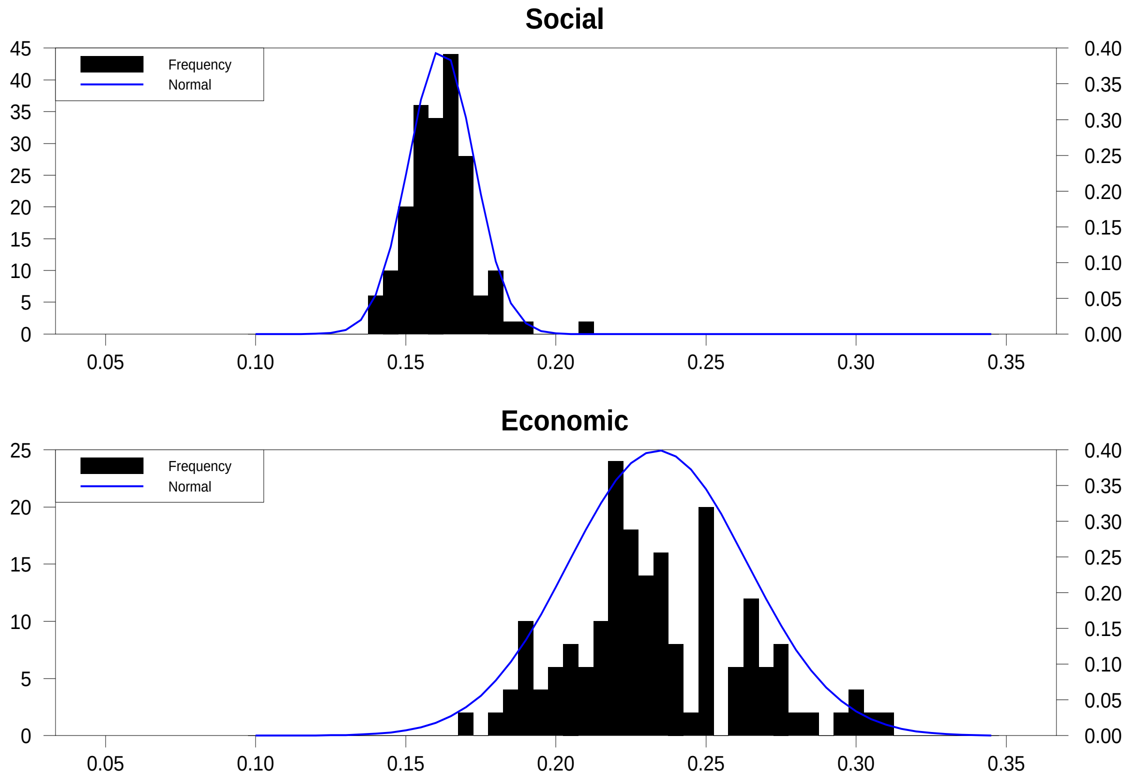

Figure 2: Distribution of shadow values for social and economic capital across cities

2 which shows the histograms for the shadow values of social and economic capital. The lines in the figure depicts a normal distribution with means and variances equal to the two corresponding moments of the two shadow value samples.

Nevertheless, the calculated shadow values confirm once more the importance of the elasticity of substitution. Increasing the substitution possibilities reduces the relatively scarcity of single capital stocks. This can be seen by the decreasing spread between largest and smallest shadow value among the cities in Table 3. Accordingly, for a high substitution elasticity like $\sigma = 100$ the human capital stock becomes the most scantiest stock for all cities because this capital stock is assigned the largest weight. However, the variation in spreads across the capital stocks confirms again the limits of the Max-Min transformation.

Table 3: Spread between largest and smallest shadow value for variation of substitution elasticity

	Environment	Energy	Human	Social	Economy
$\sigma = 0.5$	0.3902	0.6084	0.3100	0.2139	0.7776
$\sigma = 2$	0.0913	0.1157	0.0754	0.0679	0.1416
$\sigma = 10$	0.0178	0.0211	0.0147	0.0141	0.0252
$\sigma = 50$	0.0008	0.0008	0.0005	0.0004	0.0010
$\sigma = 100$	0.0004	0.0004	0.0003	0.0002	0.0005

5. Empirical analysis with house renting rates

Finally, we investigate how our wealth index, a measure for social preferences, is reflected by price signals that are influenced by individual preferences. To this end, we analyze how well our index explains the variation of rent levels across the cities. According to urban economic theory, housing rents reflects how urban residents value the bundle of private and public goods available in the city, as well as their expectations on the city's future development (e.g. Fujita and Thisse, 2002).

