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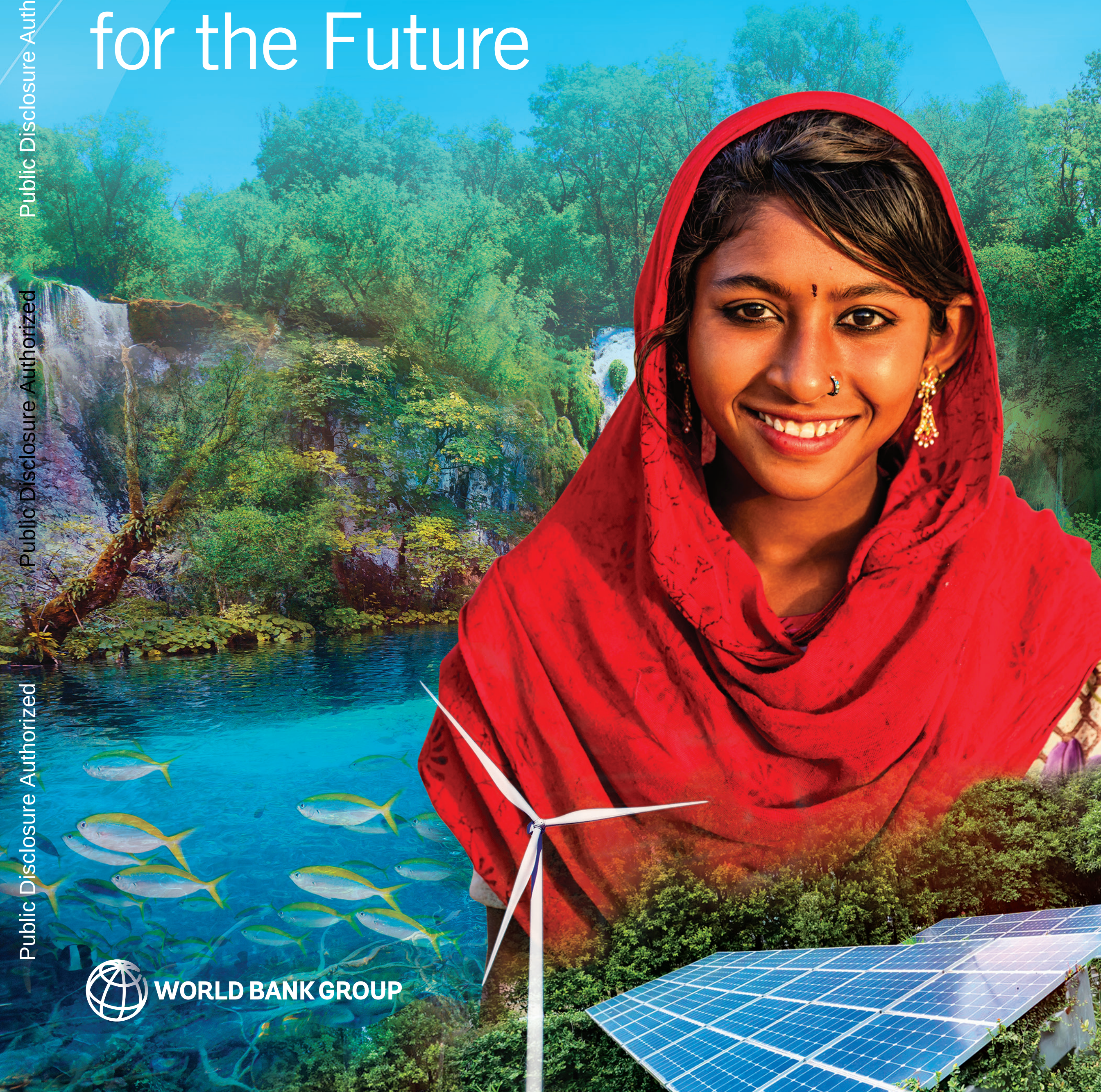
VALUATION OF RENEWABLE ENERGY RESOURCES IN THE CONTEXT OF THE CHANGING WEALTH OF NATIONS

The Changing Wealth of Nations 2021

Managing Assets for the Future



WORLD BANK GROUP

THE CHANGING WEALTH OF NATIONS 2021

Managing Assets for the Future

TECHNICAL REPORT

VALUATION OF RENEWABLE ENERGY RESOURCES IN THE CONTEXT OF THE CHANGING WEALTH OF NATIONS

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Valuation of Renewable Energy Resources in the Context of the *Changing Wealth of Nations*

Experimental Results

Final report

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Abstract

To date, the natural capital accounts compiled in the *Changing Wealth of Nations* (CWON) reports have not included renewable energy assets. This is in part because few empirical studies of renewable energy asset values have published (Rothman, 2000) and also because the studies that have been undertaken have been hampered by data and methodological shortcomings. Furthermore, the measurement of renewable energy resources as assets has not been systematically addressed in either the *System of National Accounts 2008* (SNA; European Commission *et al.*, 2009) or in the accompanying *System of Environmental-Economic Accounting 2012 – Central Framework* (SEEA-CF; United Nations *et al.*, 2014).

In this report, we address this concern by proposing and then implementing an approach to the valuation of renewable energy assets. We begin by reviewing and discussing the conceptual treatment of renewable energy assets in the SNA and the SEEA-CF. Following this, we propose a treatment that is grounded in theory but differs from that in the SNA and SEEA-CF, which we find unsuitable for a number of reasons. We then propose a practical approach to valuation of renewable energy assets and test the methodology using data for a variety of important renewable energy-producing countries. Based on the results, we discuss how the experimental asset values presented here might be improved and expanded so that renewable energy assets might eventually be incorporated in the natural capital accounts of the CWON.

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List of Acronyms

CSP – Concentrated solar power
CWON – Changing Wealth of Nations
FIT – Feed-in-tariff
GDP – Gross domestic product
GW – gigawatt
IEA – International Energy Agency
IMF – International Monetary Fund
IPCC – Intergovernmental Panel on Climate Change
IRENA – International Renewable Energy Agency
MW – megawatt
NPV – Net present value
O&M – Operations and maintenance
OECD – Organisation for Economic Co-operation and Development
PMR – Product Market Regulation
PV – Photovoltaic
RVM – Residual value method
SEEA-CF – System of Environmental-Economic Accounting – Central Framework
SNA – System of National Accounts
UN – United Nations
UK ONS – United Kingdom Office of National Statistics
USEIA – United States Energy Information Agency

1 Introduction[1]

1.1 Background and objectives

To date, the natural capital accounts compiled in the *Changing Wealth of Nations* (CWON) reports have not included renewable energy assets. This is in part because few empirical studies of renewable energy asset values have published (Rothman, 2000) and also because the studies that have been undertaken have been hampered by data and methodological shortcomings. Furthermore, the measurement of renewable energy resources as assets has not been systematically addressed in either the *System of National Accounts 2008* (SNA; European Commission *et al.*, 2009) or in the accompanying *System of Environmental-Economic Accounting 2012 – Central Framework* (SEEA-CF; United Nations *et al.*, 2014).

The lack of attention paid to the valuation of renewable energy assets is a concern. These assets – especially hydroelectric assets – are likely worth trillions of dollars worldwide today based on the estimates we present in this report. We estimate Canada's hydroelectric resources alone to have been worth something on the order of $US456 billion (2018 dollars)[2] in 2017. This would have made them more valuable than any other natural resource asset in Canada in that year (other than land), including the country's large fossil fuel reserves. To the extent that our estimates are accurate, then, the failure to account for renewable energy assets as part of national wealth sends flawed signals to policy makers in many countries about both total national wealth and the contribution of natural capital to that wealth.

In this report, we address this concern by proposing and then implementing an approach to the valuation of renewable energy assets. We begin by reviewing and discussing the conceptual treatment of renewable energy assets in the SNA and the SEEA-CF. Following this, we propose a treatment that is grounded in theory but differs from that in the SNA and SEEA-CF, which we find unsuitable for a number of reasons. We then propose a practical approach to valuation of renewable energy assets and test the methodology using data for a variety of important renewable energy-producing countries. Based on the results, we discuss how the experimental asset values presented here might be improved and expanded so that renewable energy assets might eventually be incorporated in the natural capital accounts of the CWON.

Our focus is on geothermal, hydroelectric, solar and wind resources and their use to generate electricity. We realize this ignores other important benefits of these resources; for example, the use of geothermal and solar resources as direct sources of heat. We realize as well that other renewable energy assets are of economic importance, most notably biological resources (fuelwood and other biomass) but also ocean energy (waves and tides). Our restricted focus is partly pragmatic – to keep the scope of analysis reasonable – but also reflects the heightened policy and economic interest in renewable electricity generation. Renewable energy assets offer the possibility of low-carbon electricity[3] to power homes, factories, communications and,

[1] The author wishes to thank Andrei Ilas for his assistance with the development of the database used in the valuation of renewable energy assets in this report. Thanks are due as well to Karen Wilson, former Assistant Chief Statistician for National Accounts and Analytical Studies with Statistics Canada, for assistance with several of the concepts underlying the report and to Grzegorz Peszko, Glenn-Marie Lange, Esther Naikal and Shun Chonabayashi of the World Bank for the opportunity to undertake the study and for their helpful direction and comments during its completion. Any errors or omissions remain entirely ours.

[2] Unless otherwise specified, all values in this report are expressed in United States dollars measured in constant 2018 prices.

[3] We say "low-carbon" rather than "zero-carbon" because, even if carbon-free at the point of production, there are emissions associated with renewable energy assets. Production of solar panels, wind turbines and hydroelectric

increasingly, transportation networks and are, therefore, the subject of much attention from governments, businesses and civil society. Greater insight into the economic value of these assets is, therefore, likely to be considerable relevance in many countries.

We consider our estimates experimental and they should be taken in that spirit. They represent the most extensive effort to value renewable energy assets we are aware of and the only one to do so for a variety of assets and countries using a consistent methodology. They have been compiled in the interest of testing methodologies and evaluating data sources for eventual development of more refined and comprehensive estimates that could be incorporated in the CWON natural capital accounts. Though based on well-established methods and the most reliable national and international data we could obtain, the estimates are meant to be illustrative rather than definitive. We discuss possibilities for their improvement at the end of the report.

The remainder of the report proceeds as follows. In Section 2 we discuss the treatment of renewable energy resources as assets, starting from what is proposed in the SNA and SEEA-CF and ending with our own proposal. Section 3 is devoted to a discussion of the concept of resource rent – central to the valuation of natural resources – and how it applies in the case of renewable energy asset valuation. In Section 4, we present the results of our application of the valuation method we outline in Section 3 to hydroelectric, solar and wind resources in selected countries.[4] Section 5 concludes with a discussion of our findings and recommendations for future research.

dams all require materials that are today, and will be for some time into the future, produced using fossil fuels as inputs in supply chains. Additionally, flooding of land for hydroelectric reservoirs results in signification GHG emissions (Deemer *et al.*, 2016).

[4] We do not apply the valuation methodology to geothermal electricity resources since relatively few countries have developed these to any significant extent, despite their enormous potential.

2 Renewable energy resources as assets

Any discussion of renewable energy resource as assets must start with a clear understanding of their physical nature. To this end, we offer brief descriptions of geothermal, hydroelectric, solar and wind resources in physical terms below. We then turn to their treatment as economic assets. This requires discussion of the way assets are defined in general terms in SNA and the SEEA-CF. We follow this with more detailed discussions of the SNA and SEEA-CF treatments of natural resources broadly and of renewable energy assets specifically. The SEEA-CF treatment of renewable energy assets, in particular, is reviewed thoroughly and found to have a limited range of application. The section ends with our own recommendations for the treatment of renewable energy resources as assets in the context of the CWON.

2.1 Renewable energy assets in physical terms

2.1.1 Geothermal energy

Geothermal energy is derived from heat stored in rock, steam and water found deep in the earth. Enormous quantities of heat are found in the earth's core (mantle) due to trapping of the heat created at the time of the planet's formation (primordial heat) and through on-going decay of radioactive elements in the mantle. This heat radiates outward from the mantle to the crust, where it is accessible for human use. Geothermal energy extracted from the crust can be used directly for space and water heating in buildings or for electrical generation in cases where temperatures are high enough to create the steam required to run turbines (Natural Resources Canada, 2012).

2.1.2 Hydroelectric energy

Hydroelectric energy is driven by the flow of water from high elevations on continents back to the ocean. Mountainous areas have the greatest potential hydroelectric resources. Hydroelectric power plants vary in size, based on the characteristics of the site. Reservoirs and dams are often designed for multiple uses, including flood control, water supply, waterway navigation and recreation and agricultural irrigation.

Hydroelectric power plants can be classified by type:

- **Run-of-river** - Power generation is driven primarily by the normal flow of the river, although there may be some capacity for short-term storage. Generation is dependent on precipitation and runoff and may vary substantially day-to-day and between seasons. Run-of-river plants may be located downstream from reservoir-type plants.
- **Storage hydropower** - Hydropower projects with dams create reservoirs to store water for later use. The type of reservoir depends on the characteristics of the site. Often reservoirs are created by flooding river valleys. High altitude lakes in mountainous areas are another common type and often maintain the characteristics of the original lake.
- **In-stream** - In-stream production, an emerging technology, functions similarly to run-of-river by making use of existing water control infrastructure through the installation of small turbines (IPCC, 2011).

2.1.3 Solar energy

The electromagnetic radiation emitted by the sun, or solar irradiance, can be harvested for use directly as heat or for conversion into electricity. Solar irradiance varies over the surface of the earth, with the highest levels at the equator. The quantity of solar energy reaching any given point on the earth's surface is impacted by atmospheric characteristics; including cloud cover, aerosols, water vapor and other trace gases in the atmosphere (IPCC, 2011).

Passive solar energy technologies have been used for millennia to capture the sun's energy without use of mechanical or electrical equipment. Examples include orientating windows toward the sun to warm buildings, drying of fish and evaporating seawater to collect salt. Active solar technologies convert solar energy to heat or electricity through the use of mechanical or electrical equipment and have only been in use since the late 1800s (Kabir *et al*., 2018). Examples include pumped solar water heating systems for swimming pools or domestic hot water, the aforementioned photovoltaic cells for electricity production and concentrated solar power systems that use lenses or mirrors to focus solar energy and heat a fluid to power a steam turbine (Malinowski, Leon and Abu-Rub, 2017).

2.1.4 Wind energy

Wind energy is driven in the first instance by the sun and by the earth's rotation. Some solar radiation is converted into kinetic energy in the form of moving air molecules (wind) due to differences in solar radiation received at high and low latitudes. The earth's rotation also contributes to the movement of air through the Coriolis effect. Winds are impacted by geographic features and are unevenly distributed over the planet.

Wind energy has long been converted to mechanical power through the use of windmills. These have served to pump water, grind grain and power saw mills. Wind energy continues to be important for pumping water in remote areas.

Commercial conversion of wind energy to electricity began in the 1970s. The majority of wind turbines have been sited on land, but off-shore wind is growing in importance. Wind turbines convert the kinetic energy of the wind into mechanical energy and then to electrical energy. Taller turbines are typically able to produce more energy, as wind speed increases with height above the ground (IPCC, 2011).

2.2 Renewable energy asses in economic terms

2.2.1 Assets in general terms in the SNA and SEEA-CF

According to the SNA, an asset is an entity over which ownership rights are enforced "by some unit, or units, and from which economic benefits are derived by their owner(s) by holding or using them over a period of time." (SNA ¶1.46). Key to this definition is the notion of an *economic* benefit, which is defined in the SNA as a benefit, measurable in monetary terms, from the use of an entity in the context of a market activity (production, consumption or accumulation) or from holding the entity as a store of monetary value (SNA ¶3.19). In order for something to be considered an asset, then, any benefits it provides must flow in the context of productive activity. This excludes entities that provide benefits outside the scope of human productive actives from consideration as assets. Conveniently, this means that economic assets are "revealed" by these activities (often market activities); anything outside them may be excluded.

Also key to the SNA asset definition is the notion of ownership. Since the SNA focuses on benefits arising from market activity and market activity is defined as interactions between economic units, an identifiable economic unit must be the beneficiary of every activity. In the SNA, that beneficiary is always taken to be the owner of the entities involved in the activity. Thus, entities over which ownership rights are not (or cannot) be enforced cannot be defined as assets in the SNA, since no beneficiary can be identified. Examples of entities over which ownership rights are considered unenforceable in the SNA include the high seas and the atmosphere.

The SNA is explicit in noting that ownership need not be private for an entity to qualify as an asset (SNA ¶1.46). Collective ownership by all members of a country is acceptable, allowing the SNA to define natural resources – like oil reserves – owned by governments on behalf of all citizens as assets. Collective ownership does not extend beyond the national level, however, since the focus of the SNA is on accounting for the economies of nation states; this explains the SNA's rejection of the high seas as an economic asset.

The SEEA-CF follows the SNA almost completely in its basic asset definition, with one important difference. Unlike the SNA, which focuses only on assets that provide economic benefits, the SEEA-CF extends its asset boundary to include "all resources that may provide benefits to humanity", opening the door to inclusion of resources that provide both economic and non-economic benefits (SEEA-CF ¶5.14). However, resources of the latter type are measured only in physical terms in the SEEA-CF and are not referred to as "economic" assets. Like the SNA, only assets that provide economic benefits are measured in monetary terms and labelled "economic". Thus, in physical terms, all land within a country lies within the asset boundary of the SEEA-CF, while, in monetary terms, some land may have zero economic value and be excluded from consideration as an economic asset.[5]

2.2.2 Natural resources as assets in the SNA and SEEA-CF

In keeping with its general definition of assets, the SNA recognizes as assets only natural resources over which ownership rights can be – and are – enforced. As noted, ownership of the resources need not be private; resources owned collectively (for example, by a national government) may also qualify as assets. This permits the SNA to recognize as assets a wide range of resources that are generally collectively, rather than privately, owned. In further keeping with the general definition of assets, the SNA only recognizes as assets those resources that generate economic benefits for their owners under 1) existing conditions of technology, knowledge, economic infrastructure and prices, or 2) conditions that can be reasonably expected to prevail in the immediate future (again, as revealed by market activity). Thus, resources known to exist but, for whatever reason, not suitable for economic exploitation do not qualify as assets in the SNA; for example, timber that is too far from wood processing facilities to be profitable for exploitation. Resources that provide non-economic benefits also do not qualify as assets in the SNA. Thus, remote forests that do not qualify as assets for timber purposes also do not qualify as assets for any ecological benefits they might provide – carbon sequestration, for example – since those benefits arise outside of the market and are not economic in nature.

The specific natural resources recognized as assets in the SNA are: land (including soil and associated surface water); mineral and energy resources found on and under the earth's surface (including underwater); biological resources (trees, plants and animals) that grow under natural conditions (as opposed to those, like farm animals or plantation forests, that grow under managed conditions); surface and groundwater, so long as it is regularly used for extraction; and the electromagnetic (radio) spectrum used for telecommunications purposes.

As with its basic definition of assets, the SEEA-CF largely mirrors the SNA in its recognition of natural resources as assets, though it treats some resources – especially land – differently. The

[5] An example is remote public land, such as wilderness forest, that provides no economic benefits. Such land is generally not included on national balance sheets. Australia is an exception, however; a measure of the value of "other land" (government-owned land that is not used for residential, commercial or other economic purposes) is included on Australia's national balance sheet (Cadogan-Cowper and Comisari, 2009).

SEEA-CF places land in a separate category from other natural resource assets, seeing it as an asset only from the perspective of its use for the provision of space. “Soil resources” are a separate asset unto themselves in the SEEA-CF. In contrast, the SNA considers “land” to comprise both the space it provides as well as the soil underlying it. The other assets in the SEEA-CF natural resource category are, as in the SNA: mineral and energy resources, biological resources and water resources. Interestingly, however, the SEEA-CF does not recognize the radio spectrum, arguing that it is “not part of the biophysical environment” (SEEA-CF ¶5.36, footnote 48).

2.2.3 Renewable energy resources as assets in the SNA and SEEA-CF

The SNA says little regarding renewable energy resources as assets. It simply states, as noted above, that entities “over which no property rights can be exercised” do not qualify as assets, using the high seas and atmosphere as examples. This suggests that both solar and wind resources would not be recognized as assets within the SNA, since they are closely linked to the atmosphere. What the SNA actually intends with respect to solar and wind resources is unclear, as neither is mentioned anywhere in the text. It is worth recalling, however, that the SNA does recognize the radio spectrum used by telecommunications companies as a natural resource asset (SNA ¶10.185). The reasons for this are not fully spelled out in the text but appear related to 1) the unprecedented demand created for access to the spectrum by 3G cellular telephone technology in the early 2000s and 2) the fact that use of the spectrum is rival (users can disrupt and degrade one another’s uses) but not physically excludable (no user can physically prevent another’s use). Governments greatly expanded regulation of access to the spectrum through auctioning of cellular communications licenses beginning in the late 1990s. This generated billions of dollars in public revenues (Jilani, 2015). When this happened, the authors of the SNA seemingly agreed to include the radio spectrum within its asset boundary.[6] It is noteworthy that they argued “land, mineral deposits and the spectrum are similar types of assets” and consequently classified the spectrum as a natural resource asset (SNA ¶17.317). This is an important example of an entity previously considered to have no economic value and deemed impossible to “own” coming to meet both SNA tests of asset status through governments’ decisions to assert public ownership rights. The parallels with solar and wind energy resources are clear.

