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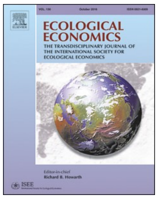

Analysis

Backward- and Forward-looking Shadow Prices in Inclusive Wealth Accounting: An Example of Renewable Energy Capital

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ABSTRACT

Attaching weights to the list of capital assets is crucial in inclusive wealth accounting and sustainability assessments. These weights, or shadow prices, can be constructed in theory by looking prospectively at future social profits that the capital in question is expected to yield. In practice, however, both backward- and forward-looking shadow prices are used. This study confirms that these two approaches are theoretically equivalent under strong assumptions and reviews how and why the two approaches are taken. The two approaches are then applied to renewable energy capital (REC), which has rarely been done in either produced or natural capital accounting and sustainability assessments. Renewable energy capital provides an ideal example with which to compare the two approaches, as it is a class of produced capital that substitutes both produced and natural capital. The numerical results of both approaches demonstrate that renewable energy capital starts to account for as large a share as natural capital does, if not produced capital or inclusive wealth, in those countries where natural capital is poorly endowed and investment in renewable energy capital has been witnessed.

1. Introduction

The literature on green national accounting has demonstrated that net investment in broadly defined wealth can be an indicator of changes in social well-being. Genuine savings measurement (World Bank, 1999–2016) and inclusive or comprehensive wealth accounting (UNU-IHDP and UNEP, 2012, 2014; World Bank, 2011) have attempted to put theory into practice. A critical point in this literature is shadow prices, which reflect a marginal contribution to social well-being, as they determine the relative weights attached to changes in different capital assets.

In theory, shadow prices should embody future income flows, as “all wealth is, strictly speaking, for future use. It is impossible to push back its use into the past; neither is it possible to confine it to the present” (Fisher, 1906). It has been established that shadow price dynamics can be derived for both optimal and imperfect economies (Hamilton and Clemens, 1999; Dasgupta and Mäler, 2000; Fenichel and Abbott, 2014). In practice, produced and natural capital are measured by backward- and forward-looking approaches, respectively. This is done partly for practical reasons but chiefly because it is difficult to assume or predict the future income flows a capital asset will yield, and natural capital is not accumulated by humans. In this study, we first review both approaches and demonstrate that both are equivalent under strong assumptions. We then provide what is, to the best of our knowledge, the first estimate of renewable energy capital (REC) stocks. Although renewable energy has been a focus of attention and massive investment in both developed and emerging economies for greener growth, it has surprisingly not appeared in practical accounting or even in debates over inclusive wealth accounting and sustainability assessment. We fill this gap by making a crude but important first step in measuring REC in the wealth accounting context.

The absence of renewable energy in debates around inclusive wealth is not the only reason this study focuses on this particular class of energy. Traditionally, produced capital has been valued using a backward-looking cost-based approach, while natural capital has only just begun to be valued, through an income-based approach. As we discuss in detail below, REC can be positioned at the intersection of produced and natural capital, as it jointly substitutes for conventional power plants and nonrenewable resources. Thus, it provides an excellent example of measurement using both approaches.

An important distinction in terminology must be made. Throughout this paper, REC refers to manufactured power plants such as photovoltaic power plants and wind farms. This is distinct from renewable energy, which is energy converted from renewable energy sources such as sunlight and wind. Discussion of REC should be separate from discussion of other produced capital, such as coal- or gas-fired power

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plants.

The rest of the paper is organized as follows. In the next section, the basic features of backward- and forward-looking shadow prices are illustrated, and they are shown to be equivalent under simple conditions. Section 3 reviews the practice of various capital asset accounting and summarizes the advantages and shortcomings of both approaches. Section 4 conceptually clarifies the place of renewable energy capital in inclusive wealth accounting, and shows the methodology for and results of renewable energy capital in both approaches. The figures we will present are for illustrative purposes and should be enhanced and updated in both depth and width. Section 5 concludes the paper by suggesting possible future research directions.

2. Theoretical Equivalence Between Backward- and Forward-looking Shadow Prices

The increase in inclusive wealth as an indicator of sustainable development is based on the equivalence idea that intergenerational (i.e., social) well-being is determined by the current set of relevant capital assets. On the one hand, social well-being is the discounted sum of the utility of all future generations, including the present, in the economy under study.[1] On the other hand, inclusive wealth is the weighted sum of capital assets existing in the economy. Both are connected through shadow prices (Dasgupta and Mäler, 2000). The shadow price of a capital asset is defined as the marginal contribution of the capital in question to social well-being,[2] given a specific forecast of how the economy will evolve. Since capital assets are for future purposes (Fisher, 1906), a shadow price should reflect the future consequences of present perturbation for the capital in question.

This justifies the forward-looking nature of shadow prices. It is useful to reproduce the basic model (Arrow et al., 2003a; Fenichel and Abbott, 2014). Assuming away population change and the divergence between static and dynamic average utilitarianism (Arrow et al., 2012; Yamaguchi, 2018), let the social well-being at t be

$$V(t) = \int_t^{\infty} U(C(\tau))e^{-\delta(\tau-t)}d\tau \tag{1}$$

where $\delta > 0$ denotes the utility discount rate. $U(C)$ is the utility derived from consumption C. The dynamics of natural capital, N, can be described by

$$\dot{S}(\tau) = G(S(\tau)) - R(\tau), \tag{2}$$

where $G(S(\tau))$ is a mapping from natural capital stock to its production, and $R(\tau)$ denotes the extraction. Along with natural capital, the economy also has produced capital, which we denote by $K(\tau)$. It changes according to

$$\dot{K}(\tau) = F(K(\tau), R(\tau)) - C(\tau) - \gamma(\tau)K(\tau), \tag{3}$$

where the production function has two inputs—the produced capital itself and the extraction of natural capital. It is also subject to depreciation at the rate of $\gamma(\tau)$. Given the initial stocks, $K(t)$ and $S(t)$, as well as fixed preference, technology and institutions, the economy has a certain forecast of how consumption and the two capital stocks will evolve, at t. Eq. (1) can then be rewritten as the value function (Dasgupta, 2009)

$$V(K(t), S(t), t) = \int_t^{\infty} U(C(K(t), S(t), \tau))e^{-\delta(\tau-t)}d\tau. \tag{1′}$$

The shadow prices of produced and natural capital are determined by

$$p_K(t) = \frac{\partial V(t)}{\partial K(t)};\ p_S(t) = \frac{\partial V(t)}{\partial S(t)}. \tag{4}$$

The time derivative of social well-being is, on the one hand,

$$\dot{V}(t) = p_K(t)\dot{K}(t) + p_S(t)\dot{S}(t) + \frac{\partial V(t)}{\partial t}, \tag{5}$$

and on the other hand,

$$\dot{V}(t) = \delta V(t) - U(C). \tag{6}$$

Thus, the return on social well-being can be written as

$$\delta V(t) = U(C) + p_K(t)\dot{K}(t) + p_S(t)\dot{S}(t) + \frac{\partial V(t)}{\partial t} \tag{7}$$

Partially differentiating both sides of (7) with regard to produced and natural capital, their shadow prices defined by (4) should satisfy, respectively,

$$\begin{aligned}\delta p_K(t) = {} & U_C(t)\frac{\partial C(t)}{\partial K(t)} + \frac{\partial p_K(t)}{\partial K(t)}\dot{K}(t) + p_K(t)\frac{\partial \dot{K}(t)}{\partial K(t)} + \frac{\partial p_S(t)}{\partial K(t)}\dot{S}(t) \\ & + p_S(t)\frac{\partial \dot{S}(t)}{\partial K(t)},\end{aligned} \tag{8}$$

$$\begin{aligned}\delta p_S(t) = {} & U_C(t)\frac{\partial C(t)}{\partial S(t)} + \frac{\partial p_K(t)}{\partial S(t)}\dot{K}(t) + p_K(t)\frac{d\dot{K}(t)}{dS(t)} + \frac{\partial p_S(t)}{\partial S(t)}\dot{S}(t) \\ & + p_S(t)\frac{\partial \dot{S}(\mathrm{t})}{\partial S(t)}.\end{aligned} \tag{9}$$

In our setting, it follows that $\frac{\partial p_K(t)}{\partial K(t)}\dot{K}(t) = \dot{p}_K(t)$, $\frac{\partial \dot{K}(t)}{\partial K(t)} = F_K(t) - \gamma(t)$, and $\frac{\partial \dot{S}(t)}{\partial K(t)} = 0$. Plugging these equations into (8), we obtain

$$\dot{p}_K(t) - [\delta - (F_K(t) - \gamma(t))]p_K(t) = -U_C(t)\frac{\partial C(t)}{\partial K(t)} - \frac{\partial p_S(t)}{\partial K(t)}\dot{S}(t), \tag{8′}$$

Changing t to τ, and differentiating (8′) with regard to time from t to infinity yields

$$\begin{aligned}p_K(t) = \int_t^{\infty} & \left[U_C\frac{\partial C(\tau)}{\partial K(\tau)} + \frac{\partial p_K(\tau)}{\partial K(\tau)}\dot{K}(\tau)\right. \\ & \left. + \frac{\partial p_S(\tau)}{\partial K(\tau)}\dot{S}(\tau)\right]e^{-\int_t^{\tau}(\delta-(F_K(v)-\gamma(v)))dv}d\tau.\end{aligned} \tag{10}$$

Thus, the shadow price of produced capital is the net present value of the income flow the capital yields in the future. Likewise, since $\frac{\partial p_S(t)}{\partial S(t)}\dot{S}(t) = \dot{p}_S(t)$ and $\frac{\partial \dot{S}(t)}{\partial S(t)} = G_S(S(t))$, the shadow price of natural capital reads:

$$\begin{aligned}p_S(t) = \int_t^{\infty} & \left[U_C\frac{\partial C(\tau)}{\partial S(\tau)} + \frac{\partial p_K(\tau)}{\partial S(\tau)}\dot{K}(\tau)\right. \\ & \left. + p_K(\tau)\frac{d\dot{K}(\tau)}{dS(\tau)}\right]e^{-\int_t^{\tau}(\delta-G_S(S(v)))dv}d\tau.\end{aligned} \tag{11}$$

As is seen in the above expression, the proper discount rate to be used is the rate of discount of the numeraire (utility or consumption), adjusted for the marginal rate of reproduction of the capital in question (Arrow et al., 2003a; Fenichel and Abbott, 2014).