The information about average rent levels were obtained from F+B (2012), who provide rent level data for the various cities that is constructed to reflect the rent for a standardized "reference flat". Unfortunately, the data set does not cover all of the 100 cities of our sample. The reason is that there exists no legal obligation for communities to provide rent level information. Overall, we have rent level information for 74 cities.[7]

To analyze if the ranking of capital stocks derived in the previous part of the paper has explanatory power for the rent level in the cities, we regress the log-level of rents on the cities' ranks using different specifications. Due to the absence of any obvious misspecifications we estimate these regression equations by means of Ordinary Least Squares (OLS). If an individual's willingess to pay for housing is indeed driven to a substantial degree by the availability of the capital stocks that we measure in this paper, then we should observe that rent levels are positively related to comprehensive wealth as measured by the index. We thus expect that a city with a higher rank number (i.e., with a lower comprehensive wealth) has lower rent level.

[7] It has to be noted, however, that coverage increases with the size of the city. Among the cities, which have more than 500,000 residents, only the city of Bremen does not provide rent level information. For those cities with 100,000 to 500,000 residents the coverage is about 87 percent and for the smaller cities of our sample (less than 100,000 residents) it is about 77 percent.

Table 4: Explanation of housing rent levels by social preferences

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Constant	1.9065***	1.0125***	1.0976***	2.0020***	1.2568***	1.3421***
	(0.0274)	(0.1599)	(0.1544)	(0.0382)	0.1902	(0.1832)
Total rank	-0.0026***	-0.0027***	-0.0030***			
	(0.0005)	(0.0004)	(0.0003)			
D(state c.)		0.0381	0.0240		0.0374	0.02822
		(0.0321)	(0.0307)		0.0314	0.02999
ln(population)		0.0691***	0.0612***		0.0550***	0.04770***
		(0.0141)	(0.0136)		(0.0156)	(0.0150)
D(West-G.)		0.0665**	0.0695***		0.0691**	0.0684**
		(0.0255)	(0.0241)		(0.0341)	(0.03243)
D(Munich)			0.2351***			0.2477***
			(0.0878)			(0.0876)
rank(environ.)				0.0005	-0.0002	-0.0003
				(0.0004)	(0.0004)	(0.0004)
rank(energy)				-0.0012***	-0.0009**	-0.0010**
				(0.0004)	(0.0004)	(0.0004)
rank(human)				-0.0005	-0.0011**	-0.0009*
				(0.0005)	(0.0005)	(0.0004)
rank(social)				-0.0010*	-0.0010**	-0.0008*
				(0.0005)	(0.0005)	(0.0004)
rank(economic)				-0.0024***	-0.0011**	-0.0012**
				(0.0005)	(0.0005)	(0.0005)
R^2	0.31	0.60	0.64	0.50	0.62	0.65
N	74	74	74	74	74	74

Notes: ***, **, and * denote significance at the 1%-, 5%-, and 10%-level, respectively

In a first set of regressions, we use only the ranks with respect to the total capital stock of the cities (Model 1) as an explanatory variable. Table 5 shows that the ranking has a significant effect on the rent level and explains a considerable fraction of variation in rents (about one third). To get an impression of the economic size of the effect: An improvement of 10 ranks in our ranking goes, on average, along with an increase of rents of 2.6 percent. To control for important factors that could lead to an omitted-variable bias we include a dummy variable for state capitals, the log-population level of cities and a dummy for West-German cities in a different specification (Model 2). The estimates show that while the specification is now able to explain about half of the variation in rents, the marginal effect of the ranking is not changed much. In a third specification, we additionally control for special circumstances in the region around the city of Munich (F+B, 2012).[8] Again, this control variable is highly significant and rent levels are more than 20 percent higher in this region than implied by the other factors (Model 3); all other marginal effects are little changed in the new specification.

[8]To this end, we include a dummy variable that is equal to 1 for the cities of Munich, Augsburg, Ingolstadt, as well as Rosenheim-and 0 for all other cities.

In a second set of regressions, we shed some light on the question of which of the different capital stocks that we consider is particularly relevant for explaining rent levels. To this end, we replace the ranks based on the total capital stock by the 5 ranks for environmental, energy, human, social, and economic capital stocks, respectively (Models 4-6). The results show that the different ranks alone can account for roughly half of the variation in rents; this measure is increased to about 0.65 if all control variables are included. In terms of relative importance of the different capital stocks for the level of rents the estimates suggest that all but the environmental capital stock have a significant effect. For all four capital stocks the effect of an improvement by 1 rank is roughly 0.001, once we control for all other factors. In other words, if a city improves its relative position with respect to the energy, human, social, or economic capital stock by 10 ranks the rent level increases by about 1 percent.