As with solar and wind resources, the SNA is silent on geothermal and hydroelectric resources. It does, however, acknowledge that water “regularly” used for extraction can be considered a natural resource asset. Assuming that the temporary diversion of water through electric power turbines constitutes regular extraction, it is plausible that water in a hydroelectric power reservoir could be considered an asset in the SNA. Similarly, extraction of hot water from an underground geothermal reservoir may be sufficient for the SNA to recognize those reservoirs as assets (though it is unlikely that extraction of heat from dry, hot bedrock would qualify). Again, the SNA’s intentions are unclear, as neither resource is mentioned explicitly.

In contrast to the SNA, the SEEA-CF is explicit and quite detailed in its discussion of renewable energy resources as assets. The SEEA-CF recognizes that energy from renewable sources is already important in many countries and increasingly seen as an alternative to fossil fuels and nuclear power. Renewable energy assets recognized in the SEEA-CF include, in addition to the four considered here, wave/tidal power and undefined “other” sources. The SEEA-CF argues that these resources

[6] The SNA was undergoing a major revision around the same time as the spectrum issue came to the fore.

> "cannot be exhausted in a manner akin to fossil energy resources and, unlike biological resources, they are not regenerated. Thus, in an accounting sense, there is no physical stock of renewable sources of energy that can be used up or sold" (SEEA-CF ¶5.226).[7]

The SEEA-CF therefore limits physical measurement of these resources to flows of energy produced from them; no measurement of the stock of the resources in physical terms is proposed. Further, physical measurement of renewable energy production is limited to the amounts actually produced given currently installed generation capacity. No account is taken of the potential amounts of energy that could be produced from renewable sources if investment and technology were to change in the future, consistent with the SEEA-CF's exclusion of sub-soil energy resources that are not currently under active development from consideration.

Though the SEEA-CF argues that the concept of a physical stock does not apply to renewable energy resources, it does acknowledge that the resources have value unto themselves, recognizing that a stock does not have to be measurable in physical terms in order to have a monetary value. The SEEA-CF argues that this value should be captured in the value of the land associated with renewable energy facilities: "Opportunities to earn resource rent based on sources like wind, solar and geothermal should be expected to be reflected in the price of land" (SEEA-CF ¶5.228). Thus, the asset value of wind power should, according to the SEEA-CF, be captured in the value of land where windmills are sited or where they might be one day. Similarly, the value of solar and geothermal resource assets should be reflected in the value of the associated land, even though it is not clear in the case of geothermal resources (particularly deep-earth geothermal) what would constitute the associated land. In the case of hydro resources, the SEEA-CF argues it is more relevant to consider the value in relation to the water used to generate the energy than to an area of land. Thus, in the case of hydropower, it is the value of the water resource that will capture the value of the hydro asset according to the SEEA-CF.

2.2.4 Exploring the assumptions underlying the SEEA-CF's treatment of renewable energy resources

While the SEEA-CF's argument that changes in land value will arise "due to the scarcity of the sites used for energy generation" (SEEA-CF ¶5.310), has *prima facie* appeal, it does not appear plausible in many instances. The conditions in which the value of such assets could be expected to be reflected in the observed land values are limited to land-based production of solar and wind energy only and then only on land that is 1) privately owned; 2) has a positive economic value for something other than solar/wind energy production; and 3) is located in a country where renewable energy markets could be said to be in something like long-run equilibrium. It is questionable whether these conditions hold to any significant extent anywhere in the world. In many countries, solar and wind energy markets are nascent and do not yet approach the long-run equilibria in which private land values could be reasonably expected to accurately reflect the potential for renewable energy production. Even in countries with long histories of solar/wind energy production, it is not clear that the SEEA-CF approach is always appropriate; for example, it would not apply to the 32% (and growing) of Denmark's wind energy capacity that was installed off-shore in 2016 nor would it apply to the massive, utility-scale solar farms rapidly developing in remote regions of China and elsewhere. It cannot apply to these, since neither off-shore water bodies nor remote land have any observed economic value in the absence of renewable energy production. There is no possibility, therefore, that the value of off-

[7] This point is somewhat puzzling, as solar, wind, hydroelectric and geothermal resources would all seem to be regenerated. The first three will regenerate so long as the sun shines. The fourth will regenerate so long as the earth's core remains molten. In both cases, the processes of regeneration are expected to last for billions of years.

shore wind resources or remote solar farms could be captured by measuring the (non-existent) market value of the water and land on which they are sited.

With respect to the most important contemporary renewable energy asset, hydroelectric power, the SEEA-CF's argument does not seem appropriate at all. Hydroelectric dams and generating stations are almost exclusively built on publicly owned waterways that have no economic value other than for hydroelectric production. As with off-shore wind and remote solar farms, there is no possibility that the value of hydroelectric resources could be captured by measuring the (non-existent) market value of the waterways on which they are sited.

Finally, there is similarly no reason why the value of geothermal resources should be reflected in the value of the land that lies above them. Geothermal resources are publicly owned in most countries, with property rights separate from the land found above them. It is not obvious, given this, why the value of the land above the resources should be influenced by their presence. Even in the United States, where sub-soil asset property rights do vest by default with the owner of the land's surface, many land parcels have had their associated sub-soil resource rights severed and, therefore, land values would not change even if geothermal resources were discovered.

Given the above, it would seem that application of the SEEA-CF's approach to the valuation of renewable energy assets risks missing much of the value of these increasingly important resources. For example, none of the 56% of Canada's total electricity generating capacity accounted for by hydroelectric resources in 2016[8] would be captured in any existing land (or water) value on Canada's national balance sheet. **The approach we recommend for treatment of renewable energy resources as assets in the CWON is, then, to adopt the approach the SEEA-CF applies to other natural resource assets.** That is, the asset value of renewable energy resources should be explicitly calculated as the net present value of the future stream of rent attributable to the resources and these values should be assigned to explicit renewable energy assets in national balance sheets. This would require addition of a new category of natural resource assets to both the SNA and SEEA-CF asset classifications (Table 1), paying attention to possible confusion with existing terminology since both existing classifications include "mineral and energy" assets; these may require re-naming to "mineral and non-renewable energy" assets.

Table 1 - Suggested additions to SNA and SEEA-CF natural resource asset classifications

SNA	SEEA-CF
Land	*Mineral and energy resources*
Mineral and energy reserves	*Land*
Renewable energy resources	*Soil resources*
Non-cultivated biological resources	*Renewable energy resources*
Water resources	*Timber resources*
Other natural resources - *Radio spectra* - *Other*	*Aquatic resources*
	Other biological resources
	Water resources

Note: Suggested additions shown in green.

[8] Statistics Canada, Table 25-10-0022-01, *Installed plants, annual generating capacity by type of electricity generation.* Available from https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510002201.

The approach recommended here has two advantages. Firstly, it ensures consistency in the accounting for all natural resource assets in the SNA and SEEA-CF. Secondly, it ensures the full value of all renewable energy assets will be captured in national economic and environmental accounts.

A potential disadvantage of the approach is that it could lead to double counting of some renewable energy assets. We acknowledge that there are instances where the price of land assets already measured in the national account will be influenced by the possibility (or reality) of using the land for renewable energy production. Adding explicit values for renewable energy assets on top of these existing values could lead to double counting; for example, measuring both the increase in value of a farmer’s land from installation of a wind turbine and the asset value of the associated wind energy production. There are two reasons why the size of this double counting might be small however.

Firstly, as argued above, the share of the total value of renewable energy assets that would be captured if the SEEA-CF approach were implemented is likely small. It would, for example, entirely miss the value of hydroelectric resources – the most important renewable energy asset globally. On top of this, geothermal and much of solar and wind energy resources would not be captured.

Secondly, and more importantly, double counting could be all but eliminated in practice by national accountants in their land valuation methods. Since transactions in bare land are relatively rare (the majority of land transactions include both land and related produced assets, such as buildings, orchards, roads and industrial equipment), there is little empirical evidence for national accountants to use in directly valuing land itself. As a result, their methods are frequently based on estimating land values indirectly using either land/structure value ratios or as a residual (Eurostat and OECD, 2015). In both approaches, care is taken to exclude the value of all assets associated with the land in arriving at the value of land itself. In the case of land used for renewable energy production, the value of the wind turbines, solar panel arrays and other renewable energy equipment would be deducted in arriving at the land residual. In addition, national accountants would also deduct an estimate of the value of the associated renewable energy assets. Thus, if wind turbines were known to be operating on private farmland in country X, national accountants would (to avoid double counting) estimate the asset value of the wind energy resource and deduct this from the value in arriving at the value of the farmland.

This ends our discussion of the nature of renewable energy resources and their treatment as assets in the national accounts. In the following section, we turn to the question of what method to use in placing values on the resources.

3 Valuing renewable energy assets in concept

The approach to the valuation of natural resource adopted in the SEEA-CF rests on the concept of resource rent, or the value that can be attributed to natural resources (as opposed to some other factor of production) in a production process. The nature of rent has always been of central interest to economists. Perhaps because of its fundamental role in economic theory, particularly its relation to theories of value, no consensus view has developed (Fine, 1982). All rent concepts share a focus on the payments accruing to a factor of production over and above what is required to maintain that factor in the productive process (Text Box 1). Within the SNA, rent is defined (SNA ¶7.109 and ¶7.154) as "the income receivable by the owner of a natural resources (the lessor or landlord) for the putting the natural resources at the disposal of another institutional unit (a lessee or tenant) for use of the natural resource in production."

Text Box 1 - Rent concepts

Ricardian/differential rents - Rents that accrue to the more productive factors of production in homogenous input markets. In equilibrium, the price at which the least-productive firm is willing to produce clears the market; all firms with marginal costs below this price earn Ricardian (also called "differential") rents (Hartwick and Olewiler, 1991). Classical economists (for example, von Thünen) recognized that location of a resource could be the source of Ricardian rents.

Scarcity/absolute rents – Rents that arise when demand exceeds supply in the long run. Since supply cannot be increased either for natural (produced physical stock) or arbitrary (regulated entry barriers) reasons, "limits on the supply of a resources allow producers to charge prices greater than their marginal cost" (Rothman, 2000, p. 4).

Marshallian short-run/quasi rents – Rents that arise in the short-run; that is, in the absence of a stable long-run equilibrium. Quasi-rents arise when demand exceeds supply at a fixed point in time and are dissipated as the prospect of rent capture encourages more entrants to the market.

Source: Sinner and Scherzer, 2007

The evolving nature of renewable energy resource markets is essential to any analysis of the rent accruing to the resources. Not all renewable energy markets can be considered to be in long-run competitive equilibrium, especially not those in the rapidly emerging areas of solar and wind energy. This has implications for the nature and level of rents and their distribution among factors of production. An additional challenge is that the inexhaustible nature of renewable energy resources poses challenges to theories of value and thus to theories of rent. This is most obvious for wind and solar resources, which are globally available (through variable in quality). At foreseeable demand levels, there is no natural scarcity of these resources. Scarcity can arise locally, of course, as a given site can only be used for production by one economic unit at a time. Scarcity may also be arbitrarily imposed; for example, *via* legislation granting excludable rights to generate and sell energy from these sources.

Hydropower is a well-established technology and factor markets can reasonably be assumed to be in something close to long-run competitive equilibrium in countries where electricity markets have been deregulated. Marked heterogeneity and scarcity amongst sites for hydro power implies that hydro projects should earn both Ricardian and scarcity rents. In countries where electricity prices remain regulated and where hydroelectric power utilities remain publicly owned, the assumption of factor market equilibrium likely does not hold. Ricardian and scarcity rents may still arise, though they will be captured by electricity consumers rather than by the owner of the resource (government) and their measurement is made more difficult.

Rights to subsoil resources, including geothermal resources, are generally recognized (and assumed by governments) and markets often exist in which such rights are traded (for example, resource development auctions) and priced. Sites for geothermal power generation are both heterogeneously distributed and scarce.[9] The technology for geothermal power production is relatively well established. Under these circumstances, both Ricardian and scarcity rents should accrue to geothermal resources.

Wind and solar energy are rapidly emerging technologies. Though the sun and the wind are not scarce in any meaningful sense, different locations have a greater or lesser access to them due to latitude or physical features of the surface. In long-run equilibrium, more productive (sunnier, windier or closer-to-market) sites should therefore earn Ricardian rents only. Because solar and wind energy markets are not in equilibrium today, they should not be generating Ricardian or scarcity rents. However, they may yield short-run Marshallian/quasi-rents in certain instances.

Where rent does arise from the use of renewable energy assets for the generation of electricity, it can be valued, in principle, using the same approach recommended in the SEEA-CF for the valuation of other natural resource assets (SEEA-CF ¶5.94-¶5.125). In this approach – called the residual value method – rent is estimated as the difference between the annual revenues earned from sale of the renewable electricity and the annual cost of its production, including normal returns to both workers (wages) and entrepreneurs (return on produced capital) as well as an estimate of the consumption of produced capital. Any specific subsidies received by renewable electricity producers must be deducted from the value of sales and any specific taxes must be added.

For the residual value method (RVM) to have theoretical validity, electricity markets must be competitive and in something close to long-run equilibrium. If factors are present in markets that distort either the revenues earned from the sale of renewable electricity or the costs of its production, or both, then rent so calculated cannot be relied upon to reflect the true marginal value of the resource. For much of the world, until relatively recently, such distortions were commonplace in electricity markets. Historically, these markets were dominated by large, publicly owned utilities that operated in highly regulated markets. Until at least the 1980s, electricity prices were kept artificially low by governments through a combination of direct subsidies to consumers and monopoly power for producers. Public utilities were permitted to borrow at preferential rates, were not held to account by shareholders for normal levels of profit and could assume that governments them would bail them out of financial difficulties. As a result, both the revenues earned from the sale of electricity and the costs of its production were distorted from their long-run competitive equilibrium values.

Electricity market reform has been going on around the world to varying degrees since the 1980s. Its focus has been separation of transmission and generation, breaking up monopolies, privatization and reduction of subsidies and tariffs (Hyland, 2015; Jamasb *et al*., 2015). By one measure, the OECD's product market regulation (PMR) indicators,[10] electricity markets are more broadly competitive than natural gas markets today in OECD countries. As for developing countries, a World Bank review (Jamasb, *et al*. 2015) found that many have undertaken electricity market reform but that progress varies between countries and most remain in transition. These results suggest that the results of electricity market reform have been at least partly successful in most countries and considerably so in developed countries. Given this, it is reasonable to suggest that application of the RVM to estimation of renewable electricity rents

[9] An exception to this is so-called “enhanced geothermal systems”, in which extremely deep (> 5000 m) wells are drilled to access the hot rock that exists essentially uniformly across the planet at that depth. Development of these resources, which obviously have considerable potential, is just beginning.

[10] See http://www.oecd.org/economy/reform/indicators-of-product-market-regulation/.

would be appropriate today for countries well advanced in electricity market deregulation. Its application to hydroelectric resources would seem particularly appropriate, since those markets have long histories. Its application to the valuation of geothermal, solar and wind energy resources may be less justified, since these markets are generally less well developed. Heavy subsidization of solar and wind energy, especially, is more the norm than the exception, even in developed countries. The Netherlands, a country with a long history of wind energy production, for example, has only recently seen development of its (and the world's) first subsidy free wind-energy project (Radowitz, 2019). At the end of 2017, 113 countries had feed-in-tariff (FIT) subsidy programs to support renewable energy generation. However, there has been a shift toward more competitive support policies, with 29 countries holding capacity auctions in 2017 (REN21, 2018).

The nature of government support for solar and wind energy is also different than it was in the past. For one, solar and wind energy producers in many countries operate in the context of broadly deregulated and competitive electricity markets, where consumers face prices that reflect marginal costs of production. Even publicly owned utilities are generally expected to operate with profit maximization in mind in many countries today. Producers, moreover, are more likely to be private companies than large public utilities lacking profit motives. Today's solar and wind energy producers do not benefit greatly from preferential borrowing rates[11], must keep an eye on long-run shareholder returns and cannot accumulate unsustainable levels of debt, as public utilities once did. Thus, the distortions of both revenues *and* costs that would have made use of the RVM inappropriate in the past are of less concern today.

We argue that the RVM, while not without concerns from theoretical and practical points of view due to distortions in renewable energy markets, is the best choice available for valuation of renewable energy asset rents in the CWON.[12] In the next section, we apply the RVM to the valuation of hydroelectric, solar and wind resource assets in selected countries.

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[11] Though concessionary financing is available to renewable producers, its use accounted for a "near-negligible" share of total renewable energy finance in the period 2013-2016 (IRENA and CPI, 2018).

[12] Other approaches are also possible. One that has been applied to the valuation of hydroelectric resources in Canada (Bernard *et al.*, 1982; Zuker and Jenkins, 1984; Gillen and Wen, 2000), Iceland (Hreinsson, 2008a; Hreinsson, 2008b) and Cameroon (Wandji, 2018) is the **least-cost alternative method**. In it, resource rent is calculated as the difference in cost between using a given resource (say hydroelectric resources) in a given production process (electricity generation) and using the next least expensive alternative (say, coal-fired thermal generation). The method is complex and data intensive; as Young and Loomis (2014; p. 213) note, "the analyst who undertakes to estimate the alternative cost of electricity generation 'from scratch' faces a major task." Another approach is the **appropriation method**, in which resource rents are assumed to be equal to the payments (for example, license fees and royalties) that governments demand from resource companies in return for the right to exploit resource assets. For a variety of reasons, the value of these payments does not usually reflect the full value of the underlying resource assets (see SEEA-CF ¶5.126-5.130).

4 Experimental values of hydroelectric, solar and wind assets – Methodology, scope, data sources and results

In this section, we discuss the approach used in to implement the conceptual approach to valuing renewable energy assets discussed in the previous section. We begin by laying out the methodology in a series of simple equations that move from estimation of annual rent to the renewable energy asset values that are required for the CWON natural capital database. We then discuss the scope of the estimates, the data sources used[13] and the approach taken to filling data gaps in implementing the methodology. We conclude with a presentation of our experimental results. Discussion of the results and suggestions for future improvements are covered in Section 5.

4.1 Methodology

According to standard economic theory, the value of any asset is equal to the discounted present value of the stream of benefits it provides its owner over its useful lifetime (SNA ¶3.137). In most instances, this value is revealed through transactions in assets between buyers and seller in the marketplace; the values of both bulldozers and laptop computers are determined this way. Purchasers of bulldozers and laptops are assumed to know the benefits they will derive from them over time and to be willing to pay no more for them than the present value of these benefits.

In the case of natural resource assets, however, markets are either very thin (that is, there are few transactions) or absent entirely.[14] Given this, the market cannot be relied upon to reveal natural resource asset values as it can for bulldozers and laptops. Thus, the value of resource assets must be estimated indirectly by calculating the net present value of their lifetime benefits, with the latter taken to be the stream of rents they generate over their lifetimes. Valuation is, thus, a three-step process. First, the rent accruing to a given resource asset in a given year must be estimated. Second, the expected pattern of future rents for the remainder of the asset's life must be estimated. Finally, the present value of this expect future stream – that is, the asset value – must be calculated. Each of these steps is outlined below.

4.1.1 Estimating rent

Though different approaches may be taken to estimating resource rent, our view (as discussed in Section 3) is that the residual value method (RVM) is the most appropriate for use in valuing renewable energy assets for the purposes of the CWON. Equation 1 expresses the RVM in algebraic notation specific to renewable energy assets.

[13] In the interest of keeping the text here as plain as possible, we do not go into great depth regarding data sources. Readers will find the data sources used in the study fully documented in the Excel database that accompanies this report.

[14] It is important to recall that when we are speaking of natural resource *assets*, it is the *in situ* natural resources (for example, an underground oil deposit or a tract of trees in a forest) we are referring to and not the associated natural resource *commodities* (such as a barrel of pumped oil or a cubic metre of sawn timber). In many countries, governments hold the property rights to sub-soil resources, most forestland and many other *in situ* natural resource assets. They typically do not sell these rights outright. Rather, they license third parties (usually corporations) to extract and process resource commodities on their behalf. As a result, markets in natural resource assets are often thin and they cannot be relied upon to reveal true asset values.

$$RR_t^i = TR_t^i - O\&M_t^i - (rK_t^i + \partial^i) \qquad \text{Equation 1}$$

where,

RR_t^i = residual value estimate of the resource rent accruing to renewable energy asset *i* in year *t*

TR_t^i = total revenue from sales of electricity generated from renewable energy asset *i* in year *t*, net of any direct subsidies paid on generation

$O\&M_t^i$ = cost for labour, materials, fuel and other supplies to operate and maintain the produced assets (wind turbines, solar panels, hydro dams, etc.) used to generate electricity from renewable energy asset *i* in year *t*

r = economy-wide average annual rate of return to produced assets (a constant)

K_t^i = total value of produced assets used to generate electricity from renewable energy asset *i* in year *t* (for example, the value of wind turbines and other equipment required for the production of wind energy)

∂^i = annual rate of depreciation of produced assets used to generate electricity from renewable energy asset *i* (a constant).