However, postulating future income for calculating net present value is not always easy. Here, we recall that future income is not the whole story of capital assets. Investing in capital is, after all, "spending resources now to produce an object that will contribute to production (and profit) in the future" (Solow, 1995). If forward-looking shadow prices correspond to the capital's contribution "to production (and profit) in the future," then backward-looking shadow prices can be constructed by looking at the other end of the time horizon and using the "spending resources now"

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[1] It can also be argued that discounted utilitarianism, which discriminates future generations, should not be used in a sustainability assessment, which is distinctive from our current wealth accounting (Cairns and Long, 2006).

[2] As the capital in question becomes scarcer, its shadow price also changes (Fenichel et al., 2016). Inclusive wealth accounting gets around this issue by assuming that shadow prices do not change in a relatively short period of time and by adopting period-average shadow prices. As it stands, therefore, shadow prices are in practice effective only at the margin. The product of shadow prices and capital quantities has an economic significance only in characterizing changes in current capital stocks.

portion of the capital dynamics Solow (1995) mentions.

It proves very useful to compare our conceptual framework with financial capital assets. In a fascinating account of where post-crisis monetary policy should be headed, Mehrling (2010) summarizes how different the current views of capital asset values are:

> On the one hand, we have the view of *economics*, which resolutely looks through the veil of money to see how the prospects for the present generation depend on investments in real capital goods that were made by generations *past*. On the other hand, we have the view of *finance*, which focuses on the present valuations of capital assets, seeing them as dependent entirely on imagined *future* cash flows projected back into the present.
>
> The economics view and the finance view meet in the present, where cash flows emerging from past real investments meet cash commitments entered into in anticipation of an imagined future. This *present* is the natural sphere of the *money* view.
>
> (emphasis in the original)

Mehrling continues to argue that the current monetary policy discussion fails to focus on the money view, which posits that the central bank should strike a balance between discipline and elasticity in the interbank money market. The money view cares about how the money market is currently cleared, regardless of how assets have accumulated in the past or how much income will be yielded in the future. Interestingly, the economics, finance, and money views help us understand the current discussion of shadow prices. It is evident that the economics and finance views correspond exactly to the backward- and forward-looking perspectives.

Moreover, there may even be an equivalent of the present-looking money view in our current debate on wealth accounting. Capital assets, or a service flow from them, are sometimes directly traded in the market, whereby the market price of a capital asset clears the current market. For example, the rental price of a nonrenewable resource, say, oil, is equated with its discounted capital gain in the future if the market is dynamically efficient. This is another way of expressing Hotelling's rule. If the market is statically efficient as well, then the rental price is also equal to the market price. The present-looking market price, our equivalent of the money view, shows whether the market is so cleared that the rental price on the supply side is equal to the market price. For another example, human capital is traded in the labor market although, to be more precise, what is traded in the market is frequently the service flow (often for a year) of human capital. The present-looking price of human capital directly relates to the clearing of the supply-demand in the current market, irrespective of how that human capital has been accumulated in the past or what it will yield in the future. Thus, present-looking shadow prices can also be used if they are consistent with the theoretical framework to be outlined. We shall come back to this point in the discussion of natural capital shadow price in Section 3.4. Backward-, present-, and forward-looking perspectives may correspond to cost-, price-, and income-based approaches. The three may converge in particular settings. In the following, we focus on the backward- and forward-looking shadow prices.

A *forward-looking shadow price* represents the anticipated net profits from the capital that arise (only) in the future; while a *backward-looking shadow price* is based on realized expenditures that are adjusted through time via economic depreciation. In what follows, we will demonstrate that the two shadow prices are equivalent under strong assumptions.

We use a reduced form of expressions in the following. Suppose that an investment in a produced capital asset is implemented at $t = 0$. The cost incurred is ${p_K}^{BL}(0) \equiv m$. Let $D(t)$ be the net benefit that arises at t from the capital in question. $D(t)$ is assumed to be growing at the rate of g, so that $D(t) = D(0)e^{gt} = D_0e^{gt}$. Its end of life comes at $t = T$. Note that g could be positive or non-positive.[3] Letting r denote the effective discount rate, and assuming r is larger than g, the forward-looking shadow price of this produced capital at the margin at 0 can be written as $p_K^{FL}(0) \equiv \frac{D_0(1+r)}{r-g}\left(1-\left(\frac{1+g}{1+r}\right)^{T+1}\right)$. Assuming completely informed agents and perfect foresight with no uncertainties, arbitrage (${p_K}^{BL}(0) = {p_K}^{FL}(0)$) suggests that

$$\frac{D_0(1+r)}{r-g}\left(1-\left(\frac{1+g}{1+r}\right)^{T+1}\right) = m, \tag{12}$$

provided that the investment market is competitive and all forms of capital and sectors have decreasing returns. The LHS of this equation is the forward-looking shadow price at 0, which is equated with the backward-looking price on the RHS.

Over time, both forward- and backward-looking shadow prices change. The forward-looking shadow price at t is

$$p_K^{FL}(t) \equiv \frac{D_0(1+r)(1+g)^t}{r-g}\left(1-\left(\frac{1+g}{1+r}\right)^{T-t+1}\right), \tag{13}$$

since D is assumed to grow at g. Now the backward-looking price at $t > 0$ should reflect economic depreciation, defined as the decline in asset value with age (Hulten and Wykoff, 1981; Fraumeni, 1997). Let $\delta(t)$ denote the rate of economic depreciation at t, so that the backward-looking price at t is[4]

$$p_K^{BL}(t) = m\left(1-\sum\nolimits_{s=1}^{t}\delta(s)\right) \tag{14}$$

Again, arbitrage in the market at t requires that

$$\frac{D_0(1+r)(1+g)^t}{r-g}\left(1-\left(\frac{1+g}{1+r}\right)^{T-t+1}\right) = m\left(1-\sum\nolimits_{s=1}^{t}\delta(s)\right). \tag{15}$$

Using the arbitrage Eq. (12), this relationship is equivalent to

$$(1+g)^t\frac{\left(1-\left(\frac{1+g}{1+r}\right)^{T-t+1}\right)}{\left(1-\left(\frac{1+g}{1+r}\right)^{T+1}\right)} = \left(1-\sum\nolimits_{s=1}^{t}\delta(s)\right). \tag{16}$$

This central result implies that, broadly speaking, the proper depreciation rate should be the rate of change of future incomes. It follows that a given, constant depreciation rate of produced capital, as is currently applied in practice, can be deemed a strong assumption. It is also worthwhile adding that Eq. (15) may not be satisfied if the initial investment is irreversible and a sunk cost, which is often the case in utilities. Then the RHS's in Eqs. (15) and (16) could be larger.

We have argued that backward- and forward-looking shadow prices are equivalent without assuming any uncertainties. In practice, as we will see in Section 3, both approaches are used in spite of, or owing to, their equivalence. A practical advantage of backward-looking shadow prices is that, by construction, there seems to be no inherent uncertainty as such.[5] Actual expenditure or its estimate can simply be used, so data availability rationalizes the use of this methodology. Moreover, the backward-looking approach seems to be aligned with the idea of exchange value used in national accounting (Obst et al., 2016). However, to ensure the equivalence of both prices, the depreciation rate, $\delta(s)$, should be properly defined for the computation of backward-looking prices. Moreover, it is sometimes tricky to distinguish past investment from consumption. For example, expenditures on food and clothing for pupils could be either investment in human capital or pure consumption (UNU-IHDP and UNEP, 2014).

Perhaps most significantly, backward-looking shadow prices may seem hardly conceivable using the information on the buildup of

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[3] We can also postulate a more general form of $D(t)$ without assuming its growth, in which case it holds that $p_K^{FL}(0) = \sum_{s=0}^{\infty}\frac{D(s)}{(1+r)^s}$. The central result in this section does not change with this alternative formulation.

[4] We are grateful to Ayumi Onuma for correcting the wrong equation of depreciation in the draft.