The coefficients for the ranks of the individual capital stocks imply a different weighting scheme than the one obtained from the expert questioning. The experts assigned the highest value to the human capital stock, followed by the environmental, economic, energy, and social capital stock. On the contrary, the regression analysis yields the highest explanatory weight for the economic capital stock, followed by the energy, human, and social capital stock, while a zero weight is assigned to the environmental capital stock due to its insignificance (Model 6). Assuming that the level of housing rents is a good proxy for the average individual valuation of the capital stocks (and not too much distorted by supply side factors), the revealed individual preferences with respect to the relative importance of the different capital stocks are substantially different from the subjective view of the expert panel.

6. Conclusion

Assessing wealth and development requires a comprehensive approach that focuses not only on economic performance. Taking the focus to people's daily life, wealth is also influenced by factors like the cleanness of the air, the availability of child care, or the quality of health care to name just a few. Several of these factors are influenced by decisions on the local level and in particular on the city level. Consequently, in this paper we develop an approach to assess wealth on the city level and apply our approach to the 100 largest autonomous cities in Germany.

We develop a comprehensive wealth index for cities based on concepts of comprehensive, genuine or inclusive wealth (Pearce and Atkinson, 1993; Hamilton, 1994; Hamilton and Clemens, 1999; Arrow et al., 2003). The wealth index reflects social welfare as a constant elasticity of substitution (CES) function of capital endowments. Assuming that all cities have the same natural, social, and technological preconditions, the application of the index allows ordinal comparison of cities. For this purpose, we measure the endowments of the 100 largest autonomous cities in Germany, with environmental, energy, human, social, and economic capital stocks. We select 46 different indicators to measure these capital stocks. Indicators are selected by (i) collecting indicators from five wealth and sustainable studies in the literature which either focus on cities or on Germany and by (ii) selecting among the collected indicators those with relevance for German cities. Where data availability at the city level limits the application of a certain indicator we tried to approximate this indicator by another variable. The indicators are standardized with respect to range so that all of them are between zero and one, where one is the best value to achieve. The resulting values are aggregated into five categories of capital stocks by means of another CES function. The resulting comprehensive wealth index thus is a two-stage nested CES composite of measured variables. The use of a CES functional form allows an explicit treatment of the substitution possibilities among indicators influencing wealth. The weighting factors for the various indicators in the index, and therefore the relative weights for the five types of capital on social wealth depends on societal value judgements. We obtain the weighting scheme from an expert questionnaire which involved 30 experts across Germany representing the fields of research, business, NGOs, politics, and media.

The obtained ranking resolves the question which cities are currently the richest (wealthy in economic capital), the cleanest (wealthy in environmental capital), and the kindest (wealthy in social capital). Moreover, it shows which cities perform well in energy saving and which cities are smart in the sense of high human capital endowment. Overall, the structural analysis of the ranking shows that our approach does not give systematically advantage to large or small cities. Additionally, the correlation analysis reveals that in contrast to common belief a high endowment of economic capital does not need to come at the costs of poor endowment with environmental capital. However, it reveals that smaller cities seem to have a slightly advantage in preserving their environmental capital. Furthermore, the ranking reflects regional differences in Germany. First, cities in East Germany have on average a higher endowment with environment and energy capital, but a poorer endowment with social and economic capital compared to cities in West Germany. Second, cities in the North of Germany have on average a poorer endowment in human, social, and economic capital stocks than cities in the South, where in particular the high endowment of southern German cities with the social capital stock is very pronounced. The analysis of structural and regional differences shows the limits of the assumption on the same natural, social and technological preconditions for all cities which becomes for example evident by the poor performance of cities in the Rhine-Ruhr metropolitan region for the environmental capital.

The base ranking is obtained by an application of the comprehensive wealth index with an elasticity of substitution of 10 for the aggregation of indicators to measure the individual capital stocks and with an elasticity of substitution of 2 for the aggregation of capital stocks to measure the social welfare of cities. The higher substitution possibilities for the aggregation of indicators reduces the influence of measurement errors and the issue of imperfect proxies. Furthermore, we assume that there are better substitution possibilities within the capital stocks than between the capital stocks. As a sensitivity analysis we calculate the ranking also for a rather low and rather high substitution elasticity on the aggregation level of social welfare (0.5 and 100, respectively). From this analysis follows that the majority of cities in Germany has a rather balanced performance among the various capital stocks because the differences between the two rankings are relatively low. Of course, there are also some cities with an rather unbalanced performance which are accordingly assigned a much lower wealth level in a situation where substitution possibilities are very restricted.