4.1.2 Determining the expected pattern of future rent

Once resource rent has been estimated following Equation 1, the next step is to determine the expected pattern of future rents. This involves estimating two parameters: the level of rent in future years and the number of years for which rent will flow. Regarding the latter, in the case of renewable energy assets, a reasonable assumption is that rent will flow indefinitely on any human time scale since the sun will shine, the wind will blow and the water will flow permanently for all practical purposes. As for the level of rent, that will be impacted by the evolution of electricity prices, electricity production, operation and maintenance (O&M) costs and the cost of the produced capital used in the generation process. The latter will be influenced by the value of the produced capital used, its rate of depreciation and by the economy-wide rates of return to produced capital. Any and all of these can vary in time, meaning that determining future patterns of rents can be a complex modelling exercise. It is not common practice in *ex post* natural resource asset valuation to undertake such modelling. Rather, the generally approach is to assume that future rents will be equal to the rent observed in the time period in question (for example, a constant future stream of rent at 2017 levels would be assumed in the case of estimating the asset value for 2017). This is the approach used for other natural resource assets in the CWON and also recommended in the SEEA-CF: “In the absence of any additional information on expected future price changes or likely changes in [production] rates, it is recommended that estimates of expected resource rent should be set based on current estimates of resource rent” (SEEA-CF ¶5.133). Thus, in the valuation of renewable energy assets here, we have assumed rent will continue uninterrupted into the future at the level of the year in question.

4.1.3 Calculating the asset value

With the current rent and its expected future pattern determined, the final step is to estimate the asset value as the discounted present value of future rent. Equation 2 expresses the present value calculation in algebraic notation specific to renewable energy assets.

$$V_t^i = \sum_{n=1}^{T} \frac{RR_t^i}{(1+r_g)^n} \qquad \text{Equation 2}$$

where,

V_t^i = value of renewable energy asset *i* in year *t*

RR_t^i = resource rent accruing to renewable energy asset *i* in year *t* (as defined in Equation 1)

T = renewable energy asset life in years

n = future periods from 1 to T

r_g = economy-wide discount rate.

As noted, it is reasonable to assume that T in Equation 2 is infinity. In this case, Equation 2 reduces to the form shown in Equation 3.

$$V_t^i = \frac{RR_t^i}{r_g} \qquad \text{Equation 3}$$

It is important to note that Equation 3 is re-applied each year to compile the time series of asset values. That is, resource rent is estimated for each year in the time series following Equation 1 and an asset value is calculated following Equation 3 for each year using that year's rent figure. It is this time series of asset values that is required for the CWON natural capital accounts.

4.2 Scope, data sources and assumptions

In keeping with the experimental nature of this effort, we restricted valuation to renewable energy assets used for electricity production. Use of renewable assets for production of heat was not considered. Further, we restricted the analysis to hydroelectric, solar and wind electricity assets only; geothermal electricity assets were excluded since relatively little use is made of them (in spite of their massive potential).[15] For consistency with the CWON natural capital accounts, the timeframe chosen for the analysis was 1990-2017. The countries included were Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, Russian Federation[16], Spain, Sweden, Turkey, United Kingdom and United States. Collectively, these fifteen countries accounted for more than 70% of globally installed hydroelectric capacity, more than 86% of solar electricity capacity (photovoltaic and solar concentrator) and more than 87% of global wind electricity capacity (offshore and onshore) in 2017 according to the IRENA *Trends in Renewable Energy* database.[17]

Valuation of renewable energy assets began with estimation of resource rent in each of the years from 1990-2017 for each country and renewable energy asset following Equation 1 set out earlier. To recall:

$$RR_t^i = TR_t^i - O\&M_t^i - (rK_t^i + \partial^i) \qquad \text{Equation 1}$$

[15] The globally installed capacity of geothermal power was 12.7 GW at the end of 2017. Most of this was geothermal heat. In comparison, globally installed capacities of hydroelectric, solar PV and onshore wind resources in 2017 were 1,099 GW, 384 GW and 496 GW respectively (see IRENA, *Trends in Renewable Energy* database; https://www.irena.org/Statistics/View-Data-by-Topic/Capacity-and-Generation/Statistics-Time-Series)

[16] We considered only hydroelectric assets for the Russian Federation, as it is not a producer of consequence for either solar or wind electricity.

[17] See https://www.irena.org/Statistics/View-Data-by-Topic/Capacity-and-Generation/Statistics-Time-Series.

Application of Equation 1 to compile the time series of renewable energy asset rents required annual, country-specific data on the revenues (net of subsidies) from renewable electricity sales (TR); the costs of operating and maintaining the produced capital (equipment and infrastructure) used to generate renewable electricity ($O\&M$); and the costs of ownership of these produced capital stocks ($rK + \partial$) for each generation type considered (hydroelectric, solar PV, CSP, onshore wind and offshore wind). The sources of these data and the assumptions made in filling data gaps are discussed below.

Once the annual time series of renewable energy asset rents for 1990-2017 was compiled following Equation 1, the next step was to apply Equation 3 to estimate the time series of annual asset values for each renewable energy asset in each country required for the CWON natural capital accounts. To recall:

$$V_t^i = \frac{RR_t^i}{r_g} \qquad \text{Equation 3}$$

Application of Equation 3 required (in addition to the rent time series resulting from application of Equation 1) an estimate of the discount rate (r_g). Ideally, a country-specific discount rate would have been used, as time preferences for income (which is what discount rates reflect) vary from country to country. Discount rates are typically lower in more developed countries and higher in less developed countries, reflecting the greater uncertainty in the latter. However, in keeping with CWON practice in the valuation of other natural resource assets, a cross-country real (inflation-adjusted) discount rate of 4% was used.

4.2.1 Estimating revenues from renewable electricity sales

Although it is possible to obtain data on the total value of sale of all types of electricity from official statistics in some countries, such statistics do not usually provide a detailed breakdown of revenues according to type of generation. For this reason, it was necessary to estimate the annual revenues associated with electricity generation from renewable energy assets (TR) for the purposes here. This was done by multiplying the annual quantities of electricity of each type generated by the prices received for them in the market, as outlined below.

In the case of hydroelectric generation, we assumed (except in the case of China) the price received to be the average country-wide spot price for electricity in a given year, which we took from various country-specific sources. Hydroelectric generation is a mature and long-standing technology that operates at relatively low costs and, therefore, should not be expected to receive prices higher than the average spot price given a competitive electricity market. Of course, markets are not fully competitive in all countries studied, so this approach may undervalue hydroelectric assets in some countries (we discuss other possible distortions in the value of hydroelectric assets in Section 5.2). In the specific case of China, which does not have a deregulated electricity market, we used prices specific to hydroelectricity generation.

For solar PV, CSP and onshore/offshore wind, we used prices specific to each obtained from various country-specific sources.[18]

As for the yearly quantities of electricity of each type generated, we used technology-specific data from global databases; either the UNdata *Energy Statistics* database[19] or the IRENA *Trends in Renewable Energy* database depending on the generation type and year.

Once revenues from electricity generation were estimated as above, they were adjusted to a net basis by deducting subsidies received by renewable energy producers. Subsidies were

[18] See the accompanying Excel database for details.

[19] See http://data.un.org/Explorer.aspx?d=EDATA.

excluded from rent because they do not represent a return to the renewable energy asset but a transfer from one sector of the economy (the public sector) to another (the business sector). Hydroelectric generation was assumed to be receive no explicit production subsidies, so its revenues were left on a gross basis (Section 5 discusses this assumption further). Solar and wind were both assumed to receive explicit subsidies on production. Since data on solar and wind subsidies are not readily available from official statistics, we estimated them as the difference between actual revenues received by solar and wind producers (calculated as above) and the revenues they would have received had solar and wind generation been remunerated at the average electricity spot price. Subsidies so calculated were deducted from gross solar and wind electricity revenues to estimate net revenues.

To illustrate the above, Table 2 shows the data and calculations used to estimate gross revenues, subsidies and net revenues for renewable electricity generation in Canada for the year 2017. Canada produced 3,573 GWh of solar PV electricity in 2017, which was priced at $145/MWh.[20] This yielded gross revenues of $520 million for Canadian solar PV electricity in 2017. Had this electricity instead been remunerated at the average 2017 Canadian electricity spot price of $60/MWh, it would have been valued at $212 million, giving a figure of $308 million for solar PV subsidies. It is the figure of $212 million that was used (as *TR* in Equation 1) to estimate rent for Canadian solar energy assets.[21]

Table 2 – Example of renewable electricity revenue and subsidy estimation, Canada, 2017

Generation type	**A.** Generation (GWh)	**B.** Electricity price, spot ($ per MWh)	**C.** Electricity price, received ($ per MWh)	**D.** Gross revenues (million $) A x B	**E.** Subsidies (million $) (A x C) - (A x B)	**F.** Net revenues (million $) (D – E)
Hydropower	392,647	$60	$60	$23,426	$0	$23,426
Solar PV	3,573	$60	$145	$520	$308	$212
Onshore wind	28,775	$60	$73	$2,108	$391	$1,717

Source: Author's calculations.

4.2.2 Estimating operation and maintenance costs

As with revenues, it is possible to obtain data on total O&M costs associated with all types of electricity generation from official statistics in some countries. Again, though, these are rarely broken down by type of generation. Neither do global databases provide data relevant to estimating O&M costs, so we could not use an approach similar to that described above for revenues to estimate O&M costs. We were left with assuming that O&M costs are a fixed proportion of the value of investment flows. Based on information from the International Energy Agency (IEA, 2010) and IRENA (2019), we used O&M shares of 1% for onshore wind generation, 1.3% for solar PV, 1.75% for hydroelectric generation and 2% for offshore wind and CSP. In each year, we estimated O&M costs for each generation type by multiplying country-specific investment flows by the relevant O&M share. The O&M costs were then cumulated over time by country and generation type.

[20] As noted in the introduction, all values in this report are expressed in United States dollars measured in constant 2018 prices.

[21] As discussed further below, two rent estimates were actually calculated, one using the net revenues of $212 million (termed market rent) and the other using the gross revenues of $520 million (termed social rent).

Country-specific investment flows for each generation type were obtained by multiplying yearly physical additions to capacity in megawatts (from the UNdata *Energy Statistics* database or the IRENA *Trends in Renewable Energy* database depending on generation type and year) by average annual investment costs in dollars per megawatt from various global and national sources.[22]

To illustrate the above, Table 3 shows the data and calculations used to estimate O&M costs for hydroelectric electricity in Canada. Canadian additions to hydroelectric generation capacity were 854 MW in 1990 at an average cost of $1,005 thousand/MW, yielding an investment flow of $858 million. Using the assumed share of 1.75% of investment noted above for hydroelectric generation, the addition to O&M costs in 1990 was estimated to be $15 million (which came on top of the O&M costs for the 59,381 MW of hydroelectric generation capacity that existed already in Canada at the beginning of 1990). O&M costs for Canadian hydroelectric generation were estimated to have reached $2,590 million by 2017.

Table 3 – Example of O&M cost estimation, Canada, hydroelectric generation

Year	**A.** Annual capacity addition (megawatts)	**B.** Average investment cost of new capacity (thousand $ per megawatt)	**C.** Annual investment flow (million $) A x B	**D.** O&M share of new investment costs	**E.** Annual addition to O&M costs (million $) C x D	**F.** O&M costs (million $) $E_t + E_{t-1}$ (see note)
1990	854	$1,005	$858	1.75%	$15	$1,044
1991	854	$1,005	$858	1.75%	$15	$1,059
1992	1433	$1,005	$1,440	1.75%	$25	$1,085
1993	0	-	$0	1.75%	$0	$1,085
1994	1711	$1,005	$1,720	1.75%	$30	$1,115
1995	1626	$1,005	$1,634	1.75%	$29	$1,143
1996	908	$1,005	$913	1.75%	$16	$1,159
1997	1165	$1,005	$1,171	1.75%	$20	$1,180
1998	132	$1,005	$133	1.75%	$2	$1,182
1999	166	$1,005	$167	1.75%	$3	$1,185
2000	286	$1,300	$372	1.75%	$7	$1,191
2001	0	-	$0	1.75%	$0	$1,191
2002	2147	$1,300	$2,791	1.75%	$49	$1,240
2003	1168	$1,300	$1,518	1.75%	$27	$1,267
2004	483	$3,100	$1,497	1.75%	$26	$1,293
2005	1121	$3,100	$3,475	1.75%	$61	$1,354
2006	860	$2,500	$2,150	1.75%	$38	$1,392
2007	620	$3,700	$2,294	1.75%	$40	$1,432
2008	949	$3,100	$2,942	1.75%	$51	$1,483
2009	280	$3,100	$868	1.75%	$15	$1,498
2010	391	$2,800	$1,095	1.75%	$19	$1,518
2011	495	$4,100	$2,030	1.75%	$36	$1,553
2012	0	-	$0	1.75%	$0	$1,553
2013	0	-	$0	1.75%	$0	$1,553
2014	0	-	$0	1.75%	$0	$1,553
2015	3883	$2,917	$11,327	1.75%	$198	$1,751
2016	839	$2,917	$2,447	1.75%	$43	$1,794
2017	572	$2,917	$1,669	1.75%	$29	$1,823

[22] See the accompanying Excel database for details.

Source: Author's calculations.
Notes: The O&M costs for 1990 reflect the O&M costs of the 59,381 MW of hydroelectric generation capacity that existed already in Canada at the beginning of 1990 plus the additional O&M costs of the capacity added in 1990.

4.2.3 Estimating the costs of produced capital

As with revenues and O&M costs, official statistics are not suitable for measuring the costs of produced capital ($rK + \partial$) used in renewable electricity generation. Estimates were therefore required for the three variables involved: *r* – the economy-wide average annual rate of return to produced assets (a constant); ∂ – the annual rate of depreciation of produced assets used to generate electricity from renewable energy assets (a technology-specific constant); and *K* – the value of the stock of produced capital used in renewable electricity generation in each year.

Ideally, country-specific rates of return to produced capital (*r*) would be used in estimating the costs of capital. However, such rates are not readily available from official statistics and calculating them would have required estimates of the income generated through use of produced capital and the stock of produced capital that are also not readily available. For this reason, we assumed the following rates (chosen to reflect real returns): OECD countries - 4%; Russia, Brazil and Turkey - 8%; India and China – 10%.

As for the annual rate of depreciation of produced assets used to generate electricity from renewable energy assets (∂), we assumed asset lives of 50 years for hydroelectric generation infrastructure and 25 years for solar and wind electric generation infrastructure, giving values of 2% and 4% for ∂ for hydroelectric generation and solar/wind generation respectively. These rates were applied to all countries.

Estimating the value of the stock of produced capital used in renewable electricity generation (*K)* was straightforward for solar and wind generation (solar panels, solar concentrators, wind turbines and related infrastructure) since there was little investment in these assets prior to 1990 in any of the countries studied. Therefore, we set the annual value of these produced capital stocks equal to the cumulated value of annual investment flows less annual depreciation calculated using the assumed 25-year lifespan for solar and wind generation equipment.

Estimating *K* for hydroelectric generation was more complicated because considerable investment in hydroelectric generation infrastructure took place prior to 1990 in all countries studied. Therefore, an estimate was required of the 1990 produced capital stock value for each country before the entire 1990-2017 time series could be compiled. The 1990 estimate was derived by applying an approach outlined in the OECD manual on measuring capital stocks (OECD, 2009; Section 15.7). According to that approach, a reasonable estimate of the stock of any produced asset in any base year may be derived by dividing the value of investment in the base year by the sum of the asset's deprecation rate plus the long-term growth rate of real GDP. Equation 4 expresses this approach to estimating base-year stocks of hydroelectric generation equipment and infrastructure in algebraic notation.

$$K_0^{hydro} = I_0^{hydro} \Big/ (\partial^{hydro} + \theta) \qquad \text{Equation 4}$$

where,

- K_0^{hydro} is the value of the produced capital stock used for hydroelectric generation in the base year (1990 in most cases[23])

[23] The base year for the Russian Federation was 1992, as years prior to that pertained to the USSR.

- I_0^{hydro} is the value of investment in produced capital used for hydroelectric generation in the base year
- ∂^{hydro} is the annual rate of depreciation of produced capital used for hydroelectric generation (a constant)
- θ is the long-term annual growth of real GDP in the economy.

In implementing Equation 4, we wanted to avoid situations in which outlier investment values for 1990 would unduly influence the value of I_0^{hydro} given the "lumpiness" of major investment expenditures such as those in hydroelectric generating infrastructure. To do this, we assumed that the 1990 addition to hydroelectric generating capacity was equal to the average addition over the previous 50 years (the assumed lifetime of the infrastructure). We calculated this by dividing the 1990 installed capacity in MW, which we obtained from the UNdata *Energy Statistics* database, by 50. We then multiplied this figure by the 1990 investment cost of new capacity to obtain I_0^{hydro} .

The annual rate of depreciation of produced capital used for hydroelectric generation (∂^{hydro}) was, as noted above, set to 2% based on the assumed life of 50 years for the generating infrastructure. For the long-term growth rate of real GDP (θ), we used country-specific data for 1950-2016 from the IMF macroeconomic and financial database.[24]

To illustrate the above, Table 4 shows the data and calculations used to estimate costs of produced capital for hydroelectric generation in Canada. The value of the produced capital stock used in Canadian hydroelectric generation was estimated to have been about $28.3 billion in 1990 (column E) and to have risen to about $53.3 billion by 2017. The cost of the use of this produced capital ($rK + \partial$) was estimated to have grown from about $1.7 billion in 1990 to $3.2 billion in 2017 (column H).

Table 4 – Example of produced capital cost estimation, Canada, hydroelectric generation

Year	**A.** Annual capacity addition (MW)	**B.** Installed capacity (MW)	**C.** Average investment cost of new capacity (thousand $ per MW)	**D.** Annual investment flow (million $) A x C	**E.** Produced capital stock (million $) See note 1	**F.** Return to produced capital stock (million $) See note 2	**G.** Depreciation of produced capital stock (million $) See note 3	**H.** Cost of produced capital (million $) F + G
1990	854	59,381	$1,005	$858	$28,297	$1,132	$566	$1,698
1991	854	60,235	$1,005	$858	$28,590	$1,144	$572	$1,715
1992	1,433	61,668	$1,005	$1,440	$29,458	$1,178	$589	$1,767
1993	0	61,668	-	$0	$28,869	$1,155	$577	$1,732
1994	1,711	63,379	$1,005	$1,720	$30,011	$1,200	$600	$1,801
1995	1,626	65,005	$1,005	$1,634	$31,045	$1,242	$621	$1,863
1996	908	65,913	$1,005	$913	$31,337	$1,253	$627	$1,880
1997	1,165	67,078	$1,005	$1,171	$31,881	$1,275	$638	$1,913
1998	132	67,210	$1,005	$133	$31,376	$1,255	$628	$1,883
1999	166	67,376	$1,005	$167	$30,915	$1,237	$618	$1,855
2000	286	67,662	$1,300	$372	$30,669	$1,227	$613	$1,840
2001	0	67,662	-	$0	$30,055	$1,202	$601	$1,803
2002	2,147	69,809	$1,300	$2,791	$32,245	$1,290	$645	$1,935
2003	1,168	70,977	$1,300	$1,518	$33,119	$1,325	$662	$1,987
2004	483	71,460	$3,100	$1,497	$33,954	$1,358	$679	$2,037
2005	1,121	72,581	$3,100	$3,475	$36,750	$1,470	$735	$2,205
2006	860	73,441	$2,500	$2,150	$38,165	$1,527	$763	$2,290
2007	620	74,061	$3,700	$2,294	$39,695	$1,588	$794	$2,382
2008	949	75,010	$3,100	$2,942	$41,843	$1,674	$837	$2,511

[24] See https://data.imf.org/?sk=388DFA60-1D26-4ADE-B505-A05A558D9A42&sId=1479331931186.

2009	280	75,290	$3,100	$868	$41,874	$1,675	$837	$2,512
2010	391	75,681	$2,800	$1,095	$42,132	$1,685	$843	$2,528
2011	495	76,176	$4,100	$2,030	$43,319	$1,733	$866	$2,599
2012	0	76,176	-	$0	$42,452	$1,698	$849	$2,547
2013	0	76,176	-	$0	$41,603	$1,664	$832	$2,496
2014	0	76,176	-	$0	$40,771	$1,631	$815	$2,446
2015	3,883	80,059	$2,917	$11,327	$51,282	$2,051	$1,026	$3,077
2016	839	80,898	$2,917	$2,447	$52,704	$2,108	$1,054	$3,162
2017	572		$2,917	$1,669	$53,319	$2,133	$1,066	$3,199

Source: Author's calculations.
Notes:
1. Produced capital stock for **1990** was calculated as per Equation 4 assuming that the 1990 addition to hydroelectric generating capacity was equal to the average addition over the previous 50 years (the assumed lifetime of the infrastructure). We calculated this by dividing the 1990 installed capacity (59,381 MW) by 50, which yielded a value of 1,188 MW. We then multiplied this figure by the 1990 investment cost of new capacity ($1,005,000/MW) to obtain I_0^{hydro}. This value was then divided by the sum of the assumed annual depreciation rate of hydroelectric generation equipment and infrastructure (2%, based on an assumed 50 year lifespan) and the long term growth rate of real GDP for Canada (2.22% according to IMF data for the period 1950-2016). Produced capital stocks for the period **1991-2017** were calculated as sum of current year's investment flows (column D) plus previous year's stocks (column E) less current year's depreciation (column G).
2. Return to produced capital was calculated as the produced capital stock (column E) times the assumed rate of return to produced capital in Canada (4%).
3. Depreciation of produced capital was calculated as the produced capital stock (column E) times the assumed annual rate of depreciation of hydroelectric generation infrastructure (2%, based on an assumed 50 year lifespan).