[5] Of course, data availability and informational asymmetry may make cost information uncertain as well. This is distinct from the future uncertainty we discuss here.

natural capital, since it is "invested" by Nature. However, once natural capital has prices that are determined by their forward-looking valuation at $t \geq 0$, then one can construct backward-looking shadow prices from t onward using depletion, regeneration and investment, if any. For instance, a coal mine can be evaluated in a forward-looking shadow pricing at t. Let that price be $p_N^{FL}(t)$. The forward-looking price can be updated in any following period, $t' > t$. Starting from the same price, $p_N^{FL}(t)$, backward-looking price at $t' > t$ can also be updated using depletion at t'. This way, both shadow pricings can be done consistently.

3. Forward- and Backward-looking Shadow Prices in Inclusive Wealth Accounting in Practice

In this section, we reveal that inclusive wealth accounting is, as currently practiced, actually a blend of backward- and forward-looking perspectives in determining shadow prices. It is important to avoid confusion here. Our interest lies in how shadow prices are measured in theory and practice, not quantities of capital stock per se, although we occasionally discuss the latter as well. The quantity of capital stock can be measured either directly or indirectly (i.e., in present- or backward-looking ways). A direct method will be the most accurate, reflecting a snapshot, but it is typically costly. An indirect method of accumulating past investments while adjusting for depreciation is frequently referred to as the "perpetual inventory method" (PIM). This approach is used in the measurement of produced capital in both national and inclusive wealth accounting. This discussion on measuring quantities of capital stock is not the focus of our paper, but accounting for produced capital stock retrospectively is closely related to why its shadow price is also measured retrospectively.

We look at specific capital assets in turn. What we mainly have in mind is inclusive wealth accounting and sustainability assessments (UNU-IHDP and UNEP, 2012, 2014), but we occasionally mention earlier work by the genuine savings database (World Bank, 1999–2016) and comprehensive wealth accounting (World Bank 2006, 2011). It is not our intention to provide an exhaustive review of this literature of wealth accounting in general.[6] Rather, we wish to clarify that both approaches are used in inclusive wealth accounting as it stands and that produced and natural capital provide interesting polar cases.

3.1. Produced Capital

On the face of it, produced capital measured by PIM seems to provide a textbook example of backward-looking shadow prices, following capital accounts of conventional national accounting. However, it will be proved that things are not that simple.

What is distinct about the case of produced capital in the context of inclusive wealth accounting is that past investment data are already expressed in dollars. Thus, one way to explain the practice seems that the quantity of capital stock is measured retrospectively, employing PIM, and its shadow price is simply assumed as unity. This view requires that produced capital be the numeraire in the accounting. As long as the productivity of capital assets is fully explained by their shadow prices, the choice of numeraire does not matter to wealth accounting and sustainability analysis (Dasgupta, 2009). In theoretical formulations, $\frac{\dot{V}}{p_K} = \dot{K} + \frac{p_S}{p_K}\dot{S} + \frac{1}{p_K}\frac{\partial V}{\partial t}$, derived from Eq. (5), is often used as genuine savings or the change in inclusive wealth. This expression uses produced capital as the numeraire. In practice, however, the numeraire in wealth accounting is supposed to be money, given that it is measured at constant US dollars (UNU-IHDP and UNEP, 2012).[7]

In a more plausible account of things, price and quantity of produced capital is measured in an inseparable fashion. This can be justified by appealing to the dynamic equation of produced capital given in Eq. (3): depreciation is accounted for. The declining value of produced capital is embodied in the combined price and quantity change. In the previous section, we showed that proper accounting of depreciation is critical in equating backward- and forward-looking shadow prices. Including depreciation thus means that the retrospective shadow price is already embodied in the current accounting. In fact, the SNA standards suggest that the changes in value through depreciation are the first-best option for valuing produced capital (Droste and Bartkowski, 2018). If a market fails to exist for a certain capital stock, then measuring the asset value by calculating the net present value of future flows is suggested (United Nations et al., 2014).

The previous section also implies that, instead of accumulating investment net of depreciation according to PIM, a forward-looking shadow price multiplied by the stock quantity can also be used in principle. A forward-looking shadow price could be obtained as the net present value of income gain, discounted at the discount rate net of the marginal productivity of produced capital, as described in Eq. (10).[8] Accounting for the forward-looking shadow price and quantity separately, although difficult in practice, would enable one to tell which drives the value of produced capital.

In sum, the produced capital is measured retrospectively and already includes information on potential future income flows.[9] The price and quantity of produced capital are inseparable, and the backward-looking shadow price reflecting depreciation is embodied in its accumulation equation.[10]

3.2. Human Capital

As is elaborated in UNU-IHDP and UNEP (2014), the measurement of human capital can be categorized into indicator-, cost-, and income-based methodologies,[11] all of which have advantages and disadvantages. They argue that the income-based approach can be considered the best in terms of consistency with welfare economic theory.

A specific methodology based on the income-based approach—the forward-looking shadow price in our terminology—is adopted in IWR.[12] First, the population number relevant to education (i.e., 15 years or older) is obtained ($P(t)$). To address the educational effect, the exponential of educational attainment ($A(t)$ years) multiplied by the rate of return on education (i %) is attached to this population. Thus, we have the human capital stock, $H(t) = P(t)e^{iA(t)}$. Second, their unit shadow price is obtained by looking at the net present value of current

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[6] For reviews of these differences, see Arrow et al. (2012) and Engelbrecht (2016). For a critical argument, see, e.g., Roman and Thiry (2016).

[7] A reviewer has pointed out that it is not consumption but money, as the use of consumption as numeraire is an artefact of the assumption that there is a single consumption good that also serves as a single capital good.

[8] It has been observed that, when utility is not the numeraire, the comparison of wealth at different points in time can cause practical problems, as the marginal contribution of wealth to social well-being changes over time. Weitzman (2001) and Li and Löfgren (2002) proposed a price index with which to rescale the well-being measure.

[9] The genuine savings of the World Bank does not measure produced capital as such. Their accounting starting point is gross national savings, which is output net of consumption. Again, this is expressed in the unit of consumption, so the shadow price is considered unity.

[10] That separating out price and quantity is not straightforward is reminiscent of the well-known argument of ecosystem services (Boyd and Banzhaf, 2007).

[11] See Le et al. (2003, 2006) for a survey of cost- and income-based measures of human capital measurement.

[12] Along with the conventional forward-looking approach, the latest *Inclusive Wealth Report 2018* (*IWR 2018*) calculates the shadow prices of human and health capital according to the "frontier function" frequently used in data envelope analysis. This "shadow price" is by no means equal to the marginal contribution of capital assets defined by Eq. (4); moreover, GDP is used as the output of the function, rather than social well-being. Thus, we use figures according to the conventional forward-looking approach in *IWR 2018* in the application section of this paper.

labor income divided by the mass of human capital. That is, its shadow price in monetary terms in practice can be expressed as

$$q_H(t) = \int_t^{T(t)} \frac{w(t)L(t)}{P(t)e^{i\mathrm{A}(t)}} e^{-i(\tau-t)} d\tau, \tag{17}$$

where $w(t)$, $L(t)$, and $T(t)$ represent the wage, labor input, and the expected working years of the current labor cohort at t. Thus, its quantity is measured in a backward-looking manner, while its price is measured as a typical forward-looking price.

A backward-looking methodology is adopted in accounting for human capital by the World Bank (1999–2016). They record educational expenditure as an investment outlay for human capital. This is similar to the perpetual inventory method, except that depreciation does not seem to be explained. As with the case of produced capital, educational expenditure is expressed in monetary units, so the price and quantity of human capital is measured inseparably in a backward-looking way. Arrow et al. (2012) note that using this method would be equal to the value obtained using an income-based method “only if education were provided by a price system, supplemented with a credit system to permit repayment of the costs of education over time as the income generated by education accrues.” This condition corresponds to the assumptions of a complete market with perfect foresight with no uncertainties, which we have posited for the equivalence between backward- and forward-looking shadow prices.

3.3. Health Capital

Accounting for health as a capital stock has a very short history, being recently initiated in Arrow et al. (2012, 2013) and UNU-IHDP and UNEP (2012). UNU-IHDP and UNEP (2014) clarify that health capital can contribute to human well-being through at least three channels: direct well-being, productivity, and longevity. Noting that evaluating the first two would be practically difficult, they focus on the longevity value of health capital. In practice, for every age cohort, they attach the probability distribution to the remaining life years, given past performance reported in life tables, with proper time discounting and the corresponding population attached. This is the quantity of a nation's health capital, expressed as a unit of years. We could describe the health capital quantity as a backward-looking, present-looking (current population looking at past dynamics), and forward-looking (likely remaining years in business as usual) hybrid.

The value of statistical life years (VSLY) is used to attach the shadow price per unit of health capital. The value of statistical life (VSL) is an attempt to measure the marginal willingness to pay to extend a possible life year of an individual. In theory, this corresponds to the net present value of the utility of consumption divided by the marginal utility, or the utility of living in consumption units (Arrow et al., 2003b, 2013). Therefore, it is also a forward-looking shadow price using future income flows.

A backward analogue to the shadow price of health capital is easily conceived. Health expenditure could be measured the same way (educational) human capital is proxied by educational expenditure. Indeed, in competitive equilibrium, VSL is equated with the increase in health expenditure associated with the marginal increase in the likelihood of survival (Arrow et al., 2013). Empirically, however, this route is not taken, since it would be difficult to separate out the portion of healthcare expenditure specifically for the marginal increase in survival probability.