The importance of the elasticity of substitution is also confirmed in the analysis of the shadow values. From the partial derivatives of the wealth index one obtains the shadow values for the various capital stocks and therefore also information about their relative scarcity. The relation of the various shadow prices provides the marginal rate of substitution and indicates how a relative change of the capital stocks influences wealth. Consequently, important information for sustainable development can be obtained. Increasing the elasticity of substitution reduces the dominance of the relatively scarcest capital stocks which can be observed by a decreasing spread between the largest and smallest shadow value among the cities. Accordingly, for a high substitution elasticity the capital stock assigned the largest weight in the expert questioning becomes the most scantiest stock for all cities. However, the analysis of the shadow values also revealed certain limitations of the indicator transformation which provided indicators standardized with respect to range, but not with respect to average or variance. None of the cities has social capital as the most scantiest capital stock, indicating that negative outliers among the indicators for this capital stock shift the average level of the capital stock upwards.

Urban economic theory suggests that housing rents reflect how urban residents value the bundle of private and public goods available in the city. Therefore, we investigated how the social preferences reflected by our wealth index explain the variation of rent levels across German cities. Given that an individual's willingness to pay for housing is indeed driven to a substantial degree by the availability of the capital endowment of a city, a city with a higher rank number (i.e., with a lower comprehensive wealth) should have a lower rent level. We find that overall capital endowment has a significant effect on the rent level and explains a considerable fraction of variation in housing rents. An improvement of 10 ranks in our ranking goes, on average, along with an increase of rents of 2.6 percent. Looking in more detail into this relationship by investigating for the influence of individual capital stocks, the analysis showed that the different ranks alone can account for roughly half of the variation in rents. With the inclusion of further variables to control for location in West Germany, population size, and for location around the city of Munich about 0.65 of the variation is explained. In terms of relative importance of the different capital stocks for the level of rents the estimates suggest that all but the environmental capital stock have a significant effect, indicating a difference to the weighting obtained from the expert questioning.

Comprehensive measures to assess welfare and sustainable development at the local level are still rare and our study contributes to filling this gap and to provide a method to assess and compare the wealth of cities. Further improvement of our comprehensive wealth index to capture in a better way leakage effects on capital stocks outside the city area and continuous updating will provide further insights about measuring sustainable development of cities.

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Appendices

Appendix A. Proof of Proposition 1

For the optimal development path of the economy the Bellman equation

$$\delta\, V(\mathbf{k}) = \max_{\mathbf{c}} \left[\sum_{i=1}^{n} \left[\frac{\zeta_i}{1-\eta}\, c_i^{1-\eta} + \left(\frac{\beta_i}{1-\eta}\, k_i^{\eta} - \frac{\alpha_i}{1-\eta}\, k_i - c_i \right) V_{k_i}(\mathbf{k}) \right] \right] \tag{A.1}$$

must be fulfilled. We shall verify in the following that the value function is given by

$$V(\mathbf{k}) = \Phi + \sum_{i=1}^{n} \frac{\phi_i}{1-\eta} k_i^{1-\eta} \tag{A.2}$$

with some $\phi_i > 0$ and that the optimal consumption quantities are given by

$$c_i = \kappa_i\, k_i \tag{A.3}$$

with some $\kappa_i > 0$ (see also Pindyck 1984; Miranda and Fackler 2002, :331).

Using these guesses, the first-order conditions for the left-hand-side of (A.1) become

$$\frac{\zeta_i}{(\kappa_i\, k_i)^{\eta}} - \frac{\phi_i}{k_i^{\eta}} = 0 \quad \text{for } i = 1, \ldots, n. \tag{A.4}$$