To illustrate how the data from tables 2 through 4 were used to compile the actual renewable energy asset values required for the CWON natural capital accounts, Table 5 shows the calculation of hydroelectric asset values for Canada. Rent (column D) was first calculated for each year according to Equation 1 by subtracting O&M costs and the cost of produced capital from net revenue (that is, gross revenues less subsidies[25]). Using this rent figure as the input to Equation 3, an asset value was then calculated for each year as yearly rent divided by the assumed global discount rate of 4%. This calculation assumes, as discussed earlier, that asset value in each year is equal to the present value of an indefinite stream of that year's rent. This assumption is consistent both with World Bank practice in valuing other natural resource assets in the CWON natural capital accounts and with the recommended approach in the SEEA-CF.

The figures in Table 5 show that the 1990 value of Canadian hydroelectric assets was estimated to be $284 billion. By 2017, this value was estimated to have risen to $456 billion.

Table 5 – Example of rent and asset value estimation for hydroelectric assets, Canada

Year	**A.** Net revenue from electricity generation (million $)	**B.** O&M costs (million $)	**C.** Cost of produced capital (million $)	**D.** Rent (million $) A - B - C	**E.** Asset value (million $) See note
1990	$14,114	$1,044	$1,698	$11,372	$284,299
1991	$15,935	$1,059	$1,715	$13,160	$328,997
1992	$16,572	$1,085	$1,767	$13,720	$342,995
1993	$16,510	$1,085	$1,732	$13,694	$342,344
1994	$16,006	$1,115	$1,801	$13,091	$327,267
1995	$16,239	$1,143	$1,863	$13,233	$330,817
1996	$17,422	$1,159	$1,880	$14,383	$359,564

[25] As noted earlier, hydroelectric generation was assumed to be subsidy free for the purposes of this study, so gross and net revenues in the case of hydroelectric asset valuation are the same. This was not the case of solar and wind electricity assets, however, both of which were assumed to be subsidized. The calculations in this table are intended to be applicable to any of the three, which is why column A is labelled "net" rather than "gross".

1997	$16,955	$1,180	$1,913	$13,862	$346,554
1998	$14,818	$1,182	$1,883	$11,754	$293,846
1999	$15,553	$1,185	$1,855	$12,514	$312,838
2000	$16,089	$1,191	$1,840	$13,057	$326,424
2001	$14,915	$1,191	$1,803	$11,920	$298,005
2002	$16,646	$1,240	$1,935	$13,471	$336,765
2003	$18,653	$1,267	$1,987	$15,399	$384,971
2004	$19,572	$1,293	$2,037	$16,241	$406,037
2005	$23,475	$1,354	$2,205	$19,916	$497,899
2006	$23,491	$1,392	$2,290	$19,810	$495,239
2007	$25,024	$1,432	$2,382	$21,211	$530,277
2008	$25,340	$1,483	$2,511	$21,346	$533,646
2009	$22,952	$1,498	$2,512	$18,941	$473,535
2010	$25,106	$1,518	$2,528	$21,061	$526,522
2011	$28,383	$1,553	$2,599	$24,231	$605,773
2012	$28,515	$1,553	$2,547	$24,415	$610,365
2013	$30,006	$1,553	$2,496	$25,956	$648,911
2014	$25,624	$1,553	$2,446	$21,625	$540,629
2015	$20,942	$1,751	$3,077	$16,113	$402,834
2016	$22,805	$1,794	$3,162	$17,849	$446,223
2017	$23,269	$1,823	$3,199	$18,247	$456,168

Source: Author's calculations.
Note: Asset values in each year were calculated as yearly rent divided by the assumed global discount rate of 4% on the assumption that asset value in each year is equal to the present value of an indefinite stream of that year's rent. This assumption is consistent both with World Bank practice in valuing other natural resource assets in the CWON natural capital accounts and with the recommended approach in the SEEA-CF.

4.2.4 Approach to gap filling

In compiling the estimates of renewable energy asset values following the methodology outlined in this section, global databases and/or research studies have been used as the sources of all of the data required (since official statistics do not provide sufficiently disaggregated data to compile asset values for renewable energy assets). These databases and studies often contain gaps, with variables missing for one or more years. In filling these gaps, we have taken the simple approach of assuming that data for the earliest year available can be used in place of missing data for preceding years. Thus, if a data point was missing for 1990, but available for 1991, we assumed the 1991 data point applied as well to 1990. In cases where gaps in time series were long (for example, in the data for the yearly average investment cost of new generation capacity), this meant that data for a given year has been applied for several consecutive years (this can be seen, for example, in Table 4 where the same figure has been used for the average investment cost of new generation capacity from 1990 to 1999). This obviously stretches the reasonableness of the approach.

4.3 Experimental results

Below, we present our experimental results for the value of hydroelectric, solar and wind electricity assets in Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, Russian Federation, Spain, Sweden, Turkey, United Kingdom and United States from 1990 to 2017.[26]

[26] In the cases of solar and wind electricity production, results are presented from whatever year production began until 2017. Results for the Russian Federation are presented beginning in 1992 and include hydroelectricity assets only, as the country was part of the former Soviet Union prior to 1992 and it did not produce meaningful quantities of

The focus of the discussion below is primarily on our estimates of "market" asset value, or the values that accrue to renewable energy assets when renewable electricity rents are estimated on a net (that is, after removal of explicit subsidies) basis. An alternative set of results based on the concept of "social" resource rent (Statistics Netherlands, 2011), or rent estimated to include subsidies, has also been prepared for the sake of comparison.[27] Though only the market rent-based asset values are suitable for inclusion in the CWON natural capital accounts – since the existing estimates of natural resource assets included there are based on market rents – the concept of social rents is nonetheless interesting. The social rent results are included here to advance the debate regarding the most appropriate way to value renewable energy assets. We include only a small portion of our social rent results in the tables included in this section; the full results are included in the annex.

The results of our analysis are extensive. We considered five different renewable energy assets for 15 countries over a 27-year period, making for thousands of individual data points. It goes without saying that just a fraction of these could be included in this report. Though we have done our best to focus our discussion of results on figures that can actually be found in the report, in some cases we refer to results that we could not include for lack of space. Complete results are available in the Excel database that accompanies this report. Readers can consult this database to confirm any figure referred to in the discussion to that is not presented in the report itself. Readers will also find all data sources used in the study documented there.

4.3.1 Hydroelectric asset values

Table 6 presents our experimental results for hydroelectric asset values. Unsurprisingly, given the maturity of this technology (and our assumption that hydroelectric generation is not explicitly subsidized), the figures in Table 6 are positive in nearly all years and countries. Asset values are "negative"[28] only in Australia from 2001 to 2003; in China between 1999 and 2005; in India in 2016; in the Russian Federation in 1992 and 2015-2017 and in Spain and Turkey in 2017. These few negative values are explained by normal year-to-year variations in electricity prices, generation levels and other variables[29] and do not change the general conclusion that hydroelectric assets make substantial positive contributions to national wealth in all 15 countries studied.

The figures in Table 6 can be put into context by comparing them with the value of other natural resource assets in countries for which estimates are available. Both Canada and Australia have comprehensive natural resource asset data that provide a useful basis of comparison. Based on

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either solar or wind electricity from 1992 to 2017. Results for Brazil are presented beginning in 1995, the first full year of circulation of new Brazilian real introduced in mid-1994. Results for Turkey are presented beginning in 2005, the first full year of circulation of the new Turkish lira introduced at the end of 2004. We did not find electricity prices denominated in the pre-demonetization currencies in Brazil and Turkey, so results for those periods would not have been comparable either with Brazilian or Turkish figures post-demonetization or with other countries pre-demonetization. Results for Germany in 1990 (prior to unification of the former East Germany and West Germany) were calculated based on 1990 data for the former West Germany and assumptions about the level of renewable energy production in the former East Germany in that year.

[27] Since we assume that hydroelectric generation is free of explicit subsidies, market and social rents are identical for hydroelectric assets.

[28] In principle, an asset cannot have a negative value (otherwise, it is a liability rather than an asset), so negative asset values should really be presented as zeroes. We have left them as negatives for the sake of showing "how far" renewable energy assets (especially solar and wind assets) are from making positive contributions to national wealth.

[29] For instance, the negative asset values in Australia from 2001 to 2003 are mainly due to the decline in the value of the Australian dollar versus the U.S. dollar in combination with relatively low electricity spot prices.

official Canadian statistics[30], the $456 billion value of Canada's hydroelectric assets in 2017 would make them the second most valuable of its market natural resource assets (after land) in that year, with a value substantially greater than the country's vast fossil fuel assets. Even in 2008, when Canada's fossil fuel assets experienced their peak value ($CAN1.1 trillion), hydroelectric assets were worth nearly half as much as fossil fuels based on our experimental results. In the case of Australia, our results suggest that that hydroelectric resources were worth about twice as much as timber resources in 2017, though only about one tenth as much as energy assets and one sixteenth as much as mineral assets.[31]

Table 7 normalizes the asset values from Table 6 by dividing them by electricity generation (for example, the figure in the upper left-hand corner means that Australia created more than $474,000 of wealth for every gigawatt-hour (GWh)[32] of hydroelectric power it generated in 1990). Normalized values permit meaningful international comparisons, since a gigawatt-hour of electricity does not differ from one country to the next. The unit wealth countries create from their renewable energy resources is, then, a measure of their relative success in using their natural resource base to generate well-being.

As can be seen, Brazil was the most successful at converting hydroelectric resources into wealth in 2017, creating more than $1.6 million in wealth for every GWh of hydroelectricity produced. Australia, Canada, and Japan were also very successful in converting hydroelectric resources into wealth, each creating about $1.2 million in wealth per GWh. At the other end of the spectrum, the Russian Federation, Spain and Turkey created no wealth at all per unit of generation in 2017. China and India also lagged other countries, producing just $84,400 per and $46,600 per GWh respectively.

Many countries witnessed declines in the conversion of hydroelectric resources into wealth over time, most notably China, India, Italy, the Russian Federation, Turkey, the United Kingdom and the United States. While there is no single explanation for this outcome, it is clear that the efficiency with which hydroelectric generating infrastructure (dams, reservoirs, hydraulic turbines) is used played a role. For example, generation efficiency (or capacity factor) in India declined more-or-less continually over the period from 0.436 to 0.303.[33] The reason for this does not appear to be ageing of hydroelectric generating infrastructure, since only about 38% of Indian hydroelectric infrastructure had been installed by 1990 and major new investments were made in most years from 1990 to 2017. The decline may be climate-related, since hydroelectric generation relies on rivers and reservoirs being full of water, which, in turn, relies on regular precipitation.

[30] In 2017, Statistics Canada estimated that selected natural resource assets in Canada were worth: land - $CAN4,208 billion; fossil fuels - $CAN377 billion; timber - $CAN236 billion; and minerals - $CAN101 billion (or approximately $3,237 billion, $290 billion, $182 billion and $78 billion respectively). See https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3810000601.

[31] In fiscal year 2017-18, the Australian Bureau of Statistics estimated that selected natural resource assets in Australia were worth: land - $AUS5,921 billion; minerals - $AUS386 billion; fossil fuels - $AUS244 billion; and timber - $AUS12 billion (or approximately $4,441 billion, $290 billion, $183 billion and $9 billion respectively). See https://www.abs.gov.au/AUSSTATS/abs@.nsf/Latestproducts/4655.0Main%20Features22019?opendocument&tabname=Summary&prodno=4655.0&issue=2019&num=&view=.

[32] A gigawatt hour is a unit of energy approximately equal to 590 barrels of oil. It is enough to meet the electricity needs of about 100 average Canadian homes for a year.

[33] Capacity factor measures the actual amount of electricity generated as a share of the potential amount that could be generated if a system operated at maximum output over a period. India's 1990 capacity factor of 0.436 had fallen to 0.303 by 2017. In Japan, the capacity factor fell from 0.293 to 0.206 over the same period.

Falling prices for hydroelectricity[34] also played a role in declining unit wealth. This was the main reason why wealth per GWh fell from $1.4 million in 1990 to just $531,000 in the U.S. in 2017. Falling prices also played a role in declining unit wealth in Italy, Spain, Turkey[35] and the U.K.

Rising produced capital costs[36] were an important factor in declining unit wealth in several countries, most notably China and India where produced capital costs per GWh rose by 110% and 183% respectively over the period. This was the result of very large and expensive investments in new generating capacity in both countries. Chinese installed hydroelectric capacity increased almost tenfold over the period, while that in India nearly tripled.

Table 8 provides a detailed breakdown of costs, revenues and rent associated with hydroelectric assets in 2017. The data in it help explain why hydroelectric asset values vary so much across countries. Columns A through C show the costs of produced capital, O&M and subsidies[37] per GWh of hydroelectricity produced, while columns D and E show total social and private production costs per GWh. Since we assume hydroelectricity is produced without any explicit subsidies, the values in column C are all zero and the total social costs (column D) are equal to total private costs (column E). Column F shows revenue from hydroelectricity sales per GWh, which we assumed to be equal to the average annual spot price of electricity. Columns G and H show net revenues per GWh (revenues less total social costs and total private costs per GWh respectively). The former is the basis for estimating market asset values in column J. The latter, which leaves subsidies out of the calculation, is the basis for estimating social asset values in column K. Column I presents the quantities of hydroelectricity generated, which is multiplied by either G or H to produce either market or social asset values. Column L presents the “normal” return to produced capital we assumed in our calculations, which were noted in Section 4.2.3 to be 4% in OECD countries; 8% in Russia, Brazil and Turkey; and 10% in India and China. Finally, column M presents an “apparent” private return to produced capital, which is the return at which private costs are exactly equal to revenues; in other words, it is the return renewable energy producers appear to receive on their investments in produced capital based on the data we have assembled for the study. In cases where the apparent private return is higher than normal, renewable energy producers may be earning profits on their investments above what they could expect to earn on average elsewhere in the economy. In cases where the implicit return is lower than normal, producers would appear to be accepting lower rates of return than they might obtain if they invested their capital elsewhere.

Looking now at the data in Table 8, we see that Canada was the lowest cost producer of hydroelectricity in 2017, requiring just $12,800 in produced capital and O&M costs per GWh (column E). The U.S. and Sweden were the next most efficient, requiring $16,600/GWh and $18,700/GWh respectively. At the other end of the spectrum, Turkey had produced capital and O&M costs of $69,700 to generate a GWh of hydroelectricity in 2017. Other high-cost producers were India ($47,000/GWh), Spain ($61,000/GWh) and the U.K. ($48,700/GWh). Across all countries, weighted average[38] costs where $30,100/GWh.

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[34] Recall that we assumed hydroelectricity was remunerated at the average annual electricity spot price. In reality, some hydroelectric producers likely received less that the spot price through long-term contracts. In such cases, hydroelectric prices may not have fallen as much over time as we estimated, though they would likely have been lower in the early years of our time period than we estimated.

[35] In fact, Turkish energy prices were rising when measured in lira but declining when measured in $US because of the worsening lira-$US exchange rate.

[36] As discussed in Section 4.2.3, produced capital costs were estimated as the sum of the assumed long-term average return to produced capital plus depreciation of produced capital.

[37] From a societal perspective, subsidies are a cost. From a private (producer) perspective, they are a revenue.

[38] Weighted by electricity generation (column I).

The Russian Federation was the lowest revenue jurisdiction. Russian hydroelectricity earned only $22,700/GWh (column F), about one-fifth of that in the highest revenue jurisdiction (Brazil; $99,700/GWh). Weighted average revenue across all countries was $50,400/GWh.

China was the largest producer of hydroelectricity by far, generating nearly 1.2 million GWh or about three times that of the next largest producer, Canada, in 2017. Despite being the largest producer, China did not create the greatest wealth from its hydroelectric resources in that year. That achievement went to Brazil, with a market asset value of nearly $610 billion (and, since hydroelectric subsidies were taken to be zero, the same social asset value). Canada's market asset value of $423 billion placed it in second place. China ($100 billion) fell in fifth position, behind the U.S. and Japan ($173 billion and $111 billion respectively).

Considering the factors that lie behind market asset values, the net revenues from hydroelectricity generation (column G) was certainly a key determinant. Countries with low net revenues generally struggled to generate significant wealth even with very high levels of hydroelectricity production; India, for example, generated 4% of combined hydroelectricity but only 0.4% of hydroelectric asset wealth. Looking more closely at this, the real culprit can be seen to be India's high cost of production ($47,700/GWh). India was the fourth highest-cost producer, well ahead of the weighted average of $30,100/GWh. At the same time, it generated revenues of $47,900/GWh, just below the weighted average of $50,200/GWh. Had Indian production costs equaled the weighted 2017 average, it would have managed to create a market hydroelectric asset with a value of $56.6 billion, nearly 6 times greater than in fact. The U.S. and Sweden, in contrast, with net revenues well below average both managed to create hydroelectric assets worth tens of billions of dollars thanks to low production costs. Other countries that failed to create hydroelectric assets of substantial value in 2017 because of high production costs included Spain[39], Turkey and the United Kingdom.

Failure to create a hydroelectric asset of value proportional to the scale of generation because of high production costs may indicate an important element of a country's natural resource base is not well managed. Rents that may otherwise arise can be squandered in cases where hydroelectric resources are used inefficiently. In such cases, social well-being is lower than it could be under better management, as rents that do not arise cannot, it goes without saying, be captured by governments on behalf of their citizens through royalty regimes. Of course, the mere fact that rents arise in hydroelectric production (or any resource activity) does not mean that social well-being will increase, since governments must first capture rent for this to happen. Rent capture does not always occur, however, and where it does, governments may capture less rent than they potentially might without providing a disincentive for companies to remain engaged in the activity. A useful discussion of rent capture and public policy can be found in Anderson (1985).

When rents cannot be captured because they do not arise, they are instead dissipated among the private enterprises and/or workers engaged in hydroelectricity production. Much of the rent will land in the hands of sectors that support hydroelectric production rather than in the hands of the producers themselves, since it is the latter who face the higher production costs that must be absorb in the form of lower operating surplus (or profits). This can be seen in the apparent private returns to produced capital in column M of Table 8. In China, hydroelectric producers earned an apparent return in 2017 of 11%. This was little more than the normal economy-wide return to produced capital (10%), meaning that much of the rents that would arise if China were a lower-cost producer were instead captured in profits and wages in the industries that supplied

[39] Spain is an anomaly in this case. Its 2017 production costs were about 70% above its average production costs from 1990-2016 due to an exceptionally low capacity factor of 0.12 in 2017. The reason for this low capacity factor is unknown.

hydroelectricity producers with goods and services. The apparent return to Canadian hydroelectricity producers, on the other hand, is 38%, a full 34% over and above the normal rate of return in Canada. Hydroelectric producers were the clear "winners" there. Of course, a considerable portion of this rent was likely captured in royalty payments collected by Canadian governments from producers, so not all of it stayed in producers' hands.[40] Other countries in which apparent rates of return to produced capital far above normal rates included Australia (20% above normal), Brazil (+24%), France (+12%), Japan (+13%), Sweden (+9%) and the U.S. (+16%).

Whether hydroelectric resources are managed effectively for wealth creation is an important question, though not one that can be thoroughly addressed with the data compiled for this study. Some evidence of inefficiencies may, however, be found in rising production costs over time. In China, for example, steady growth in unit production costs per GWh took place from 1990 to 2017, amounting to a total increase of 85% over the period. Other countries with significant and steady cost increases included India (162%) and Turkey (164%)[41]. Further investigation would be required to determine the relationship between production costs, asset management and wealth creation in these and other countries.

While failure to create significant hydroelectric asset value because of high production costs is likely of concern from a social well-being perspective, failure do to so because of low revenues is not necessarily so. The Swedish hydroelectric asset, for example, was one of the least valuable among the countries studied ($28 billion) despite Sweden being among the lowest-cost producers ($18,700/GWh). This was because revenues in Sweden were also quite low ($35,700/GWh). If Swedish revenues reflected the actual marginal social value of electricity to Swedes as expressed through an open and competitive electricity market, then $28 billion can be taken as a good measure of the social value of Sweden's hydroelectric resources. If it is further the case that the Swedish government captures a reasonable share of this wealth through royalties, it can be further concluded that Swedish hydroelectric assets are well managed both privately and publicly and that Swedes are benefiting to the fullest extent possible given the social value they place on electricity and the degree to which they wish to develop their hydroelectric resources. Even if Swedish hydroelectricity revenues are kept artificially low through government policies that provide hydroelectric producers with implicit subsidies (such as public guarantees on debt), it could still be concluded that Swedes are benefiting appropriately from their hydroelectric resources since any resulting loss in wealth would be compensated by the fact that all Swedes benefit from lower electricity prices (leaving aside the argument that market interventions to lower prices may cause other well-being reducing distortions).