3.4. Natural Capital

Several classes of natural capital are recorded in inclusive wealth accounting, both non-renewable (oil, gas, and coal) and renewable (forest and agricultural land). The quantity of non-renewable natural capital is measured as a variant of PIM: the direct estimate of the current stock is used, and past estimates of quantity are updated by using the most recent estimates and the annual flow of extraction. Thus, their quantity is accounted for in a backward-looking manner.

The shadow price of non-renewable resources is the rental price, which is the market price net of the marginal cost of production. The use of the market price instead of the shadow price has been criticized for neglecting the scarcity of the resource. On the face of it, this rental price is present-looking. However, it can be shown that this present-looking price is equated with the net present value of income gain and capital gain from the dynamic equation of shadow prices. Using Eqs. (10) and (11), if the static efficiency is ensured regarding the extraction of resources from natural capital, its shadow price in monetary terms would be

$$q_S(t) \equiv \frac{p_S(t)}{p_K(t)} = F_R(K(t), R(t))$$
$$= \frac{\int_t^\infty \left[U_C C_S(K(\tau), S(\tau)) + \frac{\partial p_K(\tau)}{\partial S(\tau)} \dot{K}(\tau) + p_K(\tau) \frac{d\dot{K}(\tau)}{dS(\tau)} \right] e^{-\int_t^\tau (\delta - G_S(S(v)))dv} d\tau}{\int_t^\infty \left[U_C C_K(K(\tau), S(\tau)) + \frac{\partial p_K(\tau)}{\partial K(\tau)} \dot{K}(t) + \frac{\partial p_S(\tau)}{\partial K(\tau)} \dot{S}(\tau) \right] e^{-\int_t^\tau (\delta - (F_K(v) - \gamma(v)))dv} d\tau}. \tag{18}$$

Thus, their shadow price is directly present-looking (F_R), but the underlying theory suggests that it is equated with the forward-looking price.[13]

A more complex class of natural capital is renewable resources, which consist of forest resources and agricultural land.[14] Their quantity is simply measured through a hybrid of present- and backward-looking approaches, updating the current stock figures using past flows of destruction (typically deforestation and land conversion) and addition (afforestation, reforestation, and land development[15]).

The shadow price of renewable natural capital is practically measured as the net present value of future income flows. For example, the shadow price of a unit of agricultural land per hectare is the net present value of the rental price of the basket of representative agricultural products per hectare from the present year to the infinite future. Likewise, the shadow price of a unit of non-timber forest resources per hectare is the net present value of the monetary value of a hectare of forest ecosystem services. Renewable natural capital shadow prices are currently measured in a forward-looking income-based manner, although the provisioning service portion of forest resources (i.e., timber) is measured using the present rental price of timber in a way similar to that used for non-renewable resources.

3.5. Adjustments of IW

Although, in principle, social well-being moves in the same direction as capital assets, some exogenous factors need to be adjusted to arrive at an accurate index of social well-being. In particular, the exogenous price shocks of natural capital (capital gains), carbon emission damage, and total factor productivity change are added such that they are reflected in the adjusted index of inclusive wealth. Note that these are all expressed in flow variables, so they are not typical shadow prices. In this subsection, we review how each of these items is reckoned using backward- or forward-looking perspectives.

3.5.1. Oil Capital Gain and Loss

An exogenous price change earned on an existent natural resource

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[13] The present-looking market price has been known to evolve according to Hotelling's rule (e.g., van der Ploeg, 2010). The empirical evidence suggests, however, that technological change, revisions to expectations regarding the resource base, and market structure have more influence on the movement of the actual prices of non-renewable natural capital (Livernois, 2008).

[14] *IWR 2018* includes an attempt to measure fishery resources as another form of natural capital.

[15] Technically, cultivated forest is placed under the produced capital category.

such as oil and gas should contribute to social well-being to the extent that resource-holding nations can cash in on it to enhance social well-being, with no additional investment involved. They are literally windfall benefits that have been transferred to oil-exporting countries. In IWR, the actual price change observed during the studied period is accounted for as oil capital gain. This is undoubtedly a backward-looking price change in the sense that it is the actual price change that occurred in the *past* and that can be converted into real assets at the end of the studied period with no uncertainty.

Earlier studies (Asheim, 1996; Sefton and Weale, 1996; Vincent et al., 1997; Hamilton and Bolt, 2004; van der Ploeg, 2010), however, have shown that the exogenous capital gain that is to be accrued on natural capital in the *future* needs to be included in the change in social well-being. Accounting only for the current capital stock change would overestimate (underestimate) social well-being when a resource price increase (decline) is anticipated. Thus, this accounting is based on a forward-looking perspective. However, this methodology is not adopted in practical wealth accounting (World Bank, 2011; UNU-IHDP and UNEP, 2012), for reasons that are not spelled out in the literature.[16] One can infer, however, that it is not used because it is very difficult to anticipate resource price movement, in contrast to the theoretical expectation of Hotelling's rule (Livernois, 2008). In short, the forward-looking perspective is not adopted for oil capital gain due to its inherent uncertainty.

This being the case, a possible way to take a forward-looking oil capital gain would be to undertake a scenario analysis. This could be created by assuming future oil price increases at, say, $\dot{p}_r = 8\%$, 3%, and -2%, or by extrapolating from past trends (Hamilton and Bolt, 2004) to forecast the next few decades and computing the capital gain earned on oil capital in net present value. This could be done in a more sophisticated manner by simulating many more future oil price paths and generating the probable price possibilities (Collins et al., 2014).[17]

3.5.2. Carbon Emissions vs. Damage

One of the largest-scale natural capital assets in action is the carbon sink of the planet. Carbon emissions into that sink degrade natural capital. However, because carbon is a global public bad, a nation will suffer climate-change consequences even if it does not emit any carbon dioxide. Thus, to construct an indicator of the social well-being of a given country, one needs to take account of the damage done to the country by the additional carbon emissions at the global level. This is why it is carbon damage, rather than carbon emissions, that is accounted for in the adjustment of inclusive wealth. By contrast, the World Bank (1999–2016) has adjusted actual carbon emissions as a deduction from wealth, irrespective of the consequences of climate change. The bottom-line wealth change would be equal under the two methodologies if there were a perfect market for carbon emitters to compensate for those countries that are prone to actual damage (Hamilton, 2012).

While this dichotomy between emissions- and damage-based approaches may appear irrelevant to our analysis, one can regard them as corresponding to the input and output of the imaginary national carbon damage function. In this view, a damage-based accounting of carbon emissions looks forward to their consequences, while an emissions-based approach can be considered backward-looking. Again, the forward-looking approach comes at the cost of uncertainty. What is distinctly uncertain here is the way the total global damage of the carbon is allocated to each country. Both approaches are plagued by the deep uncertainty about the social cost of carbon, which is set to be, say, USD 50 per ton.

3.6. Summary

Table 1 summarizes the results of our review of the perspectives adopted for shadow pricing in inclusive wealth accounting in practice. We can see that, even within IWR, both backward- and forward-looking perspectives are taken in measuring shadow prices.

Table 1
Shadow prices in inclusive wealth accounting in practice.

Capital assets	Shadow price	Quantity
Produced capital	Backward-looking (measured jointly with quantity)	Backward-looking
Human capital	Forward-looking (IWR) Backward-looking (GS)	Backward-looking
Health capital	Forward-looking (only IWR)	Backward-looking
Natural capital - Non-renewable	Present-looking (which can be equated with forward-looking in theory)	Present- or backward-looking
Natural capital - Renewable	Forward-looking	Present- or backward-looking
Oil capital gain	Backward-looking	–
Carbon damage	Forward-looking (IWR) Backward-looking (GS)	–

Notes: IWR and GS stand for *Inclusive Wealth Report* (UNU-IHDP and UNEP, 2012, 2014) and genuine savings (adjusted net savings) in World Bank (1999–2016).

This brings us to the obvious question: Which should be used in principle? As we have argued in Section 2, both approaches should arrive at the same shadow prices in theory, so which approach to take should be a matter of practical convenience. It may seem that forward-looking prices are harder to obtain, as one needs to assume future paths of capital assets,[18] whereas all one needs in order to compute backward-looking prices are actual expenditures and depreciation. However, this seeming convenience of backward-looking prices is a superficial one, since precise accounting of the depreciation of the capital in question requires the movement of the future benefit it would yield, as we have shown in Section 2. In other words, uncertain future benefit should imply uncertainties in both backward- and forward-looking shadow prices, although simplified depreciation is frequently applied in practice.

Thus, we have to go back to the assumptions we have made to show the equivalence of the two prices. In particular, aside from uncertainties, arbitrage may not be ensured in many of the markets we observe. In the absence of arbitraging, it can be shown that, under the assumption of optimality, the forward-looking shadow price is larger (smaller) than the backward-looking shadow price if and only if the average cost of the investment is larger (smaller) than its marginal cost (Hamilton and Clemens, 1999). It can be confirmed that this is also the case in non-optimal economies if and only if the shadow price is larger (smaller) than the inverse of the average cost of investment. In both cases, it is likely that the backward-looking shadow prices are the lowest, most conservative estimates.