Furthermore, the Bellman equation (A.1) can be written as

$$\delta \left[\Phi + \sum_{i=1}^{n} \frac{\phi_i}{1-\eta} k_i^{1-\eta} \right] = \sum_{i=1}^{n} \left[\frac{\zeta_i}{1-\eta} (\kappa_i\, k_i)^{1-\eta} + \left(\frac{\beta_i}{1-\eta}\, k_i^{\eta} - \left(\frac{\alpha_i}{1-\eta} + \kappa_i \right) k_i \right) \frac{\phi_i}{k_i^{\eta}} \right] \tag{A.5}$$

$$\Leftrightarrow \qquad \delta\, \Phi - \sum_{i=1}^{n} \frac{\beta_i}{1-\eta}\, \phi_i = \sum_{i=1}^{n} \frac{k_i^{1-\eta}}{1-\eta} \left[-\delta\, \phi_i + \zeta_i\, \kappa_i^{1-\eta} - (\alpha_i + (1-\eta)\, \kappa_i)\, \phi_i \right] \tag{A.6}$$

Using (A.4) in (A.6) and equating coefficients, we obtain

$$\kappa_i = \frac{\alpha_i + \delta}{\eta} \tag{A.7}$$

$$\phi_i = \frac{\eta^\eta}{(\alpha_i + \delta)^\eta}\, \zeta_i \tag{A.8}$$

$$\Phi = \sum_{i=1}^{n} \frac{\beta_i\, \eta^\eta\, \zeta_i}{(1-\eta)\,(\alpha_i + \delta)^\eta} \tag{A.9}$$

Appendix B. Proof of Proposition 2

For the assumed resource allocation mechanism the value function is given by the functional equation

$$\delta\, V(\mathbf{k}) = \sum_{i=1}^{n} \left[\frac{\zeta_i}{1-\eta}\, (\xi_i\, k_i)^{1-\eta} + \left(\frac{\beta_i}{1-\eta}\, k_i^\eta - \left(\frac{\alpha_i}{1-\eta}\, k_i + \xi_i \right) \right) V_{k_i}(\mathbf{k}) \right]. \tag{B.1}$$

Again, we guess (A.2) for the functional form of the value function. Plugging this guess into (B.1) and equating coefficients leads to

$$\phi_i = \frac{\zeta_i\, \xi_i^{1-\eta}}{\delta + \alpha_i + (1-\eta)\, \xi_i} \tag{B.2}$$

Appendix C. Indicator selection

As explained in Section 3 we use the following indexes as source for our indicator selection: the sustainable development assessment of Santiago de Chile (SAC), the City Development Index (CDI), the German Green City Index (GGCI) , the indicator set “Zukunftsfä hige Kommune (IZK)” , the indicator report for the National Sustainable Strategy of Germany (NSSG), and the progress report for the National Sustainable Strategy of Germany (PNSSG). Table C.1 shows for various categories in the first column indicators which were used in the above mentioned indexes, shows in the second column the source, shows in the third column our interpretation for the implications for wealth of the cities, and shows in the fourth column the selected indicators for our index. Consequently, indicators which were used in the literature and by us, appear both in the first and last column (e.g., unemployment rate), indicators used in the literature but not by us, have an empty last column (e.g. organic farming), and indicators used in the literature and approximated by us with a different indicators, have the new indicator listed in the last column.

Table C.1: Indicator selection

Indicators	Source	Interpretation for city wealth	Used indicator
Indicators related to air quality			
SO_2 , O_3, and NO_2 concentration, ammonia concentration, volatile organic compounds, particulate concentration	GGCI, NSSG, PNSSG	Use of atmosphere; SO_2 emissions and concentration is too low to reflect scarcity; ammonia concentration only relevant for rural regions; data for volatile organic compounds not available at city level	NO_2, O_3, and particulate concentration
Indicators related to land use			
Human settlements and transport infrastructure areas, efficiency of land use	IZK, NSSG	environmental capital	Share of human settlements and transport infrastructure areas
Protected nature, Number of trees on human settlement areas	IZK	environmental capital	Share of natural area
Indicators related to waste			
Household waste	GGCI, IZK	Use of natural resources and use of environment for waste disposal	Household waste
Recycling quote, raw material productivity	CDI, GGCI, NSSG, PNSSG	Use of natural resources and use of environment for waste disposal	Recycling quote
Indicators related to water consumption			
Water consumption, water dispersion	GGCI, IZK	Use of natural resources; no scarcity for resource in Germany	
Indicators related to ecology			
Organic farming	IZK, NSSG	Use of ecosystem services; not relevant for urban areas	
Ecocertified companies	IZK	Use of ecosystem services; data not available at city level; no commonly agreed certificate	
Biodiversity, Presence of house martin	NSSG, IZK	Quality of ecosystem; not under main area of responsibility of cities	
Indicators related to energy			
Energy consumption, energy consumption in buildings, energy efficiency, energy productivity	GGCI, IZK, NSSG	Change in energy reserves and atmospheric CO_2 concentration	private electricity consumption, Utilization of KfW-ERP program