[40] Further analysis to determine just how much of Canada's considerable hydroelectric asset value is captured by Canadian governments and how much is permitted to be retained by producers would be worthwhile.

[41] The Turkish increase is calculated from 2005-2017. See Footnote 26 for further details

Table 6 – Hydroelectric asset value, market resource rent

	Australia	Brazil	Canada	China	France	Germany	India	Italy	Japan	Russian Federation	Spain	Sweden	Turkey	United Kingdom	United States
	million $ (2018 prices)														
1990	$7,054	*	$284,299	$86,579	$20,532	$3,054	$374,834	$52,272	$74,335		$34,871	$64,822	*	$9,520	$402,004
1991	$8,675	*	$328,997	$64,382	$23,031	$2,153	$284,367	$74,763	$99,605		$38,450	$51,200	*	$6,126	$436,157
1992	$6,879	*	$342,995	$58,149	$39,689	$5,189	$233,044	$75,786	$82,371	($81,004)	$22,982	$68,373	*	$8,410	$372,702
1993	$6,930	*	$342,344	$56,890	$30,017	$4,522	$191,600	$48,497	$137,084	$5,518,943	$22,839	$56,799	*	$3,353	$418,287
1994	$7,879	*	$327,267	$5,620	$45,617	$6,591	$222,524	$52,890	$84,878	$2,479,004	$26,497	$38,799	*	$5,336	$384,861
1995	$7,758	$776,122	$330,817	$14,216	$50,011	$11,764	$182,831	$41,378	$134,271	$1,153,174	$21,163	$54,718	*	$5,479	$479,619
1996	$8,219	$732,529	$359,564	$2,574	$41,363	$10,900	$151,162	$56,343	$96,475	$881,722	$50,163	$33,877	*	$2,385	$548,954
1997	$8,562	$712,350	$346,554	$10,190	$29,147	$3,077	$161,667	$47,019	$99,256	$790,141	$32,749	$44,809	*	$4,409	$516,433
1998	$3,040	$684,526	$293,846	$5,328	$27,455	$3,074	$155,294	$47,071	$87,475	$445,708	$31,602	$50,288	*	$7,025	$453,711
1999	$5,711	$392,143	$312,838	($14,535)	$35,605	$3,448	$136,297	$50,292	$99,738	$131,371	$13,525	$43,170	*	$9,971	$419,519
2000	$6,377	$399,153	$326,424	($51,240)	$21,290	$2,172	$109,802	$37,958	$114,030	$109,000	$10,412	$39,848	*	$7,981	$382,641
2001	($556)	$224,630	$298,005	($23,439)	$25,810	$2,671	$97,304	$39,873	$86,830	$112,373	$24,176	$38,429	*	$4,396	$267,229
2002	($1,361)	$164,228	$336,765	($25,152)	$18,810	$3,734	$84,762	$34,321	$78,755	$87,223	$4,336	$31,502	*	$6,902	$227,937
2003	($197)	$153,606	$384,971	($56,247)	$28,597	$7,692	$67,524	$42,524	$115,872	$82,174	$39,090	$29,858	*	$5,126	$385,629
2004	$2,349	$182,112	$406,037	($43,056)	$49,360	$11,596	$89,538	$61,316	$129,236	$113,840	$29,522	$42,368	*	$10,437	$391,281
2005	$4,226	$267,306	$497,899	($50,671)	$37,131	$24,886	$106,887	$56,835	$90,035	$113,317	$10,023	$61,134	$127,066	$11,252	$567,297
2006	$9,818	$325,924	$495,239	$86,800	$43,570	$29,898	$131,008	$82,762	$84,676	$121,284	$22,249	$92,345	$135,115	$13,012	$462,677
2007	$9,719	$760,358	$530,277	$105,917	$51,098	$20,456	$176,485	$70,638	$113,855	$167,917	$14,142	$56,769	$122,731	$16,028	$433,227
2008	$3,546	$1,127,657	$533,646	$115,238	$162,693	$57,290	$165,390	$131,599	$111,429	$165,614	$34,736	$126,622	$104,052	$14,217	$525,672
2009	$1,482	$96,104	$473,535	$192,917	$58,261	$17,798	$389,503	$93,472	$63,199	$101,186	$9,456	$70,271	$116,789	$10,175	$224,429
2010	$743	$528,252	$526,522	$255,486	$74,751	$25,301	$200,195	$89,605	$136,085	$137,717	$28,489	$114,794	$188,269	$5,652	$256,481
2011	$2,672	$1,410,780	$605,773	$153,526	$54,894	$25,115	$210,589	$92,377	$321,222	$137,521	$30,298	$95,301	$166,651	$10,930	$281,723
2012	$12,839	$1,025,907	$610,365	$311,147	$69,664	$22,600	$171,473	$75,806	$307,223	$97,603	$9,395	$62,743	$142,116	$8,584	$148,512
2013	$14,675	$1,343,174	$648,911	$246,886	$76,590	$18,605	$55,641	$82,730	$289,658	$95,001	$31,761	$61,182	$113,051	$8,634	$218,585
2014	$7,029	$2,968,652	$540,629	$387,374	$46,785	$8,909	$99,469	$71,127	$222,140	$38,978	$31,899	$45,489	$34,721	$8,483	$275,666
2015	$6,755	$616,764	$402,834	$378,745	$31,177	$1,853	$23,416	$33,011	$98,156	($12,684)	$12,256	$17,391	$20,787	$5,255	$135,018
2016	$16,636	$36,594	$446,223	$239,325	$30,953	$1,303	($22,298)	$16,830	$78,946	($11,169)	$12,289	$21,520	$589	$2,343	$113,591
2017	$18,092	$607,435	$456,168	$100,386	$35,654	$5,878	$6,124	$22,227	$110,841	($31,393)	($650)	$27,572	($25,475)	$2,690	$172,552

Source: Author's calculations.
Note: * indicates years for which production occurred but values are not shown because of currency changes.

Table 7 – Hydroelectric asset value per unit of electricity generated, market resource rent

	Australia	Brazil	Canada	China	France	Germany	India	Italy	Japan	Russian Federation	Spain	Sweden	Turkey	United Kingdom	United States
	thousand $ per GWh (2018 prices)														
1990	$474	*	$958	$683	$358	$159	$5,231	$1,490	$766		$1,332	$888	*	$1,324	$1,391
1991	$539	*	$1,067	$515	$374	$115	$3,907	$1,639	$931		$1,359	$804	*	$997	$1,411
1992	$436	*	$1,084	$439	$547	$245	$3,335	$1,655	$906	-$471	$1,098	$913	*	$1,180	$1,356
1993	$409	*	$1,058	$375	$442	$209	$2,719	$1,090	$1,281	$31,666	$886	$755	*	$584	$1,380
1994	$473	*	$992	$33	$563	$276	$2,690	$1,108	$1,108	$14,084	$908	$653	*	$814	$1,353
1995	$478	$3,057	$984	$75	$656	$448	$2,518	$987	$1,451	$6,537	$861	$803	*	$857	$1,420
1996	$522	$2,756	$1,011	$14	$589	$409	$2,193	$1,197	$1,079	$5,713	$1,227	$654	*	$482	$1,457
1997	$508	$2,553	$988	$52	$431	$147	$2,165	$1,010	$988	$5,015	$910	$648	*	$780	$1,440
1998	$193	$2,349	$885	$26	$415	$145	$1,871	$994	$853	$2,795	$883	$670	*	$1,042	$1,409
1999	$345	$1,338	$904	-$71	$462	$147	$1,686	$971	$1,044	$814	$532	$602	*	$1,210	$1,390
2000	$381	$1,311	$910	-$230	$299	$84	$1,471	$746	$1,178	$663	$327	$507	*	$1,026	$1,367
2001	-$33	$839	$894	-$84	$329	$98	$1,307	$739	$925	$642	$551	$486	*	$679	$1,244
2002	-$85	$574	$960	-$87	$286	$134	$1,186	$726	$858	$534	$165	$474	*	$928	$781
2003	-$12	$503	$1,140	-$198	$445	$336	$1,007	$960	$1,113	$524	$891	$557	*	$860	$1,261
2004	$144	$568	$1,191	-$122	$761	$438	$1,150	$1,229	$1,253	$644	$857	$704	*	$1,393	$1,313
2005	$271	$792	$1,375	-$128	$659	$942	$1,188	$1,324	$1,043	$653	$435	$839	$3,212	$1,433	$1,904
2006	$613	$934	$1,403	$199	$706	$1,117	$1,210	$1,906	$870	$697	$746	$1,493	$3,054	$1,541	$1,456
2007	$669	$2,033	$1,442	$218	$808	$728	$1,478	$1,836	$1,352	$944	$463	$857	$3,423	$1,794	$1,572
2008	$294	$3,051	$1,413	$197	$2,380	$2,164	$1,352	$2,787	$1,334	$1,002	$1,329	$1,829	$3,128	$1,540	$1,864
2009	$125	$246	$1,284	$313	$940	$721	$3,426	$1,749	$754	$578	$324	$1,065	$3,248	$1,142	$752
2010	$55	$1,310	$1,498	$354	$1,107	$925	$1,785	$1,647	$1,501	$822	$626	$1,726	$3,635	$838	$896
2011	$159	$3,294	$1,612	$220	$1,081	$1,068	$1,689	$1,934	$3,503	$826	$921	$1,432	$3,184	$1,271	$818
2012	$912	$2,470	$1,605	$357	$1,078	$812	$1,288	$1,729	$3,673	$587	$389	$794	$2,456	$1,037	$498
2013	$803	$3,435	$1,656	$268	$995	$646	$442	$1,513	$3,412	$524	$774	$995	$1,903	$1,135	$753
2014	$382	$7,949	$1,413	$364	$672	$350	$706	$1,180	$2,555	$222	$742	$712	$854	$967	$979
2015	$502	$1,714	$1,054	$335	$516	$74	$173	$703	$1,075	-$75	$391	$231	$310	$581	$498
2016	$1,086	$96	$1,152	$201	$471	$50	-$171	$380	$931	-$60	$308	$346	$9	$281	$389
2017	$1,111	$1,638	$1,162	$84	$647	$225	$47	$585	$1,229	-$168	-$31	$423	-$438	$306	$531

Source: Author's calculations.
Note: * indicates years for which production occurred but values are not shown because of currency changes.

Table 8 – Details of costs, revenues and asset values, hydroelectric assets, 2017

	Produced capital costs per GWh, normal return to capital (A)	O&M costs per GWh (B)	Subsidies per GWh (C)	Social costs per GWh, normal return to capital (D = A+B+C)	Private costs per GWh, normal return to capital (E = A+B)	Revenues per GWh (F)	Net social revenues per GWh, normal return to capital (G = F-D)	Net private revenues per GWh, normal return to capital (H = F-E)	Generation (GWh) (I)	Market asset value, normal return to capital (J = G*I/0.04)	Social asset value, normal return to capital (K = H*I/0.04)	Normal private return to produced capital (L)	Apparent private return to produced capital (M)
	thousand $ (2018 prices) unless otherwise indicated												
Australia	$13.2	$13.7	$0.0	$26.8	$26.8	$71.3	$44.4	$44.4	16,285	$18,092,452	$18,092,452	4%	24%
Brazil	$27.5	$6.6	$0.0	$34.2	$34.2	$99.7	$65.5	$65.5	370,907	$607,434,906	$607,434,906	8%	32%
Canada	$8.1	$4.6	$0.0	$12.8	$12.8	$59.3	$46.5	$46.5	392,647	$456,167,540	$456,167,540	4%	38%
China	$29.2	$5.4	$0.0	$34.6	$34.6	$38.0	$3.4	$3.4	1,189,840	$100,386,173	$100,386,173	10%	11%
France	$13.4	$10.9	$0.0	$24.3	$24.3	$50.2	$25.9	$25.9	55,108	$35,653,506	$35,653,506	4%	16%
Germany	$18.5	$11.8	$0.0	$30.4	$30.4	$39.4	$9.0	$9.0	26,155	$5,878,165	$5,878,165	4%	7%
India	$39.1	$8.6	$0.0	$47.7	$47.7	$49.6	$1.9	$1.9	131,360	$6,124,163	$6,124,163	10%	11%
Italy	$24.2	$14.3	$0.0	$38.5	$38.5	$61.9	$23.4	$23.4	38,025	$22,227,288	$22,227,288	4%	10%
Japan	$22.9	$14.5	$0.0	$37.4	$37.4	$86.6	$49.2	$49.2	90,162	$110,840,782	$110,840,782	4%	17%
Russian Federation	$21.1	$8.4	$0.0	$29.5	$29.5	$22.7	-$6.7	-$6.7	187,131	-$31,392,904	-$31,392,904	8%	4%
Spain	$36.3	$24.8	$0.0	$61.0	$61.0	$59.8	-$1.2	-$1.2	21,070	-$650,233	-$650,233	4%	4%
Sweden	$10.9	$7.8	$0.0	$18.7	$18.7	$35.6	$16.9	$16.9	65,168	$27,572,021	$27,572,021	4%	13%
Turkey	$56.9	$12.8	$0.0	$69.7	$69.7	$52.2	-$17.5	-$17.5	58,219	-$25,475,201	-$25,475,201	8%	5%
United Kingdom	$30.1	$18.6	$0.0	$48.7	$48.7	$60.9	$12.2	$12.2	8,800	$2,689,594	$2,689,594	4%	7%
USA	$7.9	$6.3	$0.0	$14.2	$14.2	$35.5	$21.2	$21.2	325,114	$172,552,209	$172,552,209	4%	20%

Source: Author's calculations.

4.3.2 Solar electricity asset values

Table 9 and Table 10 present our experimental results for the market value of combined solar electricity assets[42] (in total in Table 9 and per unit of solar electricity generated in Table 10). They show negative values for solar electricity assets in all countries across all years. This is not unexpected, given the relative immaturity of the solar electricity sector, its generally high cost structure and the significant subsidies paid by governments to support its development in the last two decades. Four countries produced electricity from both solar PV and CSP assets (China, India, Spain, and the U.S.). In all of them, both solar PV and CSP assets had negative asset values.

Though market solar electricity asset values remained negative in all countries in 2017, Table 10 shows that they also become more valuable on a unit basis (even if still negative) over the period in every country. Thus, it is reasonable to expect that asset values will eventually turn positive in all countries. This is explored in Table 11, where we show projected values for solar PV electricity assets in 2035 and the first year in which they are expected to have permanent positive value between 2018 and 2035.[43] The figures in Table 11 are based on extrapolations of the data we collected for 1990-2017 and assumptions regarding the likely evolution of solar electricity technologies and markets (Text Box 2). They should be taken as indicative and assumed to have considerable margins of error. Nonetheless, we believe they provide a basic sense of when it might be expected that solar PV electricity assets could begin to have positive values and how big those values might eventually be.

As can be seen in Table 11, all but 2 of the 14 countries studied[44] are projected to have positive solar PV asset values by 2035.[45] The earliest to do so is Japan (2026). By 2035, the total value of solar PV assets across the countries studied is expected to $4.3 trillion.[46] Total solar PV electricity generation is expected to be 6.3 million GWh, or about 17 times what it was in 2017.[47] Nearly half (48%) of the value of solar PV assets in 2035 is expected to be found in Japan, thanks to its high rates of investment in solar generating capacity[48] and its relatively high spot price for electricity.[49] China has the next highest share (36%). No other has more than 5% of the asset value in 2035.

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[42] Solar PV and CSP assets.

[43] CSP assets were not considered because no country has long experience with this technology and we did not feel confident extrapolating the value of these assets from the data we collected for this study.

[44] The Russian Federation did not produce solar PV electricity during the study period and was not included in this analysis.

[45] Spain and Turkey are not projected to have positive solar PV asset values until sometime after 2035.

[46] Note that we do not believe the inclusion of CSP assets in our projections, had that been done, would have materially changed our estimated 2035 solar electricity asset value.

[47] As explained in Text Box 2, we constrained our projection to align with the U.S. Energy Information Authority's 2019 international projection of solar electricity generation. Thus, we are confident that our projection is consistent with the plausible evolution of the solar electricity market. See the accompanying Excel database for details of our projections.

[48] Other than China, no other country studied added more solar PV capacity on average between 2013 and 2017 than Japan.

[49] Recall that we take the difference between renewable electricity prices and spot prices to be the subsidies paid on renewable electricity. Since Japanese spot prices are relatively high, our project solar electricity price converges more quickly with spot prices in Japan than in other countries, meaning that subsidies disappear more quickly and positive market asset values emerge sooner.

Text Box 2 – Assumptions used in projecting asset values for solar PV, onshore wind and offshore wind

To project asset values for solar PV, onshore wind and offshore wind beyond 2017, we made a series of assumptions about trends in renewable energy technologies and electricity markets. We believe our assumptions to be reasonable and conservative. They were applied uniformly to all countries.

- Annual nominal rate of general price growth: 2%
- Annual nominal rate of electricity spot price growth: 2%
- Annual nominal rate of decline of solar/wind electricity prices: 5%
- Annual growth rate in capacity factor[50], solar PV: 3%
- Annual growth rate in capacity factor, onshore wind: 2%
- Annual growth rate in capacity factor, offshore wind: 1%
- Maximum solar PV capacity factor[51]: 0.23
- Maximum onshore wind capacity factor: 0.38
- Maximum offshore wind capacity factor: 0.50
- Annual real rate of decline in unit cost ($/MW) of new solar PV capacity: 7%
- Annual real rate of decline in unit cost ($/MW) of new onshore wind capacity: 3%
- Annual real rate of decline in unit cost ($/MW) of new offshore wind capacity: 5%
- Annual growth rate of capacity additions, solar PV: 12.8%
- Annual growth rate of capacity additions, onshore and offshore wind: 2.0%

To project solar/wind electricity prices, we simply extrapolated 2017 values; for example, the 2018 price for solar electricity in each country was estimated by multiplying the 2017 solar electricity price by 0.95 (given our assumption of 5% annual declines in solar/wind electricity prices). Solar prices for 2019 and beyond were similarly calculated, but only up to the point where solar prices and overall electricity spot prices converged. From that point forward, solar prices were assumed to equal spot prices (as we did not want to create an unrealistic scenario where solar electricity would sell for less than the spot price). Wind electricity prices and electricity spot prices were similarly projected.

In projecting yearly additions to installed capacity, we took a slightly different approach to avoid over-weighting 2017 in the projections. Rather than simply extrapolating from 2017 values, we instead multiplied average capacity additions from 2013-2017 by the appropriate factor (1.128 for solar and 1.020 for onshore/offshore wind) to estimate 2018 capacity additions. Subsequent capacity additions were then simply calculated the previous year's value times the appropriate factor. A similar approach was used to estimate 2018 capacity factors, again to avoid over-weighting 2017 in the projections. We allowed capacity factors to grow annually until they reached the maximum values outlined above, after which they were held constant. Electricity generation for 2018-2035 was then estimated as the projected cumulated installed capacity times the projected capacity factor in each country.

To ensure our projections aligned with expert opinion on the likely evolution of solar/wind electricity markets, we constrained the annual rate of growth of capacity additions so that our projected solar and wind electricity generation in 2030 equalled the 2030 projections in the U.S. Energy Information Agency's 2019 International Energy Outlook (USEIA, 2019), with the assumption that the countries in our study will produce the same shares of global solar and wind electricity in 2030 that they produced in 2017 (86% and 87% respectively). The rates of annual capacity additions that ensured this alignment were, as noted above, 12.8% for solar PV and 2.0% for onshore/offshore wind.

The reason no wealth arises from solar PV electricity assets before 2026 in our projections is made clear by the figures in Table 12, which offer a detailed breakdown of costs, revenues and asset values associated with solar PV assets in 2017. Market solar asset values were (as already noted) negative in all countries in 2017 and social asset values were negative in all but

[50] Our assumptions regarding the rate of improvement of capacity factors are based on IRENA (2019).

[51] Maximum capacity factors are taken as the middle of the ranges projected by IRENA (2019).

three (France, Germany and Spain). Private production costs were very high, with weighted average[52] costs of $213,000/GWh. Subsidy rates were also high ($111,000/GWh weighted average) and were particularly so in France ($420,000/GWh), Germany ($307,000/GWh) and Spain ($307,000/GWh). Subsidies varied greatly from country to country, however, with Brazil offering no subsidies at all and Australia, India, Sweden and the US all subsidizing at rates of less than $50,000/GWh. As a result of generally high subsidies, weighted average social production costs were very high at $324,000/GWh. When compared with the weighted average social production costs of hydroelectricity ($30,100/GWh), it is clear why solar electricity assets struggle to gain positive market values. Producing solar electricity is both privately and socially expensive and will remain so for many years into the future, as older generating infrastructure is gradually replaced by newer, less expensive and more efficient equipment. There is no “magic” level of production costs at which solar PV assets flip from having negative to positive market values. That said, it is worth noting that social production costs had fallen by, on average, 119% from their 2017 levels in the years in which positive values first emerged.