It also follows that backward-looking shadow prices fit better with circumstances where the actual, certain recording of prices is preferred. In this vein, it aligns well with conventional national accounting and its

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[16] In a similar vein, Hamilton and Bolt (2004) do not account for forward-looking interest rate changes, as there is no reason to anticipate their increase or decrease in the long run.

[17] Averaging uncertainty via Monte Carlo runs, however, should be done with care (Crost and Traeger, 2013).

[18] Looking at the future, some assumptions should be imposed. Hamilton and Clemens (1999), the theoretical backbone of the World Bank, assume an optimal growth path, whereas Dasgupta and Mäler (2000), the theoretical backbone of IWR, adopt the concept of economic forecast under a resource allocation mechanism in imperfect economies. These two devices are adopted to get around the issue of changing resource allocation mechanisms, as the latter would alter the marginal effect of a capital asset on social well-being.

extension to environmental accounting, because the System of National Accounts (SNA) focuses on exchange values, not surplus values, which pertain to social well-being (Obst et al., 2016).

4. Backward- and Forward-looking Shadow Prices of Renewable Energy Capital (REC)

4.1. The Place of Renewable Energy in Inclusive Wealth

We have seen that the shadow values of produced and natural capital are measured in backward- and forward-looking ways, respectively, in inclusive wealth accounting in practice. In the following, we investigate accounting for renewable energy capital (REC) as a component of inclusive wealth. REC provides an intriguing example for both accounting approaches, since it has characteristics of both produced and natural capital, or more precisely, it dually substitutes for produced and natural capital, as expounded below.[19]

Non-renewable fuels such as coal, oil, and natural gas have been extensively used to make our economies more industrialized and our lives more convenient. The role they have played as a fuel for power plants and economic development cannot be overstated. Recently, however, fossil fuel-fired and nuclear power plants have been gradually replaced by renewable energy power plants, including photovoltaic, wind, geothermal, and biomass plants. There are several reasons behind this move. First, the dual problem of resource depletion and carbon emissions has long been considered unsustainable by many nations. Second, there has been a move toward phasing out nuclear power plants across the globe, particularly in the aftermath of the Fukushima–Daiichi accident. Third, thanks to such governmental incentives as subsidies and feed-in tariffs, waves of massive investment have been induced. Consequently, and as a result of expectations concerning the long-run growth of the sector, private initiatives have been made to boost investment, not only in the production process but also in installment and operation projects. Fourth, renewable energy power has become increasingly competitive with conventional power supplies, making investment in the sector increasingly economical. However, key obstacles remain, including scale economies, externalities (such as noise pollution and accidents), the stability of the distribution network, and adjustments with conventional power supplies.

Despite the growth in the share of power supplies and though its role in achieving sustainable development is being stressed everywhere, REC has not been addressed in the context of inclusive wealth accounting and sustainability assessment. To do this, we must illustrate how REC can be accounted for in the inclusive wealth framework. First, as demonstrated in the introduction, REC can be defined as the capital facility to produce electricity, such as solar power stations, windfarms, or biomass power plants. This no doubt falls under the category of "produced capital". Second, a renewable energy (RE) source can be defined as the input into the production process of renewable energy power, such as sunlight, wind, or biomass resources. Renewable energy power as an output is thus a joint product of an REC and RE source. However, an RE source can be postulated to be extracted indefinitely with effectively no cost. Thus, RE capital essentially substitutes for both produced capital and non-renewable natural capital.[20] In a coal-fired power plant, by contrast, the plant itself is a produced capital, and the fossil fuel source to be fed into that capital is an extraction (service) of natural capital, which has both a market price and an externality portion.[21] The method of inclusive wealth accounting would thus depend on the type of resource the manufactured capital interacts with.

This point can be made clearer by explicitly comparing non-renewable, renewable resources, and renewable energy sources as they are fed into power plants employing each type of resource. Here we introduce produced energy, $E(\tau)$, so that the produced capital dynamics becomes

$$\dot{K}(\tau) = F(K(\tau), E(\tau)) - C(\tau) - I_1(\tau) - I_2(\tau) - I_3(\tau) - \gamma(\tau)K(\tau), \tag{19}$$

where $I_i(\tau)$ expresses investment into power plants of type i ($i = 1$ for non-renewable resource-based energy, $i = 2$ for renewable resource-based energy, and $i = 3$ for RE source-based energy). Note that the resource extraction $R(\tau)$ in Eq. (3) is replaced by energy $E(\tau)$ in Eq. (19), to focus on the substitution of "old" power plants by REC. Assume an explicit energy production sector, which is subject to production

$$E(\tau) = E_1(\tau) + E_2(\tau) + E_3(\tau), \tag{20}$$

where non-renewable resource-based energy $E_1(\tau)$, renewable resource-based energy $E_2(\tau)$, and RE source-based energy $E_3(\tau)$, are produced by

$$E_1(\tau) = f_1(K_1(\tau), R_1(\tau)) \tag{21-1}$$

$$E_2(\tau) = f_2(K_2(\tau), R_2(\tau)) \tag{21-2}$$

$$E_3(\tau) = f_3(K_3(\tau)) \tag{21-3}$$

respectively. Here K_1, K_2, and K_3 represent power plants fueled by non-renewable resource (oil, gas, and coal), renewable resource (biomass), and RE source (sunlight and wind). R_1 and R_2 are non-renewable and renewable resources. Note that the RE source is absent from Eq. (21-3), as it can be obtained in a costless way. Let f_{1K}, f_{2K}, and f_{3K} denote the partial derivative of the production functions with regard to capital (power plants); also let f_{1R} and f_{2R} denote that with regard to resources. Non-renewable and renewable resource stocks, denoted by S_1 and S_2, respectively, change according to

$$\dot{S}_1(\tau) = -R_1(\tau) \tag{22}$$

$$\dot{S}_2(\tau) = G(S_2(\tau)) - R_2(\tau). \tag{23}$$

Finally, each power plant capital of type i is subject to the following equation of motion:

$$\dot{K}_i(\tau) = g_i(K_i(\tau), I_i(\tau)). \tag{24}$$

The current-value Hamiltonian associated for maximizing social well-being (Eq. (1)) is[22]

$$\begin{aligned} H = U(C) + p_K[F(KE) - C - \gamma K - I_1 - I_2 - I_3] + p_1 g_1(K_1 R_1) \\ + p_2 g_2(K_2 R_2) + p_3 g_3(K_3) - q_1 R_1 - q_2[G(S_2) - R_2], \end{aligned} \tag{25}$$

where p_i and q_i are shadow prices associated with capital and resource stock of type i. Necessary conditions for optimality include the equations of motion of shadow pries:

$$-p_K F_K = \dot{p}_K - \delta p_K \tag{26}$$

$$-p_K F_E f_{iK} - p_i g_{iK} = \dot{p}_i - \delta p_i \tag{27}$$

for all i, where g_{iK} represents the partial derivative of g_i with regard to the first argument.

Rearranging (27) yields

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[19] The rent for renewable energy source may be captured by the land price suitable for installing REC. However, urban or rural land is not always accounted for as part of national wealth, so the current exercise does not double count. Exceptions include Petty (1665), Chapter 3 of UNU-IHDP and UNEP (2012), among others.

[20] The literature on renewable energy economics has focused on the substitution between fossil fuel input and renewable energy sources (e.g., Gerlagh and van der Zwaan, 2004; Lazkano et al., 2017; Lecca et al., 2017; Popp, 2006; Papageorgiou et al., 2017).

[21] The shadow price of natural capital can be decomposed into a market price portion and an externality portion (UNU-IHDP and UNEP, 2012).

[22] To avoid unnecessary clutter, we omit time subscripts in the following where confusion does not arise.

$$p_i = \frac{p_K F_E f_{iK} + \dot{p}_i}{\delta - g_{iK}} \tag{28}$$

which can be further changed to the forward-looking form:

$$p_i = \int_t^{\infty} p_K F_E f_{iK}\, e^{-\int_t^{\tau} (\delta - g_{iK}) dv} d\tau. \tag{29}$$

Eq. (29) says that the shadow price of capital (power plant) of type i is just the present value of the products of the three components: the marginal productivity of produced capital, the marginal productivity of energy, and the marginal productivity of capital of type i in producing energy. The discount rate to be used is dependent on the utility discount rate (δ) and the marginal productivity of capital of type i in accumulating capital i (g_{iK}).

To fix ideas, suppose that comparison is being made between a coal-fired power plant (non-renewable resource-based power plant, $i = 1$) and a photovoltaic power plant (REC, $i = 3$) of the same capacity. To simplify the matter, assume also that the marginal productivities of capital of each type in reproducing them are equal constants:

$$g_{1K} = g_{3K} = \theta. \tag{30}$$

This may not seem an innocuous assumption, but can be rationalized considering the case where, for example, technological progress occurs in both types, or only investment outlay matters in the accumulation of capital of each type. Combining (29) and (30), we can write the shadow price of REC relative to non-renewable resource-based power plant as

$$\frac{p_3}{p_1} = \int_t^{\infty} \frac{f_{3K}(K_3)}{f_{1K}(K_1, R_1)} e^{-(\tau - t)(\delta - \theta)} d\tau. \tag{31}$$

The component of the integral in Eq. (31) suggests that REC and RE source substitute not only for produced capital (K_1) but also natural capital resource (R_1). The dual substitution of produced and natural capital by REC can justify both the backward- and forward-looking shadow pricing of REC. In the following, we take solar photovoltaic (PV) and wind energy, the world's two most prevalent sources, as measurement examples. It is not our intention here to perform an accurate estimate of REC. We aim instead to demonstrate that both approaches can be reasonably taken to measure this increasingly relevant class of capital.