Indicators	Source	Interpretation for city wealth	Used indicator
Renewable energy provision	GGCI, IZK, NSSG	Change in energy reserves and atmospheric CO_2 concentration; however, energy supply does not to be satisfied by generation in urban area (wind energy); decentralized supply of heating task in urban area	solar thermal power
CO_2 emissions	GGCI, NSSG	change in atmospheric carbon concentration; data not available at city level	Utilization of KfW-CO_2 program
Indicators related to traffic			
Number of cars	IZK	Change in energy reserves and atmospheric CO_2 concentration, air and noise pollution	Number of cars
Length of bicycle paths	GGCI, IZK	Change in energy reserves and atmospheric CO_2 concentration, quality of public transport, data not available for majority of cities	
Utilization of public transport, bus and train connections	GGCI, IZK	Change in energy reserves and atmospheric CO_2 concentration, quality of public transport	Reachability of railway stations
Freight transport intensity, share of railroad traffic, share of inland waterway transport	NSSG	Change in energy reserves and atmospheric CO_2 concentration; however not directly related to urban responsibilities	
Indicators related to job market			
Unemployment, employment rate	IKZ, NSSG	Change in human capital	Unemployment and employment rate
Trainee positions	IKZ	Change in human capital	Youth unemployment rate and number of trainee positions
Indicators related to eduction			
School attendance, illiteracy rate, number of internet connections in households	SAC, CDI	Change and quality of human capital; however indictors are more appropriate for cities in developing countries	
Education level of young people and migrants	NSSG, IZK	Change and quality of human capital	School leavers without certification, school leavers with admission to university, migrants in higher education
First-year student rate	NSSG	Change in human capital	Students, research institutes
Educational opportunities	IZK	Change in human capital	Adult eduction
Indicators related to child care			
Child care, All-day child care	NSSG, IZK	Change in human capital	Children in care center (below 3 years and pre-school), quality of child care
Indicators related to demographics			

Indicators	Source	Interpretation for city wealth	Used indicator
Population development, gender balance	SAC, IZK, NSSG	Change and quality of social capital	age structure and gender balance
Indicators related to crime			
Criminal acts, clearance rate	SAC, IZK, NSSG	Quality of social capital	criminal acts, clearance rate
Indicators related to justice and poverty			
Gini-coefficient	SAC	Quality of social capital; data not available on city level	
Poverty rate, share of overcrowded houses, households with freshwater connection	SAC, CDI	Quality of social capital; however indicators are more appropriate for cities in developing countries	
Recipients of unemployment benefit/ Hartz IV	IZK	Quality of social and human capital; however, influence already covered in unemployment rate	
Indicators related to health, recreation, and polity			
Basic supply services close to residential areas	IZK	Quality of social capital; data not available at the city level	
Noise pollution	IKZ	Quality of social capital, change in environmental capital; data not available at the city level	
Children and/or citizen with overweight	IKZ, NSSG	Quality of human capital; data not available at the city level	
Traffic accidents with childern	IKZ	Quality of social capital; data not available at the city level	
Smoking rate	IKZ	Quality of social capital; data not available at the city level	
Life expectancy	IKZ, NSSG	Quality of social capital	Life expectancy
Community engagement, facilities for childern, youth people, or disabled people, sport clubs	IKZ, PNSSG	Quality of social capital	share of recreational area, number of sport clubs in higher leagues
Access to medical support	NSSG	Quality of social capital	Physician supply, hospital care
Indicators related to economic performance			
Output, GDP	CDI	Change in economic capital	GDP, income, productivity
Inflation rate, export success	PNSSG	Change in economic capital; not directly in area of responsibility of cities	
Indicators related to public finances			
Public debt	IKZ, NSSG	Change in economic capital	public debt, tax revenues

Indicators	Source	Interpretation for city wealth	Used indicator
Labor costs	PNSSG	Change in/ quality of economic capital; data not available at city level	
Indicators related to innovation capabilities			
Public and private spending for R&D	IKZ, NSSG	Change in economic capital	Workers in R&D, knowledge-intensive industries, creative industries
Start-up dynamics	IKZ, PNSSG	Change in economic capital	Start-ups
Indicators related to development aid			
Imports from developing countries, development aid	IKZ, NSSG	International leakage and spill-over effects; not directly in area of responsibility of cities	