Looking at the apparent private rates of return to solar PV assets in Table 12 (column M), we find rates in excess of normal only in France (+8%), Germany (+4%) and Spain (+8%) in 2017.[53] Apparent rates fell far below normal in Australia (-6%), Brazil (-10%), China (-6%), India (-9%), Sweden (-6%), Turkey (-6%) and the U.S. (-5%). Elsewhere, apparent rates were about 3% below normal. Rates were actually negative – meaning solar PV producers apparently lost money on their investments – in Australia, Brazil, Sweden and the U.S..

Unlike in the case of hydroelectric assets (where apparent returns to capital are not necessarily the rates producers actually earn because governments capture some rents through royalty regimes), when it comes to renewable technologies like solar PV, which are subsidized rather than subject to royalties, the apparent return is a good indication of what producers earn on their investments in generating infrastructure. Given this, it is surprising how many countries showed apparent returns well below what investors might expect to earn elsewhere in the economy and even negative in some cases. It is worth recalling that these apparent returns accounted for the benefits solar PV producers received in the form of subsidies; that is, even taking subsidies into consideration, solar PV producers in most countries earned returns on their investments far below levels at which any incentive to remain in business would seem to have disappeared. It is not clear how this can be the case and the finding deserves further study. One possibility is that important subsidies to solar electricity producers may not captured in our analysis; preferential capital cost allowance provisions, concessionary loans or waiver of grid connection fees, for example. All of these would add to the financial incentive for firms to remain engaged in the industry. It could also be that solar producers take very long views of the industry and are willing to accept low returns in the short run for the promise of higher returns in the future. Or it could be that companies involved in solar electricity production are also involved in wind production (which, as discussed next, yields better returns) and consider their returns across their full portfolios.

[52] Weighted by solar electricity production.

[53] It will be noted that these are the same countries for which social asset values are positive. This is as expected, since the apparent rate of return is the rate at which private production costs exactly balance revenues. This, by definition, is the point at which positive social asset values begin to emerge.

Table 9 – Combined solar PV and CSP electricity asset value, market resource rent

	Australia	Brazil	Canada	China	France	Germany	India	Italy	Japan	Spain	Sweden	Turkey	United Kingdom	United States
	million $ (2018 prices)													
1990								($84)	($598)	($63)				($10,816)
1991						($39)		($102)	($555)	($83)				($10,181)
1992			($25)		($43)	($115)		($159)	($1,213)	($77)				($11,333)
1993	($111)		($23)		($42)	($172)		($248)	($2,017)	($105)				($10,794)
1994	($139)		($50)		($40)	($222)		($287)	($3,056)	($126)				($10,509)
1995	($165)		($47)		($39)	($333)		($320)	($4,491)	($137)				($10,314)
1996	($189)		($70)		($60)	($517)		($305)	($6,547)	($135)				($10,017)
1997	($231)		($94)		($79)	($775)		($318)	($9,653)	($133)				($9,930)
1998	($274)		($115)		($98)	($974)		($329)	($14,181)	($178)				($10,500)
1999	($325)		($136)		($117)	($1,264)		($316)	($21,232)	($168)				($14,082)
2000	($343)		($155)	($1,253)	($133)	($2,081)		($331)	($32,442)	($347)	($42)			($15,374)
2001	($412)		($197)	($1,354)	($127)	($3,591)	($206)	($342)	($35,590)	($407)	($40)		($22)	($15,707)
2002	($481)		($209)	($1,853)	($144)	($4,591)	($236)	($373)	($41,005)	($481)	($38)		($39)	($16,203)
2003	($543)		($237)	($2,054)	($159)	($7,133)	($259)	($442)	($47,311)	($560)	($50)		($76)	($25,462)
2004	($628)		($277)	($2,220)	($195)	($16,633)	($248)	($520)	($54,137)	($739)	($48)		($110)	($25,656)
2005	($680)		($312)	($3,611)	($226)	($27,483)	($332)	($555)	($60,490)	($997)	($46)	($18)	($155)	($26,068)
2006	($745)		($353)	($3,851)	($252)	($35,013)	($325)	($714)	($65,999)	($2,310)	($54)	($21)	($202)	($28,895)
2007	($801)		($402)	($4,416)	($418)	($47,769)	($650)	($1,693)	($67,336)	($6,887)	($64)	($20)	($256)	($32,468)
2008	($913)		($464)	($5,115)	($1,123)	($57,617)	($680)	($6,635)	($69,526)	($39,638)	($77)	($22)	($323)	($32,202)
2009	($3,559)		($1,057)	($7,327)	($3,649)	($99,024)	($779)	($15,077)	($77,597)	($42,537)	($82)	($23)	($371)	($38,458)
2010	($10,792)	($46)	($2,106)	($15,407)	($12,353)	($148,965)	($1,256)	($40,448)	($89,652)	($54,529)	($87)	($23)	($1,234)	($48,697)
2011	($22,067)	($37)	($4,278)	($39,313)	($33,793)	($177,600)	($6,470)	($124,548)	($89,586)	($59,729)	($89)	($26)	($10,445)	($68,378)
2012	($29,325)	($46)	($6,223)	($70,813)	($45,427)	($211,279)	($9,142)	($120,369)	($90,102)	($75,323)	($148)	($42)	($12,651)	($94,206)
2013	($32,987)	($67)	($8,873)	($148,282)	($50,103)	($213,723)	($14,462)	($110,962)	($103,880)	($77,016)	($200)	($59)	($16,660)	($126,557)
2014	($37,548)	($127)	($11,619)	($187,607)	($52,307)	($210,213)	($28,722)	($115,419)	($124,659)	($73,993)	($251)	($235)	($24,138)	($137,069)
2015	($37,502)	($242)	($14,542)	($241,020)	($53,320)	($212,666)	($34,671)	($125,230)	($175,758)	($70,834)	($362)	($1,263)	($32,250)	($169,379)
2016	($35,033)	($905)	($14,582)	($354,959)	($52,764)	($211,641)	($48,906)	($122,317)	($203,767)	($72,559)	($418)	($3,368)	($35,277)	($213,072)
2017	($33,073)	($6,696)	($14,063)	($510,658)	($49,776)	($200,157)	($68,675)	($120,764)	($192,737)	($63,630)	($948)	($14,613)	($34,461)	($217,364)

Source: Author's calculations.

Table 10 – Combined solar PV and CSP electricity asset value per unit of electricity generated, market resource rent

	Australia	Brazil	Canada	China	France	Germany	India	Italy	Japan	Spain	Sweden	Turkey	United Kingdom	United States
	thousand $ per GWh (2018 prices)													
1990	$0	$0	$0	$0	$0	$0	$0	-$21,044	-$8,928	-$6,959	$0	$0	$0	-$16,240
1991	$0	$0	$0	$0	$0	-$39,058	$0	-$20,482	-$7,495	-$7,580	$0	$0	$0	-$13,019
1992	$0	$0	-$12,606	$0	-$43,166	-$28,683	$0	-$17,704	-$14,977	-$6,423	-$12,374	$0	$0	-$15,131
1993	-$10,108	$0	-$7,677	$0	-$41,714	-$57,197	$0	-$22,564	-$22,667	-$8,051	-$12,069	$0	$0	-$11,980
1994	-$10,684	$0	-$16,614	$0	-$40,231	-$31,708	$0	-$26,053	-$31,837	-$8,380	-$11,628	$0	$0	-$12,692
1995	-$10,314	$0	-$11,700	$0	-$38,709	-$47,586	$0	-$24,597	-$42,371	-$6,853	-$24,734	$0	$0	-$12,457
1996	-$9,953	$0	-$11,706	$0	-$59,526	-$43,057	$0	-$21,776	-$53,668	-$7,522	-$23,885	$0	$0	-$11,056
1997	-$10,049	$0	-$13,445	$0	-$39,372	-$43,037	$0	-$21,201	-$64,786	-$6,979	-$23,158	$0	$0	-$11,070
1998	-$9,798	$0	-$11,546	$0	-$49,083	-$27,822	$0	-$20,550	-$75,032	-$8,113	-$22,355	$0	$0	-$11,797
1999	-$9,558	$0	-$10,432	$0	-$58,499	-$42,134	$0	-$18,617	-$83,593	-$6,736	-$35,253	$0	$0	-$20,439
2000	-$9,017	$0	-$9,668	-$33,773	-$25,526	-$34,690	$0	-$18,384	-$90,873	-$24,753	-$29,816	$0	$0	-$84,010
2001	-$9,371	$0	-$10,371	-$31,405	-$20,557	-$30,953	-$27,484	-$18,004	-$65,064	-$23,915	-$26,705	$0	-$12,156	-$71,395
2002	-$9,619	$0	-$9,487	-$27,336	-$20,299	-$24,422	-$25,885	-$17,747	-$63,672	-$26,730	-$22,498	$0	-$14,464	-$62,082
2003	-$9,362	$0	-$10,296	-$25,298	-$20,431	-$22,768	-$24,429	-$18,431	-$55,140	-$28,017	-$27,767	$0	-$26,331	-$30,026
2004	-$9,242	$0	-$21,274	-$23,713	-$23,202	-$29,883	-$23,646	-$17,918	-$48,423	-$31,174	-$23,828	$0	-$27,462	-$26,586
2005	-$8,722	$0	-$18,325	-$26,336	-$21,502	-$21,432	-$21,276	-$17,908	-$42,598	-$20,772	-$21,703	-$5,972	-$18,934	-$23,275
2006	-$8,276	$0	-$16,795	-$24,831	-$20,867	-$15,771	-$25,019	-$20,387	-$38,349	-$16,914	-$22,559	-$5,698	-$18,924	-$22,451
2007	-$7,627	$0	-$15,458	-$23,070	-$23,752	-$15,535	-$18,829	-$43,420	-$34,146	-$13,276	-$20,615	-$4,370	-$18,272	-$19,395
2008	-$7,420	$0	-$13,256	-$21,774	-$26,938	-$13,036	-$18,188	-$34,379	-$31,517	-$15,375	-$19,256	-$3,944	-$19,028	-$15,386
2009	-$22,815	$0	-$9,693	-$21,237	-$20,970	-$15,042	-$16,937	-$22,287	-$29,205	-$7,015	-$11,680	-$3,256	-$18,542	-$15,292
2010	-$27,958	-$46,428	-$8,259	-$21,132	-$19,924	-$12,701	-$19,298	-$21,225	-$25,304	-$7,588	-$10,164	-$2,661	-$30,631	-$12,353
2011	-$15,898	-$14,796	-$7,479	-$19,678	-$14,482	-$9,062	-$20,659	-$11,537	-$18,513	-$6,355	-$8,058	-$2,579	-$42,879	-$11,002
2012	-$12,629	-$6,653	-$7,064	-$16,124	-$10,260	-$8,009	-$9,325	-$6,382	-$13,625	-$6,294	-$7,776	-$2,404	-$9,345	-$9,286
2013	-$9,501	-$3,613	-$5,919	-$16,853	-$9,649	-$6,892	-$8,175	-$5,140	-$8,065	-$5,881	-$5,724	-$2,232	-$8,288	-$7,974
2014	-$9,371	-$2,069	-$5,481	-$7,896	-$8,185	-$5,830	-$8,301	-$5,174	-$5,431	-$5,412	-$5,339	-$13,533	-$5,954	-$5,320
2015	-$7,472	-$3,070	-$5,023	-$6,028	-$6,880	-$5,492	-$5,469	-$5,459	-$5,050	-$5,111	-$3,731	-$6,509	-$4,281	-$4,753
2016	-$5,646	-$6,520	-$4,466	-$5,230	-$6,095	-$5,555	-$4,639	-$5,534	-$4,453	-$5,319	-$2,925	-$3,229	-$3,388	-$4,233
2017	-$4,098	-$6,712	-$3,936	-$4,318	-$5,200	-$5,080	-$3,714	-$4,954	-$3,500	-$4,420	-$4,123	-$5,057	-$2,990	-$3,062

Source: Author's calculations.

Table 11 - Projected value of solar PV electricity assets

	Australia	Brazil	Canada	China	France	Germany	India	Italy	Japan	Spain	Sweden	Turkey	United Kingdom	United States
	Asset values in billion $ (2018 prices)													
First year of positive rent	2029	2035	2028	2031	2029	2034	2034	2032	2026	post 2035	2032	post 2035	2028	2033
Asset value in 2035	$91	$0	$64	$1,557	$116	$43	$57	$70	$2,090	-$1	$2.0	-$62	$206	$130

Source: Author's calculations.

Table 12 – Details of costs, revenues and asset values, solar PV electricity assets, 2017

	Produced capital costs per GWh , normal return to capital (A)	O&M costs per GWh (B)	Subsidies per GWh (C)	Social costs per GWh, normal return to capital (D = A+B+C)	Private costs per GWh, normal return to capital (E = A+B)	Revenues per GWh (F)	Net social revenues per GWh, normal return to capital (G = F-D)	Net private revenues per GWh, normal return to capital (H = F-E)	Generation (GWh) (I)	Market asset value, normal return to capital (J = G*I/0.04)	Social asset value, normal return to capital (K = H*I/0.04)	Normal private return to produced capital (L)	Apparent private return to produced capital (M)
	thousand $ (2018 prices) unless otherwise indicated												
Australia	$196.5	$38.7	$18.6	$253.8	$235.2	$89.9	-$163.9	-$145.3	8,071	-$33,072,928	-$29,319,475	4%	-2%
Brazil	$329.5	$36.0	$0.0	$365.6	$365.6	$97.1	-$268.5	-$268.5	998	-$6,696,214	-$6,696,214	8%	-2%
Canada	$181.4	$34.7	$85.8	$301.9	$216.1	$144.4	-$157.4	-$71.7	3,573	-$14,062,775	-$6,402,139	4%	1%
China	$205.2	$20.6	$78.6	$304.3	$225.7	$131.7	-$172.6	-$94.0	118,258	-$510,258,760	-$277,828,006	10%	4%
France	$215.1	$43.1	$420.3	$678.4	$258.2	$470.4	-$208.0	$212.3	9,573	-$49,775,890	$50,801,240	4%	12%
Germany	$199.2	$43.3	$306.7	$549.3	$242.6	$346.1	-$203.2	$103.5	39,401	-$200,157,235	$101,992,452	4%	8%
India	$174.5	$17.4	$32.7	$224.6	$191.9	$82.3	-$142.3	-$109.6	18,128	-$64,508,051	-$49,679,441	10%	1%
Italy	$204.6	$42.6	$125.3	$372.6	$247.2	$174.4	-$198.2	-$72.8	24,378	-$120,764,386	-$44,379,643	4%	1%
Japan	$188.5	$38.0	$73.8	$300.3	$226.6	$160.3	-$140.0	-$66.2	55,068	-$192,736,640	-$91,198,178	4%	1%
Spain	$167.3	$38.5	$307.4	$513.2	$205.7	$367.2	-$145.9	$161.5	8,514	-$31,063,590	$34,369,104	4%	12%
Sweden	$171.2	$29.4	$31.8	$232.4	$200.6	$67.4	-$164.9	-$133.1	230	-$948,390	-$765,610	4%	-2%
Turkey	$229.2	$25.2	$102.4	$356.8	$254.5	$154.5	-$202.3	-$99.9	2,889	-$14,612,510	-$7,219,497	8%	2%
United Kingdom	$152.3	$28.2	$117.7	$298.2	$180.5	$178.6	-$119.6	-$1.9	11,525	-$34,460,956	-$546,998	4%	4%
USA	$126.9	$24.2	$44.4	$195.5	$151.1	$79.8	-$115.6	-$71.3	67,393	-$194,827,703	-$120,104,613	4%	-1%

Source: Author's calculations.

4.3.3 Wind electricity asset values

Table 13 and Table 14 present our experimental results for the market value of combined wind electricity assets[54] (in total in Table 13 and per unit of wind electricity generated in Table 14). They show negative asset values in most years. As with solar assets, this is not unexpected given the relative immaturity of the sector and its high degree of subsidization. Among countries that produced both onshore and offshore wind electricity,[55] both had negative asset values in most years.[56] As with solar assets, wind electricity assets became more valuable (even if still negative) on a unit basis over time in all countries (Table 14).

Table 15 shows our projections for the market value of wind electricity assets in 2035 and the first year in which they are expected to have permanent positive values.[57] Of the 14 countries that produced onshore wind electricity,[58] 11 were projected to have positive onshore wind asset values by 2035.[59] In contrast, only two[60] of the 5 countries[61] that produced offshore wind electricity were projected to have positive asset values by 2035. Among countries expected to see positive onshore wind asset values, four likely already had positive values in 2018 or 2019 (Australia, Brazil, Spain and the United Kingdom). Canada was projected to do so in 2020. The remaining countries were projected to do so between 2024 and 2033. In the three countries where onshore wind assets were not projected to have positive values before 2035, the reason was a combination of relatively high production costs and relatively low spot prices in China and India, while in Turkey the issue is mainly one of low spot prices.

By 2035, the total value of wind electricity assets (onshore and offshore) across the countries studied was expected to be $1.7 trillion (essentially all attributable to onshore assets), about 40% of the expected value of solar PV assets in that year. Total wind electricity generation was expected to be 3.7 million GWh, or about 3.75 times what it was in 2017.[62] About half of the value of wind electricity assets in 2035 was expected to be found in China, in keeping with its projected share of wind generation (41%).

Table 16 and Table 17 present detailed breakdowns of costs, revenues and asset values associated with onshore and offshore wind assets in 2017. Onshore wind market asset values were negative in all countries in that year and social asset values were negative in 5 of 14 countries.[63] Weighted unit private production costs for onshore wind electricity were

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[54] Onshore and offshore wind assets.

[55] China, Germany, Japan, Spain, Sweden, the U.K. and the U.S.

[56] Onshore wind assets had positive market values in Turkey from 2005 to 2014, in the U.K. in 10 of the 17 years from 1998 to 2015 and in a handful of years (between 1 and 5) in Australia, Brazil, Canada, France, Germany, Italy, India, Spain, Turkey and the U.S. Offshore wind resources, on the other hand, had negative asset values in all countries and years.

[57] For the purposes of these projections, onshore and offshore wind assets were treated separately, as they are at quite different stages of their development and their evolutions are likely to differ.

[58] The Russian Federation did not produce meaningful quantities of wind electricity during the study period and was not included in this analysis.

[59] Only China, India, and Turkey were projected not to have positive onshore wind electricity asset values by 2035.

[60] Japan and the U.K.

[61] Offshore wind assets in Spain and the U.S. were not considered in this analysis because they each had just a few years of production during the period studied and we did not feel confident extrapolating on this basis.

[62] As explained in Text Box 2, we constrained our projection to align with the U.S. Energy Information Authority's 2019 international projection for wind electricity generation. Thus, we are confident that our projection is consistent with the plausible evolution of the wind electricity market. See the accompanying Excel database for details of our projections.

[63] Brazil, Canada, China, India and the US.

considerably lower than for offshore ($76,900/GWh compared to $153,000/GWh). Subsidy rates were also only about one tenth as much for onshore production as for offshore. The lower production costs and subsidies for onshore wind electricity explain why market asset values are expected to turn positive for onshore resources in most countries well before 2035 and result in considerable asset value, while only two countries are expected to see positive (but negligible) asset value for offshore wind electricity before 2035 .

Looking at rates of return to produced capital for onshore wind in Table 16, apparent rates of return were above normal in many countries[64], as would be expected in a highly subsidized industry. Among countries with higher than normal returns, Spain showed the greatest divergence from normal (+10%), followed by Italy (+7%) and the UK (+6%). Elsewhere, implicit rates were within 4% of normal. In countries with below normal apparent returns[65], the greatest divergence from normal was -3% (India). Unlike in the case of solar PV electricity assets, apparent returns to produce capital remained positive in all countries. These figures suggest that onshore electricity subsidy programs in 2017 were providing suitable levels of incentives in many countries (Spain, Italy and the U.K. arguably excepted) if “suitable” is taken to mean support sufficient to provide investment returns close enough to normal to encourage market entry but not so high as to provide excessive windfall returns.

In the case of offshore wind electricity (Table 17), apparent returns to produced capital in 2017 were slightly above normal (2% to 4%) in Germany, Japan, Spain and the U.K. In China, apparent returns were 7% below normal, suggesting that Chinese offshore producers may have received subsidies that were not captured in our results. In Sweden, apparent returns were 13% above normal, raising the possibility that Swedish offshore producers could have received a considerably lower price for their electricity while still providing plenty of financial incentive to them to engage in production. Of course, it may be that such elevated rates of return are required in order to attract investment in the Swedish offshore wind industry. It is not clear, however, why apparent rates of return in Germany, Japan, Spain and the U.K would be so much closer to normal, as the risks faced in offshore electricity production presumably do not vary that much from country to country.[66] Perhaps there are more non-price subsidies in those countries that would not be captured in our analysis than there are in Sweden. This deserves further study.