4.2. Measuring REC: Methodology

In the context of REC, the assumptions we have posited to show the equivalence between backward- and forward-looking shadow prices frequently do not apply. In particular, a divergence between the two shadow prices could result from externalities (missing markets) or subsidies (distortions). A considerable amount of resources has been used worldwide for the build-up of REC. If public policies are well-designed, they endogenize the externalities, and invested capital reflects future social values. However, if public policies involve subsidies or feed-in tariffs that are not consistent with social benefit, the private cost–benefit analysis for investment would be biased, so that backward- and forward-looking shadow prices would not equate.

In both measurement approaches, we first compute the current capital stock quantity by aggregating past investments, assuming a proper depreciation rate, which is assumed to be 5%. This procedure is nothing but a perpetual inventory method, adopted in conventional produced capital measurement. Thus, the estimates can reflect the vintage structure of REC compared to directly using the capital stock estimate of the current year. This is directly used in the backward-looking approach, whereas in the forward-looking approach we have used this obtained vintage structure to allocate total current income to each vintage, which is further used to estimate future income. Unlike produced capital in general, past investment is commonly not expressed in dollars. We employ a cumulative installed capacity dataset from BP (2017), which is then converted to dollars using unit cost (in the backward-looking approach) and oil price (in the forward-looking approach).

Once the current stock figure is estimated, an average unit cost is attached as the backward-looking shadow price of RE capital. In doing so, we use unit “overnight” costs for each power source, including preconstruction, construction, and contingency costs. Operation and maintenance costs should be deducted from forward-looking future income flows. Investing in new infrastructure, such as transmission and distribution networks, could also be expensive. There are also other social factors, such as landscape changes, communal conflicts, residence relocation, and a potentially unstable power supply. In general, the quality or reliability of the power generated by REC should also be considered. The maximum power available generated by REC at a single location varies over time, which may not match the demand pattern (Delucchi and Jacobson, 2011). These external costs are outside the scope of RE capital accounting, as with other capital assets.

Although the information on actual investment is subject to less uncertainty than when predicting future incomes, the cost of renewable energy, for both installation and operation, has been sharply declining in recent years. The average dollar capital expenditure per megawatt for solar photovoltaics and (onshore and offshore) wind dropped by > 10% in 2016, reflecting technology advances (UNEP and BNEF, 2017). It is interesting to investigate how the declining costs of REC can make a difference in social well-being. In both present- and forward-looking accounting, a falling marginal cost of production implies that the capital's net contribution to social well-being is rising, provided that its market price does not change. In addition, even if the market price also falls along with the decline in costs, which is what we have witnessed for solar and wind power, its shadow price rises if its net contribution to social well-being stays equal. In backward-looking accounting, however, this would shrink the value of the capital in question. Again, if markets are fully competitive and if there is no uncertainty, the methodological difference does not affect the social well-being consequences; in the real world, however, using the most recent cost should undervalue its contribution to social well-being. Thus, the use of actual or even past-average unit cost would inflate the value of the current capital stock with vintages, however accurate it may be as a depiction of actual expenditure. Moreover, the unit cost of construction is lower for a larger capacity due to scale economies.[23] Geographical factors matter as well; the unitary cost of installing solar power in Japan is double that of Europe, for example.[24] Nevertheless, for brevity and clarity of analysis, we simply assume that the unit cost of installing the plant is constant and uniform all around the world. We also account only for the initial costs that are associated with installation, as operating and maintenance costs should be reflected in either the depreciation of capital or the net income flow.[25]

As for the forward-looking shadow prices of REC, using a reduced form of Eq. (31), the net present value of future income can be

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[23] Reichelstein and Yorston (2013) find that, while commercial-scale installations have already attained cost parity with fossil fuel-fired power plants in certain parts of the U.S., utility-scale solar PV facilities are also expected to gain cost parity in a few years.

[24] Ondraczek et al. (2015) account for differences in both the solar resource and the financing cost in calculating the levelized cost of electricity (LCOE) from solar PV systems in 143 countries.

[25] Operating and maintenance costs are included in the calculation of the levelized cost of electricity (LCOE), which is inclusive of capital cost, unit variable cost, operation and maintenance, fuel, carbon, and decommissioning (e.g., Reichelstein and Yorston, 2013: IEA et al., 2015). The unit operating fixed cost seems to account for the largest share in the case of renewable energy.

employed to value them. REC has another rationale for this calculation method: its capacity utilization, which is typically lower than for conventional power plants, depends heavily on the weather, geography, and other site-specific conditions. For example, capacity factors are considered to be as low as 10% to 21% for solar PVs (even in the United States), 20% to 49% for onshore wind power, and 30% to 48% for offshore wind power (IEA et al., 2015). Thus, income flows that reflect capacity utilization, regardless of investment outlays, are more relevant to how much the capital is utilized in society.

As a proxy for future income flows, we use the fossil fuel consumption that would be expected if we assume the absence of installed renewable energy.[26] There are many facets to the benefit of trimming the use of fossil fuels by installing REC. First, fossil fuel importers can cut down on their imports by substituting them with newer forms of energy production (Eq. (31)). Second, these importers would be more immune to exogenous commodity price shocks and volatility. In wealth accounting, this translates into less exposure to oil capital loss for oil-importing countries.[27] Third, fossil fuel importers can reduce their contribution to carbon dioxide in the operation phase to nearly zero. Fourth, this would also lessen exposure to the geopolitical risk of oil-producing nations and regions. In this study, we consider only the first contribution, thereby showing the most conservative benefits. Thus, all we need is to account for the net present value of the net benefit of REC, which includes the avoided costs of buying fossil fuels in the market, net of operating costs. The foregone costs of fossil fuels can be estimated by actual renewable energy power consumption, which naturally reflects the capacity utilization of current REC.

Because the same backward-looking quantity of capital is used, what distinguish this method from the backward-looking approach are the shadow prices, which now reflect future income flows. Suppose that a PV and wind power plant can operate for 25 years ($T = 25$) after it is inaugurated (IEA et al., 2015). The remaining operating years of the plant is 25 years minus the years since its commission, t. This vintage structure depends on past investment in capacity. Let the share of vintage year t be $\alpha(T - t)$. The social discount rate is expressed as $\delta > 0$, which is assumed to be constant at 5%.[28] Suppose also that the avoided usage of fossil fuel by consuming the output of the REC is Q, measured in tonnes of oil equivalent. Q is regarded as the product of the installed capacity and the capacity factor (i.e., the capacity utilization rate). To simplify, we assume that Q is the constant flow, although the capacity utilization rate is in reality bound to gradually decline as $t \to T$. To be in line with other capitals in IWR, we take a recent figure for Q in 2014 from BP (2017). The value of the REC of vintage t is then expressed as

$$\sum_{\tau=0}^{T-t+1} \frac{(p_Q - f_Q)Q}{(1+\delta)^{\tau}},$$

where the rental price $p_Q - f_Q$ is also assumed to be constant. In practice, p_Q is the oil price (USD 716 per ton in 2014), and f_Q is the operating and maintenance costs of the renewable power plant. The data for the operation and maintenance costs are somewhat scarce, but we postulate that f_Q accounts for 20% (solar) and 27% (wind) of p_Q.[29] Thus, the total value of the avoided costs for the whole portfolio of various vintages becomes

$$\sum_{t=0}^{T} \alpha(T-t) \sum_{\tau=0}^{T-t+1} \frac{(p_Q - f_Q)Q}{(1+\delta)^{\tau}}$$
$$= (p_Q - f_Q)Q \sum_{t=0}^{T} \alpha(T-t)\frac{1+\delta}{\delta}\left(1 - \frac{1}{(1+\delta)^{T-t}}\right).$$

4.3. Solar Power

Concerning backward-looking shadow prices, we simplify the unit average cost of installing a photovoltaic (PV) power plant by making it constant and uniform, irrespective of installation time and location, at USD 2000 per kW. This is taken from a lower bound of the estimates of IEA et al. (2015), who report the overnight costs—which include pre-construction (owner's costs), construction (engineering, procurement, and construction), and contingency costs—for residential PV as ranging from USD 1867 per kW in Portugal to USD 3366 per kW in France.

The results indicate that solar power capital seems to be the highest in 2014 in Germany ($64b), followed by China ($54b), Japan ($43b), the United States ($34b), and Italy ($32b; see Table 2). It is only in 2016 that the Asia Pacific surpassed Europe and Eurasia in unadjusted capacity, aided by explosive growth in China afterwards (BP, 2017). It also proves useful to put these figures in per capita terms, using UN (2017). Germany still tops the list ($785), followed by Italy ($540), Belgium ($480), Greece ($418), and Japan ($335). Note that all of these top five countries have adopted supporting mechanisms for renewable energy, including solar power, and, typically, feed-in systems or quota obligations.