Appendix D. Ranking

Table D.1: Ranking for the 100 largest autonomous German cities

	Environ.	Energy	Human	Social	Economy	Total	Most scantiest capital stock
Berlin	87	16	83	66	80	84	Economy
Hamburg	91	26	67	68	10	54	Environment
Munich	89	49	20	1	3	11	Environment
Cologne	95	40	46	71	30	64	Environment
Frankfurt am Main	84	28	28	32	2	16	Environment
Stuttgart	54	32	13	10	4	6	Human
Düsseldorf	82	77	45	78	1	37	Environment
Dortmund	92	31	85	96	63	88	Human
Essen	99	41	92	74	23	90	Environment
Bremen	67	58	57	83	65	73	Economy
Dresden	34	30	54	65	38	40	Economy
Leipzig	61	27	87	69	73	79	Economy
Hannover	68	94	66	11	58	69	Energy
Nuremberg	47	42	77	17	36	44	Human
Duisburg	78	66	99	87	82	96	Human
Bochum	94	74	69	61	70	85	Economy
Wuppertal	63	65	90	54	39	75	Human
Bonn	56	72	25	47	34	41	Economy
Bielefeld	50	44	68	45	55	56	Economy
Mannheim	86	43	34	30	24	45	Environment
Karlsruhe	30	64	15	40	11	12	Energy
Münster	42	55	10	56	33	29	Economy
Wiesbaden	77	38	59	39	15	34	Human
Augsburg	62	50	42	3	26	27	Human
Aachen	20	97	50	90	51	70	Energy
Mönchengladbach	65	92	91	50	62	86	Human
Gelsenkirchen	100	48	100	89	76	100	Human
Braunschweig	38	59	27	52	27	32	Economy
Chemnitz	57	54	71	81	89	82	Economy

	Environ.	Energy	Human	Social	Economy	Total	Most scantiest capital stock
Kiel	55	22	56	55	54	50	Economy
Krefeld	97	83	89	41	53	89	Human
Halle	76	19	63	34	97	72	Economy
Magdeburg	83	3	65	77	83	74	Economy
Freiburg	6	4	6	13	56	5	Economy
Oberhausen	96	78	97	63	84	97	Human
Lübeck	25	13	94	86	90	80	Economy
Erfurt	48	12	44	42	81	47	Economy
Rostock	23	10	39	70	77	43	Economy
Mainz	90	35	8	12	31	30	Environment
Kassel	79	85	81	19	49	76	Human
Hagen	45	57	64	72	61	62	Economy
Hamm	64	67	84	92	85	87	Economy
Saarbrücken	21	96	49	62	32	58	Energy
Mlheim	93	11	51	88	44	68	Environment
Herne	98	75	93	80	87	98	Economy
Ludwigshafen	85	91	80	26	21	71	Human
Osnabrück	59	81	41	20	35	48	Economy
Oldenburg	40	86	55	18	42	51	Economy
Leverkusen	81	79	62	36	17	55	Human
Solingen	60	84	79	58	75	83	Economy
Potsdam	51	5	9	38	67	21	Economy
Heidelberg	2	20	3	16	18	1	Economy
Darmstadt	24	61	5	29	6	7	Energy
Regensburg	70	17	19	7	9	10	Environment
Würzburg	53	39	16	6	59	22	Economy
Ingolstadt	44	6	40	15	8	9	Human
Heilbronn	29	99	47	24	19	46	Energy
Ulm	12	1	17	8	16	2	Human
Wolfsburg	32	100	22	51	5	33	Energy
Offenbach	46	70	95	35	14	57	Human
Pforzheim	1	36	60	27	52	18	Economy
Bottrop	72	62	82	82	94	91	Economy
Fürth	28	88	73	2	28	36	Human
Bremverhaven	69	95	98	95	99	99	Economy
Remscheid	49	93	72	48	46	65	Human
Koblenz	8	53	29	60	37	25	Economy
Erlangen	19	47	2	4	13	3	Energy
Trier	14	80	12	14	74	31	Economy
Jena	13	2	1	21	66	4	Economy
Salzgitter	18	68	78	67	50	59	Human
Cottbus	73	9	53	85	71	63	Economy
Gera	39	73	43	76	98	78	Economy
Kaiserslautern	9	60	21	79	64	35	Economy
Schwerin	7	14	52	57	93	42	Economy
Flensburg	35	46	76	73	78	67	Economy
Dessau-Rolau	10	71	37	97	91	66	Economy
Worms	33	33	58	49	68	49	Economy
Wilhelmshaven	58	98	86	99	60	95	Human
Neumünster	80	34	96	98	72	94	Human
Delmenhorst	74	63	88	94	86	92	Economy
Bayreuth	22	56	23	5	41	19	Economy
Brandenburg	16	24	70	100	88	81	Economy