[64] Australia, France, Germany, Italy, Japan, Spain, Sweden, Turkey and the UK.

[65] Brazil, Canada, China, India and the U.S..

[66] One possible difference in Sweden versus other jurisdictions is wintertime temperatures and the risk of icing of wind turbines, which would certainly be great there than in, say, Spain or Japan, though not necessarily much greater than in Germany or the U.K.

Table 13 – Combined onshore and offshore wind electricity asset value, market resource rent

	Australia	Brazil	Canada	China	France	Germany	India	Italy	Japan	Spain	Sweden	Turkey	United Kingdom	United States
	million $ (2018 prices)													
1990							($228)	($8)		($3)			($55)	($5,413)
1991					($5)	($1,005)	($263)	($12)		($4)			($78)	($5,512)
1992			($19)		($5)	($1,671)	($254)	($35)		($3)			($285)	($5,375)
1993			($9)		($19)	($2,333)	($359)	($107)	($6)	($23)			($469)	($4,781)
1994	($12)		($17)		($15)	($3,539)	($284)	($117)	($16)	$31			($319)	($3,686)
1995	($8)		($14)		($14)	($5,595)	($792)	($115)	($23)	($101)			($440)	($3,860)
1996	($7)		($11)	($189)	($28)	($7,284)	($7,849)	($131)	($35)	($662)			($424)	($3,171)
1997	($7)		($9)	($556)	($29)	($8,498)	($7,916)	($456)	($47)	($1,193)			($410)	($3,141)
1998	($15)		($12)	($1,064)	($64)	($10,668)	($8,200)	($488)	($97)	($2,563)			$82	($3,835)
1999	($49)		($145)	($1,644)	($61)	($17,048)	($8,227)	($542)	($394)	($4,432)			($92)	($2,938)
2000	($204)	($231)	($82)	($2,122)	($132)	($24,151)	($6,803)	($1,006)	($1,101)	($5,077)			($187)	($1,591)
2001	($473)	($197)	($135)	($2,147)	($193)	($35,749)	($12,048)	($1,521)	($1,762)	($7,922)	($1,178)		($539)	($5,273)
2002	($592)	($169)	($142)	($2,357)	($355)	($46,472)	($10,491)	($1,509)	($2,467)	($9,547)	($1,110)		$30	($6,703)
2003	($989)	($185)	($101)	($2,598)	($481)	($48,464)	($15,466)	($1,327)	($3,895)	($6,241)	($1,110)		($758)	($5,349)
2004	($2,405)	($172)	($286)	($3,445)	($666)	($47,216)	($19,710)	($1,298)	($5,312)	($7,129)	($1,057)		$33	($851)
2005	($5,016)	($158)	$77	($4,659)	($1,506)	($36,140)	($18,391)	($1,932)	($8,930)	($3,087)	($1,051)	$125	($651)	$8,458
2006	($4,048)	($1,567)	($1,546)	($8,478)	($2,991)	($33,483)	($26,753)	$159	($14,289)	($5,338)	($506)	$120	$874	$7,168
2007	($5,848)	($219)	($2,358)	($15,518)	($3,244)	($39,011)	($26,817)	($342)	($11,404)	($19,709)	($1,963)	$697	$1,842	$6,247
2008	($7,051)	$1,171	($3,277)	($28,377)	$948	$21,458	($33,679)	$1,953	($12,460)	$15,637	($598)	$1,601	($387)	$24,482
2009	($8,539)	($3,815)	($3,589)	($54,724)	($9,269)	($46,329)	$2,808	($7,167)	($14,888)	($26,013)	($3,321)	$1,446	($3,926)	($64,325)
2010	($9,081)	($3,285)	($1,931)	($77,712)	($11,504)	($45,872)	($25,284)	($6,270)	($13,542)	($26,223)	($2,047)	$4,425	($8,708)	($45,704)
2011	($9,994)	($4,855)	($4,789)	($119,074)	($9,340)	($18,719)	($28,971)	($7,578)	($2,843)	($6,779)	($1,553)	$8,638	($3,436)	($58,851)
2012	($5,338)	($5,612)	($7,581)	($135,633)	($9,301)	($42,810)	($32,874)	($6,259)	($1,103)	($9,253)	($8,506)	$7,960	($17,806)	($130,330)
2013	($9,362)	($5,433)	($2,622)	($138,209)	($11,411)	($60,457)	($50,592)	($8,665)	($840)	($227)	($4,706)	$8,853	($10,011)	($54,470)
2014	($13,068)	($12,212)	($8,195)	($193,262)	($17,469)	($87,643)	($59,240)	($13,268)	($5,024)	($6,445)	($9,707)	$4,547	($25,026)	($2,436)
2015	($9,455)	($12,953)	($16,588)	($315,112)	($17,741)	($123,024)	($73,472)	($19,125)	($11,703)	($7,942)	($14,606)	($2,635)	($25,657)	($104,795)
2016	($2,293)	($35,441)	($10,070)	($335,419)	($23,098)	($147,915)	($90,010)	($19,379)	($12,828)	($21,351)	($13,390)	($4,929)	($42,967)	($140,528)
2017	($2,891)	($5,662)	($13,496)	($339,657)	($20,273)	($136,807)	($79,513)	($13,877)	($11,204)	($857)	($10,517)	($7,116)	($48,771)	($105,896)

Source: Author's calculations.

Table 14 – Combined onshore and offshore wind electricity asset value per unit of electricity generated, market resource rent

	Australia	Brazil	Canada	China	France	Germany	India	Italy	Japan	Spain	Sweden	Turkey	United Kingdom	United States
	thousand $ per GWh (2018 prices)													
1990							-$7,115	-$3,821		-$452	-$8,910		-$6,116	-$1,765
1991					-$2,753	-$4,675	-$6,751	-$4,151		-$421	-$5,632		-$7,088	-$1,806
1992			-$566		-$3,043	-$5,743	-$4,888	-$17,743		-$26	-$3,344		-$7,130	-$1,843
1993			-$232		-$9,383	-$3,461	-$6,299	-$26,821	-$3,183	-$199	-$3,069		-$2,153	-$1,566
1994	-$3,007		-$292		-$2,965	-$2,478	-$1,560	-$16,705	-$8,020	$179	-$2,571		-$932	-$1,058
1995	-$1,114		-$243		-$2,704	-$3,268	-$1,590	-$12,745	-$7,650	-$375	-$3,018		-$1,125	-$1,208
1996	-$966		-$182	-$4,536	-$4,002	-$3,505	-$8,476	-$3,974	-$17,655	-$1,818	-$3,165		-$870	-$930
1997	-$953		-$149	-$4,457	-$2,667	-$2,801	-$7,633	-$3,866	-$46,584	-$1,608	-$2,426		-$614	-$965
1998	-$1,847		-$194	-$4,261	-$3,391	-$2,323	-$7,276	-$2,113	-$13,876	-$1,896	-$2,013		$93	-$1,271
1999	-$1,767		-$885	-$3,951	-$1,644	-$3,084	-$5,452	-$1,345	-$10,379	-$1,615	-$1,944		-$108	-$612
2000	-$3,524	-$192,387	-$312	-$3,451	-$2,741	-$2,582	-$3,364	-$1,787	-$10,197	-$1,074	-$1,644		-$197	-$282
2001	-$2,252	-$5,608	-$400	-$2,866	-$1,471	-$3,419	-$7,839	-$1,290	-$7,021	-$1,172	-$2,444		-$561	-$775
2002	-$1,626	-$2,764	-$347	-$2,700	-$1,336	-$2,931	-$4,756	-$1,075	-$5,959	-$1,022	-$1,825		$24	-$641
2003	-$1,407	-$3,021	-$123	-$2,501	-$1,240	-$2,590	-$6,064	-$910	-$4,715	-$517	-$1,635		-$590	-$473
2004	-$3,411	-$2,817	-$300	-$2,587	-$1,119	-$1,851	-$5,024	-$703	-$4,077	-$454	-$1,244		$17	-$60
2005	-$5,668	-$1,700	$49	-$2,912	-$1,564	-$1,327	-$3,307	-$824	-$5,100	-$146	-$1,123	$2,125	-$224	$473
2006	-$2,363	-$6,605	-$625	-$3,028	-$1,370	-$1,090	-$3,892	$54	-$6,594	-$229	-$513	$949	$207	$269
2007	-$2,240	-$330	-$784	-$2,722	-$797	-$982	-$2,857	-$85	-$4,363	-$715	-$1,372	$1,962	$349	$181
2008	-$2,280	$990	-$865	$0	$166	$529	-$2,846	$402	-$4,235	$475	-$300	$1,890	-$54	$440
2009	-$2,233	-$3,081	-$540	-$2,198	-$1,172	-$1,199	$192	-$1,095	-$4,121	-$682	-$1,336	$967	-$423	-$867
2010	-$1,797	-$1,509	-$221	-$1,584	-$1,157	-$1,214	-$1,570	-$687	-$3,371	-$592	-$584	$1,517	-$847	-$480
2011	-$1,642	-$1,795	-$470	-$1,662	-$772	-$383	-$1,484	-$769	-$608	-$158	-$256	$1,829	-$215	-$487
2012	-$766	-$1,111	-$670	-$1,317	-$621	-$845	-$1,425	-$467	-$228	-$187	-$1,187	$1,358	-$897	-$918
2013	-$1,176	-$826	-$146	-$997	-$709	-$1,169	-$2,053	-$582	-$162	-$4	-$478	$1,171	-$353	-$321
2014	-$1,275	-$1,000	-$364	-$1,206	-$1,009	-$1,528	-$2,175	-$874	-$963	-$124	-$864	$534	-$783	-$13
2015	-$825	-$599	-$627	-$1,694	-$832	-$1,553	-$2,305	-$1,288	-$2,097	-$161	-$898	-$226	-$637	-$543
2016	-$188	-$1,058	-$331	-$1,384	-$1,076	-$1,882	-$2,481	-$1,096	-$2,080	-$437	-$865	-$318	-$1,153	-$612
2017	-$230	-$134	-$469	-$1,114	-$820	-$1,294	-$1,668	-$782	-$1,726	-$17	-$597	-$397	-$975	-$412

Source: Author's calculations.

Table 15 - Projected value of onshore and offshore wind electricity assets

		Australia	Brazil	Canada	China	France	Germany	India	Italy	Japan	Spain	Sweden	Turkey	United Kingdom	United States
		billion $ (2018 prices)													
Onshore wind	First year of positive rent	2018	2018	2020	post 2035	2025	2033	post 2035	2025	2025	2018	2028	post 2035	2019	2024
Onshore wind	Asset value in 2035	$71	$90	$141	$800	$88	$38	-$18	$38	$27	$114	$15	-$25	$117	$226
Offshore wind	First year of positive rent	n/a	n/a	n/a	post 2035	n/a	post 2035	n/a	n/a	2033	*See note*	post 2035	n/a	2032	*See note*
Offshore wind	Asset value in 2035	n/a	n/a	n/a	-$28	n/a	-$54	n/a	n/a	$0.2	-	-$0.1	n/a	$27	-

Source: Author's calculations.
Note: Countries with less 5 years or less of offshore wind production prior to 2017 were not projected.

Table 16 – Details of costs, revenues and asset values, onshore wind electricity assets, 2017

	Produced capital costs per GWh , normal return to capital (A)	O&M costs per GWh (B)	Subsidies per GWh (C)	Social costs per GWh, normal return to capital (D = A+B+C)	Private costs per GWh, normal return to capital (E = A+B)	Revenues per GWh (F)	Net social revenues per GWh, normal return to capital (G = F-D)	Net private revenues per GWh, normal return to capital (H = F-E)	Generation (GWh) (I)	Market asset value, normal return to capital (J = G*I/0.04)	Social asset value, normal return to capital (K = H*I/0.04)	Normal private return to produced capital (L)	Apparent private return to produced capital (M)
	thousand $ (2018 prices) unless otherwise indicated												
Australia	$69.2	$11.3	$38.9	$119.4	$80.5	$110.2	-$9.2	$29.7	12,597	-$2,891,053	$9,367,046	4%	8%
Brazil	$64.4	$6.0	$0.0	$70.4	$70.4	$65.0	-$5.3	-$5.3	42,391	-$5,661,671	-$5,661,671	8%	7%
Canada	$66.3	$10.1	$0.0	$76.4	$76.4	$57.7	-$18.8	-$18.8	28,775	-$13,495,577	-$13,495,577	4%	2%
China	$87.5	$7.3	$29.0	$123.8	$94.8	$82.1	-$41.7	-$12.7	299,838	-$312,495,743	-$94,964,968	10%	8%
France	$71.8	$11.1	$56.5	$139.5	$83.0	$106.7	-$32.8	$23.7	24,711	-$20,273,139	$14,653,800	4%	7%
Germany	$69.6	$12.1	$58.7	$140.4	$81.7	$98.1	-$42.3	$16.4	88,018	-$93,137,410	$36,049,005	4%	6%
India	$106.4	$9.9	$49.1	$165.4	$116.3	$98.7	-$66.7	-$17.6	47,670	-$79,512,644	-$20,967,523	10%	7%
Italy	$79.8	$13.4	$96.5	$189.6	$93.2	$158.4	-$31.3	$65.2	17,742	-$13,876,557	$28,904,309	4%	11%
Japan	$130.5	$23.7	$100.5	$254.6	$154.1	$187.0	-$67.6	$32.9	6,385	-$10,787,594	$5,250,657	4%	6%
Spain	$50.7	$9.8	$71.1	$131.6	$60.5	$130.9	-$0.7	$70.4	49,116	-$820,613	$86,462,125	4%	14%
Sweden	$51.3	$7.6	$31.8	$90.6	$58.8	$67.4	-$23.2	$8.6	16,939	-$9,817,940	$3,643,397	4%	5%
Turkey	$62.0	$6.0	$20.8	$88.9	$68.1	$73.0	-$15.9	$4.9	17,904	-$7,116,045	$2,202,316	8%	9%
United Kingdom	$61.3	$9.4	$53.0	$123.7	$70.7	$113.8	-$9.8	$43.2	29,088	-$7,135,906	$31,382,047	4%	10%
USA	$43.1	$7.0	$1.1	$51.2	$50.1	$36.6	-$14.6	-$13.5	257,147	-$94,150,923	-$86,994,170	4%	2%

Source: Author's calculations.

Table 17 – Details of costs, revenues and asset values, offshore wind electricity assets, 2017

	Produced capital costs per GWh , normal return to capital (A)	O&M costs per GWh (B)	Subsidies per GWh (C)	Social costs per GWh, normal return to capital (D = A+B+C)	Private costs per GWh, normal return to capital (E = A+B)	Revenues per GWh (F)	Net social revenues per GWh, normal return to capital (G = F-D)	Net private revenues per GWh, normal return to capital (H = F-E)	Generation (GWh) (I)	Market asset value, normal return to capital (J = G*I/0.04)	Social asset value, normal return to capital (K = H*I/0.04)	Normal private return to produced capital (L)	Apparent private return to produced capital (M)
	thousand $ (2018 prices) unless otherwise indicated												
China	$228.7	$34.3	$89.4	$352.4	$263.0	$142.5	-$209.8	-$120.4	5,177	-$27,161,407	-$15,590,165	10%	3%
Germany	$108.9	$29.3	$138.3	$276.5	$138.2	$177.7	-$98.8	$39.5	17,675	-$43,669,982	$17,446,069	4%	7%
Japan	$188.0	$57.1	$234.1	$479.1	$245.1	$320.6	-$158.5	$75.6	105	-$416,081	$198,360	4%	8%
Spain	$148.2	$43.6	$160.2	$352.1	$191.9	$220.0	-$132.1	$28.1	11	-$36,323	$7,731	4%	6%
Sweden	$57.1	$20.3	$135.4	$212.8	$77.4	$171.1	-$41.8	$93.7	670	-$699,324	$1,569,088	4%	17%
United Kingdom	$109.0	$31.5	$118.2	$258.7	$140.5	$179.1	-$79.6	$38.6	20,916	-$41,635,036	$20,183,376	4%	7%

Source: Author's calculations.

5 Discussion of results and future research agenda

Valuing renewable energy assets can provide vital information to policy-makers charged with ensuring the sustainability of development. Such valuation is complicated by the nascent state of renewable energy markets and technologies.

5.1 Capital cost and electricity price data

As a general statement, data for the valuation of renewable energy assets are limited both in terms of availability and quality. Good data are available from the UN data *Energy Statistics* database and the IRENA *Trends in Renewable Energy* database for annual installed generating capacity and capacity additions as well as for electricity generation, especially after 2000. The same cannot be said for data on prices of renewable electricity; on the costs of the produced capital (solar panels, wind turbines, hydro dams, etc.) used to generate renewable electricity; or on the costs to operate and maintain that infrastructure. Data on all of these suffer from gaps and uncertainties. While every effort was made to compile the best quality database for this study, we acknowledge that improvements could be made.

Given that our approach to estimating O&M costs assumed they were a fixed share of produced capital costs, it is particularly important that the latter be as accurate as possible. Additional effort to improve our capital cost estimates would therefore be worthwhile. In particular, improving the accuracy of the investment cost data used to estimate capital stocks (see Section 4.2.3) should be seen as a priority for further research. Of particular importance in this regard would be improving the investment cost used for hydroelectric generating infrastructure in 1990. This is discussed further below in the sub-section on hydroelectric assets.

Improving our estimates of electricity prices – both spot prices and prices for renewable electricity – would also be worthwhile, though prices are less likely to be inaccurate than capital costs since the former are more easily observed than the latter. Again, we pursue this point further in the sub-sections below.

5.2 Hydroelectric assets

We found hydroelectric assets to have considerable value in every country studied. This provides empirical evidence confirming the theoretical notion that resource rent should arise in mature renewable electricity markets. Hydroelectric generation has taken place on an industrial scale with little change in approach[67] since the first half of the 20th century in developed countries and since at least the 1970s in the developing world. Given this long history, and the relative simplicity of the technologies involved, the emergence of large and positive hydroelectric rents was expected. That this proved to be the case is reassuring in terms of confirming the underlying theory but also in terms of validating the reliability of the data and RVM approach used in our analysis. At the same time, as discussed earlier (Section 3), there is reason to be cautious about the use of RVM to value renewable energy assets; namely, the fact that electricity markets cannot necessarily be assumed to be in long-run equilibrium due to government intervention to control prices through implicit and explicit subsidies on production and consumption. Thus, we cannot take the fact that our valuation results for hydroelectric

[67] Of course, improvements have been made in hydraulic turbine, reservoir and dam design, but the essential approach of holding water behind a dam and releasing it slowly to spin turbines attached to electricity generators remains the same has it has been for decades.

assets cohere with expectations as proof that the RVM is an appropriate valuation approach but only as evidence that it might be.

Unfortunately, “very little has been written…on how to measure economic rent from hydroelectric development” (Rothman, 2000) in spite of the fact that hydroelectric resources account for more of the installed global capacity of renewable electricity than all other sources combined (IEA, 2017). As a result, there are few other studies against which our results can be compared. Those that are relevant pertain mainly to Canada.

Two major studies of the value of Canadian hydroelectric resources were undertaken in the 1980s (Bernard, Bridges and Scott, 1982 and Zuker and Jenkins, 1984). This was a time when Canada’s electricity markets were dominated by large, publicly owned utilities producing and selling power in highly regulated markets. Given this, it is not surprising that neither research team adopted the RVM approach. Both the price at which electricity was sold in Canada at the time and the cost structures of the public utilities that produced it were subject to substantial market intervention by governments. Instead, both studies adopted the least-cost alternative approach (see Footnote 12).

In a similar vein, Gillen and Wen (2000) proposed a method for estimating hydroelectric resource rent in the Canadian province of Ontario (which holds a substantial share of Canada’s hydroelectric resources) using the cost of electricity imports as the least-cost alternative. Gillen and Wen’s rent estimates suggest that Ontario’s hydroelectric asset was worth about $CAN33 billion in 1995[68] ($37 billion in 2018 $US). The province’s installed hydroelectric capacity grew by approximately 17% between 1995 and 2017[69], suggesting a value of around $43 billion for its hydroelectric asset in 2017. Ontario held 11% of Canada’s installed hydroelectric generating capacity in 2017[70], suggesting a rough estimate of $378 billion for Canada’s hydroelectricity asset in that year. This figure compares reasonably well with our estimate of $424 billion based on RVM. Gillen and Wen note that their rent estimate is similar to that found by Zuker and Jenkins but considerably more than Bernard, Bridges and Scott’s value.

In a study for the U.K., the United Kingdom Office for National Statistics prepared an estimate of the value of the United Kingdom’s hydroelectricity asset using the RVM (UK ONS, 2016). Data on revenues and costs were sourced from annual corporate reports and the asset was valued using a 3% to 3.5% discount rate[71] and an assumed lifetime of 50 years (which differs from our approach of assuming infinite lifetimes for renewable energy assets). The estimated value of the U.K.’s hydroelectric asset in 2014 was £9.2 billion ($16.5 billion in 2018 $US), which is about double our estimate of $8.5 billion. Further investigation would be required to explain the discrepancy in the two estimates.