The results for the forward-looking shadow prices of the PV plant show that, in absolute terms, Germany had the highest capital ($64b) in 2014, followed by the United States ($54b), China ($44b), Japan ($44b) and Italy ($40b; see Table 3). In per capita terms, the top five countries include Germany ($782), Italy ($674), Greece ($619), Spain ($496), and Belgium ($460). This underlines the fact that European countries tend to invest heavily in solar power plants relative to their population sizes. Observe also that the top countries overlap with those in the backward-looking approach. Moreover, it is interesting to note that the order of the magnitude of the capital stock value is quite similar between the two approaches, although the backward- and forward-looking approaches are sensitive to the levels of the unit cost and the opportunity cost (oil price), respectively. Sensitivity analysis would be required to show this rigorously. The oil price of USD 317 per ton, instead of 716 per ton, for instance, would decrease the forward-looking value of solar power capital in Germany from USD 64b to USD 28b.

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[26] There are admittedly many more non-economic costs and benefits that arise after construction; these have to be omitted for illustrative purposes. Examples include landscape quality, wildlife, air quality, and tourism (Bergmann et al., 2006, 2008). Renewable energy development may also become an opportunity to increase public involvement in local decision-making (Walker and Devine-Wright, 2008).

[27] Recall that oil capital gain or loss within the context of the *Inclusive Wealth Report* is unaffected, as it accounts for the price change accrued over the *past* period. As we have argued, it is the *future* price change accrued on oil capital that is affected by the current REC.

[28] IEA et al. (2015) use three discount rates (3%, 7% and 10%) to report the discounted cash flows of each form of electricity. We instead harmonize the discount rate with the literature on inclusive wealth.

[29] USDOE (2016) estimates the LCOE (levelized cost of energy) for the U.S. projects as USD 44 per MWh in 2014. This is approximately equivalent to USD 193.6 per tonne of oil equivalent, which then makes up for 27% of the current oil price in 2014.

Table 2
Renewable energy capital (REC) of selected countries in 2014, backward-looking approach.
Source: Authors' calculation, based on BP (2017), USDOE (2016), IEA et al. (2015), UN (2017), and *Inclusive Wealth Report 2018*.

Countries	Solar	Wind	REC	RECpc	REC/PC	REC/NC	REC/IW
Argentina	–	381	381	9	0.00	0.00	0.00
Australia	7262	4934	12,196	520	0.00	0.00	0.00
Austria	1440	2407	3847	446	0.00	0.07	0.00
Belgium	5389	2454	7843	699	0.00	1.21	0.00
Bulgaria	1836	795	2631	364	0.02	0.05	0.01
Brazil	–	8254	8254	40	0.00	0.00	0.00
Canada	3507	12,243	15,749	442	0.00	0.00	0.00
Switzerland	1945	–	1945	236	0.00	0.02	0.00
Chile	434	1073	1508	86	0.00	0.00	0.00
China	53,869	126,513	180,382	130	0.01	0.02	0.00
Costa Rica	–	198	198	42	0.00	0.00	0.00
Czech Republic	3376	–	3376	318	0.00	0.06	0.00
Germany	63,930	39,272	103,203	1266	0.01	0.07	0.00
Denmark	1112	3682	4794	846	0.00	0.14	0.00
Egypt	–	641	641	7	0.00	0.01	0.00
Spain	8242	22,880	31,122	669	0.01	0.10	0.00
Finland	18	792	810	148	0.00	0.01	0.00
France	10,103	11,192	21,294	332	0.00	0.08	0.00
United Kingdom	10,422	16,143	26,565	409	0.00	0.16	0.00
Greece	4706	2167	6873	610	0.01	0.03	0.00
Honduras	8	–	8	1	0.00	0.00	0.00
Hungary	149	376	525	54	0.00	0.01	0.00
India	5698	25,621	31,319	24	0.01	0.01	0.00
Ireland	–	2666	2666	569	0.00	0.09	0.00
Israel	1265	–	1265	159	0.00	0.10	0.00
Italy	32,202	9840	42,041	706	0.01	0.13	0.00
Japan	42,903	2918	45,820	358	0.00	0.10	0.00
Morocco	–	1039	1039	30	0.00	0.01	0.00
Mexico	191	3324	3515	28	0.00	0.00	0.00
Malaysia	386	–	386	13	0.00	0.00	0.00
Netherlands	2091	2715	4806	285	0.00	0.06	0.00
Norway	12	1000	1012	197	0.00	0.00	0.00
New Zealand	–	753	753	165	0.00	0.00	0.00
Pakistan	233	372	605	3	0.00	0.00	0.00
Philippines	38	408	446	4	0.00	0.00	0.00
Poland	–	5077	5077	133	0.00	0.01	0.00
Portugal	737	5110	5847	558	0.01	0.10	0.00
Romania	2506	4001	6507	326	0.01	0.04	0.00
Slovakia	918	–	918	169	0.00	0.06	0.00
Sweden	144	6919	7064	729	0.00	0.05	0.00
Thailand	2440	312	2752	40	0.00	0.01	0.00
Tunisia	–	304	304	27	0.00	0.02	0.00
Turkey	110	4783	4893	64	0.00	0.01	0.00
Ukraine	1511	–	1511	34	0.00	0.00	0.00
Uruguay	–	777	777	227	0.01	0.02	0.00
United States of America	33,947	76,642	110,589	348	0.00	0.01	0.00
South Africa	2012	830	2842	52	0.00	0.01	0.00

Note: REC, RECpc, PC, NC, and IW stand for renewable energy capital, renewable energy capital per capita, produced capital, natural capital, and inclusive wealth (in the conventional IWR 2014 approach), respectively. Solar, Wind, and REC are expressed in million USD, while RECpc is in USD.

4.4. *Wind Power*

The cost of installing wind power is more varied than that of installing solar power, particularly because there are onshore and offshore plants.[30] IEA et al. (2015) report overnight costs ranging from USD 1571 per kW in the United States to USD 2999 kW in Japan for onshore wind power and from USD 3703 per kW in the United Kingdom to USD 5933 kW in Germany for offshore wind power. We again take the lower bound of these estimates, USD 1500 per kW, as a detailed disaggregation of the current stock would be very difficult, if not impossible.

As it turns out, the top five countries in the current wind power capital stock, according to the backward-looking approach are China ($127), the United States ($76b), Germany ($39b), India ($25b), and Spain ($23b; see Table 2). In per capita terms, European countries dominate the list: Sweden ($714), Denmark ($650), Ireland ($569), Spain ($492), and Portugal ($488).

For the forward-looking estimates, our results show that wind power capital stock is highest in the United States ($288b), China ($258b), Germany ($85b), Spain ($74b), and the United Kingdom ($52b; see Table 3). In per capita terms, the capital again seems to be concentrated in Europe: Denmark ($3260), Sweden ($1891), Ireland ($1709), Portugal ($1733), and Spain ($1589). These trends are consistent overall with the backward-looking approach, although the order of the magnitude is larger in the forward-looking approach. This may suggest that the costs used in the backward-looking approach are low, as we have adopted a value within the proximity of the lower bound.

4.5. *Discussion: REC in Inclusive Wealth*

It is useful to determine the overall place of REC in inclusive wealth. Table 2 (along with Figs. 1 to 3 in Appendix A) and Table 3 (along with

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[30] Partridge (2018) notes, in particular, that the cost of capital for renewable energy can confound wind generation costs under the recent low-interest policy.

Table 3
Renewable energy capital (REC) of selected countries in 2014, forward-looking approach.
Source: Authors' calculation, based on BP (2017), USDOE (2016), IEA et al. (2015), UN (2017), and *Inclusive Wealth Report 2018*.