	Environ.	Energy	Human	Social	Economy	Total	Most scantiest capital stock
Bamberg	43	69	7	25	25	17	Economy
Aschaffenburg	37	87	18	9	20	20	Energy
Weimar	41	45	35	59	92	60	Economy
Neubrandenburg	5	76	38	43	96	52	Economy
Landshut	17	52	36	31	47	26	Economy
Kempten	31	25	30	23	22	15	Human
Rosenheim	66	23	33	22	29	28	Economy
Frankfurt (O.)	36	8	32	84	57	39	Economy
Stralsund	88	29	75	91	100	93	Economy
Greifswald	75	7	4	28	95	38	Economy
Baden-Baden	11	15	24	64	12	8	Human
Schweinfurt	52	90	26	33	7	24	Energy
Neustadt a.d.W.	3	18	14	46	69	13	Economy
Emden	27	51	74	93	48	61	Human
Passau	4	21	31	44	45	14	Economy
Speyer	15	82	11	37	40	23	Economy
Frankenthal	71	89	61	75	43	77	Economy
Hof	26	37	48	53	79	53	Economy

Appendix E. Elasticity of substitution

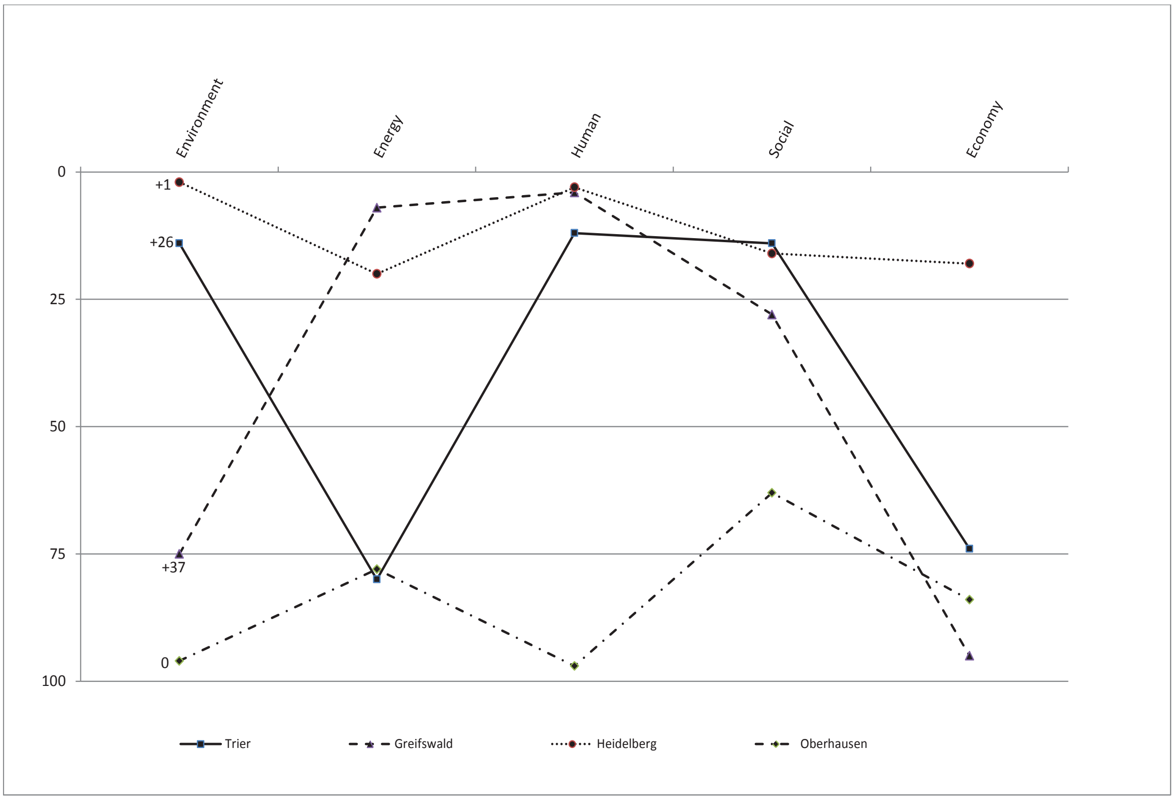

Figure E.1: Balanced versus unbalanced performance and the elasticity of substitution