Countries	Solar	Wind	REC	RECpc	REC/PC	REC/NC	REC/IW
Argentina	–	1216	1216	28	0.00	0.00	0.00
Australia	9105	15,537	24,643	1050	0.01	0.01	0.00
Austria	1454	5989	7442	862	0.01	0.13	0.00
Belgium	5157	7457	12,614	1124	0.01	1.95	0.00
Bulgaria	2289	2103	4391	608	0.04	0.08	0.01
Brazil	0	20,658	20,658	101	0.01	0.00	0.00
Canada	3459	33,441	36,900	1036	0.01	0.01	0.00
Switzerland	1579	–	1579	192	0.00	0.02	0.00
Chile	938	2455	3393	193	0.01	0.01	0.00
China	44,136	257,775	301,911	217	0.02	0.04	0.01
Costa Rica	–	–	–	–	0.00	0.00	0.00
Czech Republic	3708	–	3708	350	0.01	0.06	0.00
Germany	63,728	84,788	148,516	1823	0.01	0.11	0.00
Denmark	1102	18,466	19,568	3455	0.02	0.57	0.01
Egypt	–	1926	1926	21	0.01	0.02	0.00
Spain	23,068	73,941	97,009	2085	0.02	0.31	0.00
Finland	14	1834	1848	338	0.00	0.01	0.00
France	10,820	26,937	37,757	588	0.00	0.14	0.00
United Kingdom	7582	51,914	59,496	915	0.01	0.36	0.00
Greece	6975	5562	12,537	1113	0.01	0.06	0.00
Honduras	–	–	–	–	0.00	0.00	0.00
Hungary	106	1007	1113	113	0.00	0.02	0.00
India	8138	52,302	60,440	47	0.01	0.02	0.00
Ireland	–	8011	8011	1709	0.01	0.27	0.00
Israel	1562	–	1562	197	0.00	0.12	0.00
Italy	40,160	23,323	63,483	1065	0.01	0.19	0.00
Japan	43,670	7212	50,882	397	0.00	0.11	0.00
Morocco	–	–	–	–	0.00	0.00	0.00
Mexico	410	10,654	11,064	89	0.00	0.01	0.00
Malaysia	426	–	426	14	0.00	0.00	0.00
Netherlands	1462	8515	9977	591	0.00	0.13	0.00
Norway	18	3448	3466	674	0.00	0.01	0.00
New Zealand	–	3336	3336	730	0.01	0.00	0.00
Pakistan	422	780	1202	6	0.00	0.00	0.00
Philippines	30	262	291	3	0.00	0.00	0.00
Poland	13	12,648	12,660	331	0.01	0.03	0.00
Portugal	1188	18,150	19,338	1847	0.02	0.33	0.01
Romania	–	7900	7900	396	0.02	0.04	0.00
Slovakia	1072	–	1072	197	0.00	0.08	0.00
Sweden	88	18,322	18,410	1900	0.01	0.12	0.00
Thailand	2588	516	3105	45	0.00	0.01	0.00
Tunisia	–	–	–	–	0.00	0.00	0.00
Turkey	33	14,103	14,136	184	0.01	0.02	0.00
Ukraine	795	–	795	18	0.00	0.00	0.00
Uruguay	–	–	–	–	0.00	0.00	0.00
United States of America	54,296	287,615	341,911	1076	0.01	0.04	0.00
South Africa	2133	1844	3977	73	0.00	0.01	0.00

Note: REC, RECpc, PC, NC, and IW stand for renewable energy capital, renewable energy capital per capita, produced capital, natural capital, and inclusive wealth (in the conventional IWR2014 approach), respectively. Solar, Wind, and REC are expressed in million USD, while RECpc is in USD.

Figs. 4 to 6 in Appendix A) show our REC estimates in the backward- and forward-looking approaches, respectively. The second and third columns show solar and wind capital, which are summed in the fourth column (all expressed in million USD). This is divided by the current population, which appears in the fifth column as RECpc (in USD). The sixth, seventh, and eighth columns represent the shares of REC out of produced capital, natural capital, and inclusive wealth in 2014.[31]

We observe first that, although the two approaches yield similar orders of the magnitude of REC, the forward-looking shadow prices tend to produce larger results, despite our theoretical equivalence results for the two approaches. This implies either that some of the assumptions for the theoretical equivalence are not met in reality or that our empirical dataset or methodology is biased. The following factors could have caused the divergence. First, considerable resources have been used to facilitate the introduction of REC in the past few decades, which may have distorted the energy market.[32] For example, the green paradox argument conjectures that the availability of renewable backstop may facilitate the current extraction of carbon dioxide (Sinn, 2008; van der Ploeg and Withagen, 2012). If this is the case, then our assumption of the constant oil price may be too high to be applied to future profits of REC. Second, as is reported in IEA et al. (2015), the unit cost of installing REC has been declining with surprising rapidity. The adoption of lower values observed in recent years may have resulted in lower backward-looking shadow prices. Third, related to the second point, if the arbitrage is not in full action, the forward-looking shadow price tends to be larger than the backward-looking counterpart when the average cost of investment is larger than its marginal cost. Fourth,

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[31] Some countries – Costa Rica, Honduras, Morocco, Tunisia, and Uruguay – appear only in the backward-looking approach. This is because these countries have not yet been recorded in the wind power consumption for some reason.

[32] To show this formally requires modelling policy intervention in our theoretical model and focusing on the empirical relationship between the extent of policy and the divergence between prices, as was suggested by Ingmar Schumacher.

our theoretical model argues that a proper depreciation rate that reflects future income growth should ideally be used. However, we have followed convention here to simplify a constant depreciation rate, for want of relevant information. Fifth, future profits made by REC are subject to uncertainty regarding future oil prices, electricity prices, energy policy, and the productivity of other capital assets, among other factors. Forward-looking prices, as well as backward-looking prices through depreciation, are not adjusted until uncertainty is resolved. Sixth, as we have argued regarding Eq. (15), arbitrage in the power plant investment does not hold in reality due to large and often irreversible investment costs.

The share of REC out of produced capital (PC) is quite limited, with a maximum of 4% in Bulgaria (forward-looking approach). This is not surprising, given that power plants are only one of the produced capital stocks. More interesting is the ratio of RE capital to natural capital (NC), which ranges from 0% to 195%. In the forward-looking approach, which tends to report higher estimates than the backward-looking approach, REC accounts for > 10% of natural capital in 14 countries out of our 47-country sample. Turning to the final column, REC seems to play a minimal role in terms of inclusive wealth. In 2014, no country seems to hold REC equivalent to > 1% of national inclusive wealth.

In previous sections, we stressed that REC has the dual characteristic of substituting for both produced and (non-renewable) natural capital. While the substitution of produced capital is on the whole still gradual, natural capital is being substituted either somewhat or to a large extent in some countries. Belgium is a stark example, where REC already exceeds its natural capital, non-renewable and renewable combined. Of course, even if REC is rich in a given country, this does not stand out if the country is amply endowed with natural capital. Nevertheless, countries with high per capita REC (e.g., Germany, Denmark, Sweden, Italy, Belgium) also tend to have a higher share of REC in terms of natural capital.

5. Final Remarks

The shadow prices of capital assets in wealth accounting should reflect their forward-looking income, as they represent their contribution to the well-being of future generations. In practice, however, the backward-looking approach is also used for practical reasons, particularly to avoid uncertainty. We have shown that these two shadow prices should be equivalent under simple assumptions and that current wealth accounting employs both approaches—the backward-looking approach for produced capital and the forward-looking approach for natural capital. Renewable energy capital, then, provides a very interesting case study, as it substitutes for produced and natural capital. We have therefore calculated solar PV and wind power capital for selected countries as of 2014. The results demonstrate that REC replaces or augments natural capital, if not produced capital or inclusive wealth, according to both approaches.

The figures we presented for illustrative purposes are admittedly rough and ready, and our methodology and data can be updated as these energy sources become more mainstream. For example, in the backward-looking approach, to be on the conventional side, we used the most recent cost rather than past-average figures, a decision that might be questionable. The recent dramatic decrease in REC installation costs may provide an additional motivation to adopt forward-looking shadow prices. However, the future income REC provides is uncertain due to technological advances, the energy market, and geopolitical conditions,[33] which stresses the importance of backward-looking shadow prices. Moreover, the figures should ideally be updated using available information on site-specific costs and the income from each technology. As REC accumulates, the results should be extended to cover time, space, and scope: the studied period and countries could be expanded to the year 1990 and could cover 140 countries, in line with other capital stocks in the *Inclusive Wealth Report*, and the analysis could be expanded to other renewable resources, including geothermal and biomass energy.

The absolute value of these capital stocks, in both aggregate and per capita terms, should be interpreted with care. It can be significant when compared to the magnitudes of other capital, produced or natural capital in particular. After all, as we have argued, they have already been calculated as part of produced capital assets. Thus, simply adding REC to inclusive wealth as is currently reported would result in a double count. However, given that our conservative estimates of the forward-looking accounting of REC surpass those based on the backward-looking method, upon which produced capital accounting is based, the current estimates of the portion of REC in inclusive wealth may have been underestimated.

That said, it is of utmost importance to get back to the basics of sustainability assessment via the capital approach: it is the change of capital stocks or inclusive wealth over a certain period of time that matters, not the total stock. Thus, it is even more crucial to monitor how REC substitutes for produced and natural capital and, in particular, how it makes up for the degradation of conventional power plants and fossil fuels.[34] It would be interesting to see how REC augments natural capital in countries not endowed with non-renewable resources.

We trust that the implications on the policy front are enormous as well. The economic valuation of renewable energy projects has been based on conventional cost–benefit analysis (Snyder and Kaiser, 2009) or stated preferences (e.g., Álvarez-Farizo and Hanley, 2002; Bergmann et al., 2006, 2008; Koundouri et al., 2009). To perform a cost–benefit analysis comprehensively, it is helpful to use the project's effect on inclusive wealth, as demonstrated by Dasgupta (2009) and UNU-IHDP and UNEP (2014). In line with the case study by Collins et al. (2017), a cost–benefit analysis of a resource-rich country's prospective investment in REC that substitutes for nonrenewable natural capital, evaluated both retrospectively and prospectively as was laid out here, for example, can be policy-relevant.

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Appendix A. Supplementary data

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[33] Changes in the market include rising demand in emerging markets, an increased supply of natural gas, geopolitics in the Middle East, and the increasing output of unconventional fossil fuel use, such as shale oil and gas and oil sands.

[34] Van den Bergh et al. (2015) and Moriarty and Honnery (2016) provide a somewhat pessimistic argument on the substitution of fossil fuel by RE. Introducing RE yields other tradeoffs that, together, impact local sustainability (Schwanitz et al., 2017).

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