Though the results of these studies provide some evidence that the experiment hydroelectric assets values compiled here are at least of the right order of magnitude, there remain several areas where improvements could be made.

- **Hydroelectricity prices** – Our assumption that hydroelectricity producers are remunerated at the average annual electricity price from spot markets requires

[68] Assuming a 4% discount rate.

[69] Author’s calculations based on Statistics Canada installed hydro generation capacity data.

[70] Statistics Canada, *Installed plants, annual generating capacity by type of electricity generation*, Table 25-10-0022-01. Available from https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510002201.

[71] A 3.5% discount rate was applied during the first 30 years in the net present value calculation and a 3% discount rate thereafter up to 50 years.

validation.[72] Hydroelectric power plants have the ability to meet both base load and intermediate/peaking power load, so their output is likely remunerated at different rates depending on how and when it is used. Hydroelectric producers may sell some output through long-term power purchase agreements at fixed prices below average spot prices. It is also the case that regulated markets for electricity did not exist in many countries until relatively recently. Due to a lack of price data for prior years, we have assumed nonetheless that spot prices applied to years when markets were actually regulated, likely overstating prices in those years.

- **Validity of the RVM** – Though our results compare reasonably well with the few comparable existing studies, questions remain regarding the validity of the RVM for valuation of hydroelectric assets. This is especially the case in countries where electricity markets remain regulated, like China, since long-run equilibrium, which is one of the pre-conditions for use of the RVM, cannot be assumed in regulated markets. It would be worth undertaking least-cost alternative studies of the value of hydroelectric assets in a few countries – Canada and China would be good candidates – for comparison with our RVM-based results. If the comparison did not reveal major differences in results, that would provide further confidence that the RVM method yields acceptable results.
- **Treatment of subsidies** – We have assumed that hydroelectric generation is subsidy free because explicit production-based subsidies (like feed-in tariffs) do not generally apply. This does not mean that implicit subsidies to either producers or consumers do not exist in the form of, for example, reduced borrowing costs, debt forgiveness or government-imposed price controls. It is, on the contrary, likely that such subsidies existed in the 1990s and early 2000s before electricity market deregulation began in earnest in many countries. They may well persist today as well, especially where deregulation has not advanced. Further investigation would be warranted to determine the extent to which implicit hydroelectricity subsidies exist and how these might impact the market value of the assets.
- **Initial produced capital stock estimates and depreciation profiles** – The approach we used to estimating the value of the 1990 stock of produce hydroelectric generating infrastructure is simplistic and could certainly be improved upon. This is especially important in the U.S. and most European countries where a high percentage of the 2017 installed generating capacity was already in place in 1990. Any inaccuracies in our estimated 1990 produced capital stock estimate for these countries will propagate through the entire time series to 2017. It is less of a concern in, for example, China and Turkey, where the majority of investment came after 1990 and the accuracy of the 2017 capital stock estimate will mainly be determined by the accuracy of the post-1990 investments flows. We believe the latter to be relatively good. One possibility to improve upon the method we have applied would be to request 1990 capital stock estimates from national statistical offices in countries that are large producers and that also had large 1990 stocks relative to 2017 (Brazil, Canada and the U.S. are three countries that match this profile). With their detailed knowledge of investment and capital stock data, experts in statistical offices would be well placed make such estimates.

  A related matter is the depreciation profile applied to the produced capital stock. We have assumed the simplest of all profiles: constant linear depreciation over the assumed 50-year lifetime of the generating infrastructure. Several aspects of this deserve further investigation. Is the assumed 50-year lifetime reasonable in all cases? Do hydroelectric reservoirs and dams typicially last longer than this, for example? Should all infrastructure

[72] Recall that we used a specific hydroelectric price for Chinese production, so this concern does not apply to that country.

be assumed to depreciate linearly? Again, this may be an area where national statistical office expertise could be valuable in refining the approach.

- **Operation and maintenance costs** – For lack of actual O&M data, we assumed that O&M costs are a constant share of the produced capital stock and that these shares apply equally across countries. It would be preferable to have directly observed data on O&M costs, as they can be sizable, particularly in countries with low hydroelectricity capacity factors. Average 1990-2017 O&M costs as a share of hydroelectricity revenues in Canada, which had the highest average capacity factor of any country (0.57), were 6.5%. In Australia, where the average capacity factor was just 0.20, O&M costs as a share of revenues averaged 33%. This may not be a realistic representation of the costs of operating and maintaining Australia's hydroelectric generation infrastructure, which is likely in operation much less of the time on average than Canada's. Further investigation to see whether country-specific and, ideally, directly observed O&M estimates are available would be worthwhile.
- **Pumped storage generation** – Pumped storage hydroelectric generation is a technology in which two reservoirs are required, one above the generating station in which water is stored before it is used for electricity production and another below the station to capture water that has already passed through the generating turbines. Water is pumped from the lower to the upper reservoir at times (usually overnight) when demand for electricity is low and excess power is available at low prices from the national grid. In this way, the same water can be used many times to produce hydroelectricity. Whether such production can be considered renewable is questionable, however, since it is not nature that renews the water in the upper reservoir but the economy, the electricity used to pump the water to the upper reservoir must come from a technology other than hydro. This will be whatever technology is used to meet base electricity load in the economy, often coal and/or nuclear production. We included pumped storage as part of the hydroelectric asset in this first experimental effort. Consideration should be given to removing it in future efforts if it is agreed that pumped storage hydro should not be considered a renewable electricity source.

5.3 Solar electricity assets

We found solar electricity assets to have negative market values in every country and year studied. Even social asset values were mostly negative for solar electricity, due to its exceptionally high private production cost in many countries. These findings were expected, given that wind electricity is a nascent technology and markets remain in a state of flux. As discussed in Section 3, rents – with the possible exception of short-run Marshallian/quasi positive rents – are not expected to arise under such conditions. Though our findings are coherent with expectations based on economic theory, improvements could be made to our methodology that would provide greater confidence we have not missed any potential positive values for solar electricity assets.

- **Validity of the RVM** – Even more than in the case of hydroelectricity assets, the validity of the RVM approach can be called into question in the case of solar electricity. If hydroelectric markets are sufficiently evolved in most countries to be considered in something like long-run equilibrium, the same cannot be said of solar electricity markets. These arguably remain far from equilibrium in all countries. It would, therefore, be worth undertaking least-cost alternative valuation studies of solar electricity in a few countries to validate our finding that rents do not arise anywhere.
- **Treatment of subsidies** – We have assumed that the value of explicit subsidies on solar electricity production can be estimated as the difference between the rates at

which solar electricity producers are remunerated (for example, through feed-in tariff regimes) and average electricity spot prices. The validity of this assumption rests on the notion that solar electricity producers would receive the average spot price for their output in the absence of subsidies. Given that solar electricity is essentially non-dispatchable (that is, it cannot be increased or decreased at will by producers) and that it is available only during daylight hours when spot are electricity prices are highest means that this assumption is reasonable. That said, it likely results in some overvaluation of solar electricity subsidies, however, since average spot prices will be lower than spot prices during the daytime when solar hydroelectric generation is produced. Further investigation to determine the degree to which such overvaluation might occur would be worthwhile, since lower implicit subsidies would increase the market value of solar assets. It is doubtful that values would turn positive in many, if any, countries, however, since private production costs are very high for solar electricity.

- As with hydroelectricity assets, it may be the case that implicit subsidies exist for solar electricity producers. These could include waiver of grid connection fees, concessionary loans and favourable capital consumption allowances on corporate taxes. The possibility that these exist and their effect on solar electricity asset values would be worth investigating.
- **Depreciation profiles and operation and maintenance costs** – As with hydroelectricity assets, our approach to estimating depreciation of produced capital and O&M costs for solar electricity deserves further investigation.

5.4 Wind electricity assets

We found wind electricity assets to have mostly negative asset values from 1990-2017, though a few exceptions were noted, particularly for onshore wind assets in the U.K and Turkey. As with solar electricity assets, these findings were expected. Wind electricity is also a nascent technology and its markets too remain in a state of flux. Marshallian/quasi rents may explain why there is some evidence of rents associated with onshore resources in a few countries, as early movers in the onshore wind electricity industry may have had opportunities to earn quasi-rents by capturing prime generating sites. The fact that rents arose in some countries for onshore wind electricity but not at all for solar electricity is explained by the significant difference in their private production costs. As discussed in Section 4.3.3, solar electricity is much more expensive to produce on average than onshore wind electricity. Offshore wind rents, for their part, were negative everywhere, as would be expected given that offshore production began only relatively recently and involves high costs and risks.

Evidence supporting our findings is provided by the same U.K. study mentioned earlier (UK ONS, 2016). Using an RVM approach in which subsidies were not accounted for (meaning the asset values were social rather than market values), it found the value of U.K. wind electricity assets in 2014 to be £45.3 billion, or $81.6 billion in 2018 $US.[73] This compares reasonably well with our estimated social asset value of $55.3 billion for the U.K.'s combined onshore and offshore wind electricity assets. As in the case of hydroelectric assets, further investigation would be required to determine why our estimate is lower than the UK ONS estimate.

Further evidence supporting our findings come from a Statistics Netherlands (2011) study that estimated the value of the Dutch wind electricity asset using an RVM approach. Both market and social asset values were estimated using a nominal discount rate of 6%. The authors found

[73] As with hydroelectric assets, the U.K. study assumed a 50-year asset life for wind electricity assets (as opposed to our assumed infinite lifetime) and discount rates of 3%-3.5%.

the market value of the Dutch wind electricity asset to be negative in every year from 1990 to 2010. Its social value, in contrast, was consistently positive after 2004. They estimated it to be worth more than 5 billion euros in 2010. Though our study did not consider the Netherlands, these results are largely consistent with our findings for other European countries: little or no market value associated with wind electricity assets in any year, but positive social values on the order of $10 billion to $100 billion (depending on the country) emerging consistently in the 2000s.

As with hydroelectricity and solar electricity assets, our results for wind electricity assets could be improved with further research. The same issues mentioned above with respect to solar electricity are valid for wind electricity. The concern with regard to the value of explicit subsidies is the opposite, however; explicit wind electricity subsidies are likely to be underestimated by our approach, since wind producers would be more likely to be remunerated at a level below the average spot price rather than above if they were to stop receiving a subsidized price for their electricity. The concern with the validity of the RVM applies to wind electricity assets as well, but much more so to offshore than onshore assets, since the former are early in their development with high and uncertain costs.

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Annex – Social asset value estimates

Table A1 - Combined solar PV and CSP electricity asset value, social resource rent

	Australia	Brazil	Canada	China	France	Germany	India	Italy	Japan	Spain	Sweden	Turkey	United Kingdom	United States
	million $ (2018 prices)													
1990								($17)	($235)	$121				($7,103)
1991						($18)		($22)	($123)	$132				($5,821)
1992			$11		($25)	($26)		($13)	($710)	$156				($7,158)
1993	($31)		$27		($25)	($109)		($108)	($1,388)	$93				($5,771)
1994	($37)		($2)		($23)	($72)		($150)	($2,318)	$85				($5,893)
1995	($38)		$16		($20)	($163)		($160)	($3,606)	$158				($5,698)
1996	($29)		$25		($41)	($240)		($123)	($5,666)	$113				($4,966)
1997	($48)		$15		($46)	($414)		($141)	($8,685)	$88				($4,929)
1998	($85)		$30		($66)	($283)		($144)	($13,046)	$65				($5,538)
1999	($92)		$54		($86)	($696)		($129)	($19,480)	$92				($10,233)
2000	($114)		$78	($1,181)	($63)	($1,227)		($159)	($29,838)	($223)	($41)			($14,614)
2001	($162)		$68	($1,270)	($46)	($2,010)	($143)	($166)	($32,052)	($265)	($39)		$4	($14,818)
2002	($181)		$93	($1,722)	($46)	($1,930)	($161)	($167)	($36,968)	($329)	($37)		$1	($15,205)
2003	($122)		$116	($1,897)	($31)	($2,165)	($169)	($161)	($41,494)	($365)	($48)		($66)	($18,889)
2004	($73)		($63)	($2,038)	($44)	($7,032)	($156)	($146)	($46,015)	($493)	($45)		($94)	($18,482)
2005	($28)		($10)	($3,343)	($37)	($4,327)	($192)	($155)	($50,363)	($510)	($43)	$1	($124)	($18,665)
2006	($32)		$43	($3,540)	($33)	$5,051	($212)	($266)	($54,046)	($918)	($52)	$1	($161)	($21,017)
2007	$126		$117	($3,996)	($71)	$12,109	($319)	($1,171)	($55,043)	($1,108)	($60)	$9	($198)	($22,693)
2008	$203		$242	($4,550)	($302)	$23,994	($339)	($3,817)	($53,095)	($12,118)	($72)	$14	($260)	($20,112)
2009	($2,232)		$991	($6,519)	$12	$18,850	($511)	($6,092)	($53,504)	$23,854	($74)	$10	($307)	($22,635)
2010	($6,775)	($44)	$561	($13,616)	($704)	$42,583	($734)	($14,768)	($57,424)	$22,105	($78)	$18	($1,098)	($23,010)
2011	($7,918)	($37)	$1,693	($34,093)	($2,020)	$120,483	($4,681)	$28,382	($54,894)	$43,274	($77)	$16	($9,614)	($30,046)
2012	($7,448)	($43)	$2,696	($58,822)	$1,537	$121,780	($6,282)	($69,102)	($52,422)	$49,717	($129)	$33	($7,958)	($32,501)
2013	($13,181)	($67)	$5,558	($123,447)	$7,504	$134,014	($8,956)	($53,540)	($61,081)	$66,866	($165)	$52	($9,539)	$22,230
2014	($14,936)	($127)	($1,591)	($118,673)	$40,310	$169,608	($20,734)	($47,117)	($56,506)	$78,051	($204)	($172)	($8,799)	($96,749)
2015	($32,610)	($231)	($1,638)	($151,930)	$28,668	$112,099	($23,054)	($60,093)	($73,586)	$54,050	($283)	($601)	($5,105)	($99,224)
2016	($32,230)	($708)	($4,068)	($209,269)	$38,911	$95,220	($33,224)	($60,108)	($72,364)	$54,254	($304)	($66)	($1,990)	($120,593)
2017	($29,319)	($6,696)	($6,402)	($278,201)	$50,801	$101,992	($52,497)	($44,380)	($91,198)	$67,595	($766)	($7,219)	($547)	($104,486)

Source: Author's calculations.

Table A2 - Combined solar PV and CSP electricity asset value per unit of electricity generated, social resource rent

	Australia	Brazil	Canada	China	France	Germany	India	Italy	Japan	Spain	Sweden	Turkey	United Kingdom	United States
1990								-$4,293	-$3,500	$13,411				-$10,665
1991						-$18,119		-$4,305	-$1,660	$12,006				-$7,444
1992			$5,424		-$25,084	-$6,432		-$1,419	-$8,771	$12,967	-$11,143			-$9,556
1993	-$2,802		$9,137		-$24,812	-$36,180		-$9,810	-$15,598	$7,153	-$10,999			-$6,405
1994	-$2,829		-$777		-$22,990	-$10,295		-$13,606	-$24,147	$5,697	-$10,567			-$7,117
1995	-$2,350		$4,051		-$19,532	-$23,339		-$12,276	-$34,015	$7,906	-$23,585			-$6,882
1996	-$1,546		$4,146		-$40,813	-$19,965		-$8,769	-$46,442	$6,301	-$22,769			-$5,481
1997	-$2,076		$2,158		-$22,972	-$22,998		-$9,417	-$58,290	$4,634	-$22,162			-$5,495
1998	-$3,049		$3,015		-$32,858	-$8,075		-$8,991	-$69,028	$2,975	-$21,370			-$6,222
1999	-$2,701		$4,119		-$42,946	-$23,199		-$7,571	-$76,692	$3,689	-$34,316			-$14,852
2000	-$2,990		$4,875	-$31,838	-$12,048	-$20,448		-$8,811	-$83,579	-$15,912	-$29,005			-$79,857
2001	-$3,684		$3,597	-$29,470	-$7,487	-$17,326	-$19,083	-$8,721	-$58,596	-$15,605	-$25,918		$2,362	-$67,357
2002	-$3,615		$4,244	-$25,401	-$6,500	-$10,265	-$17,729	-$7,946	-$57,403	-$18,284	-$21,667		$268	-$58,258
2003	-$2,111		$5,027	-$23,364	-$3,924	-$6,911	-$15,919	-$6,707	-$48,361	-$18,275	-$26,773		-$22,717	-$22,274
2004	-$1,072		-$4,830	-$21,778	-$5,253	-$12,634	-$14,898	-$5,025	-$41,158	-$20,787	-$22,734		-$23,497	-$19,153
2005	-$357		-$608	-$24,381	-$3,525	-$3,374	-$12,287	-$5,013	-$35,467	-$10,624	-$20,617	$436	-$15,064	-$16,665
2006	-$354		$2,034	-$22,822	-$2,697	$2,275	-$16,270	-$7,589	-$31,404	-$6,721	-$21,482	$329	-$15,085	-$16,330
2007	$1,201		$4,509	-$20,878	-$4,044	$3,938	-$9,242	-$30,027	-$27,912	-$2,136	-$19,472	$2,001	-$14,145	-$13,556
2008	$1,649		$6,907	-$19,371	-$7,242	$5,429	-$9,075	-$19,778	-$24,068	-$4,700	-$18,068	$2,566	-$15,301	-$9,609
2009	-$14,309		$9,089	-$18,895	$67	$2,863	-$11,110	-$9,005	-$20,137	$3,934	-$10,580	$1,366	-$15,338	-$9,000
2010	-$17,552	-$44,471	$2,198	-$18,675	-$1,136	$3,631	-$11,279	-$7,749	-$16,208	$3,076	-$9,128	$2,143	-$27,254	-$5,837
2011	-$5,704	-$14,613	$2,960	-$17,065	-$866	$6,148	-$14,945	$2,629	-$11,344	$4,604	-$6,981	$1,635	-$39,465	-$4,834
2012	-$3,208	-$6,256	$3,060	-$13,394	$347	$4,616	-$6,408	-$3,664	-$7,927	$4,154	-$6,792	$1,872	-$5,878	-$3,204
2013	-$3,796	-$3,613	$3,708	-$14,030	$1,445	$4,322	-$5,063	-$2,480	-$4,742	$5,106	-$4,716	$1,991	-$4,745	$1,401
2014	-$3,728	-$2,069	-$750	-$4,995	$6,308	$4,704	-$5,992	-$2,112	-$2,462	$5,709	-$4,348	-$9,908	-$2,170	-$3,755
2015	-$6,497	-$2,922	-$566	-$3,800	$3,699	$2,895	-$3,636	-$2,619	-$2,114	$3,900	-$2,922	-$3,095	-$678	-$2,784
2016	-$5,194	-$5,102	-$1,246	-$3,083	$4,495	$2,499	-$3,151	-$2,719	-$1,581	$3,977	-$2,129	-$63	-$191	-$2,396
2017	-$3,633	-$6,712	-$1,792	-$2,352	$5,307	$2,589	-$2,839	-$1,821	-$1,656	$4,695	-$3,329	-$2,499	-$47	-$1,472

Source: Author's calculations.

Table A3 – Combined onshore and offshore wind electricity asset value, social resource rent

	Australia	Brazil	Canada	China	France	Germany	India	Italy	Japan	Spain	Sweden	Turkey	United Kingdom	United States
	million $ (2018 prices)													
1990							$98	$6		$17			($38)	$10,760
1991					($2)	($389)	$42	$8		$26			($58)	$10,582
1992			$94		($2)	($785)	$103	($22)		$362			($212)	$10,012
1993			$115		($15)	($394)	($26)	($86)	($0)	$308			($127)	$11,324
1994	($1)		$159		($6)	$647	$750	($81)	($9)	$505			$229	$14,687
1995	$12		$161		($4)	$88	$1,944	($69)	($12)	$684			$206	$12,999
1996	$14		$173	($109)	($14)	($715)	($3,193)	$47	($29)	$381			$372	$14,817
1997	$13		$172	($317)	($11)	($176)	($2,828)	$122	($44)	$645			$733	$14,024
1998	$4		$158	($585)	($32)	$1,748	($3,334)	$622	($78)	$720			$1,602	$12,085
1999	$17		$303	($845)	($1)	($2,719)	($1,983)	$1,308	($277)	$1,945			$1,347	$22,392
2000	($87)	($229)	$640	($942)	($65)	($5,523)	$1,213	$1,234	($750)	$4,443			$1,311	$28,212
2001	($106)	($144)	$735	($709)	($15)	($16,188)	($6,245)	$3,028	($1,038)	$5,278	($685)		$907	$30,687
2002	$58	($95)	$863	($681)	$26	($16,258)	($2,408)	$4,211	($1,309)	$9,715	($451)		$1,992	$46,108
2003	$461	($114)	$2,136	($603)	$184	($10,488)	($5,712)	$5,778	($1,392)	$23,542	($252)		$1,456	$37,578
2004	($807)	($98)	$2,546	($888)	$335	$9,062	($4,287)	$8,597	($1,085)	$35,453	$19		$4,183	$51,578
2005	($3,029)	($22)	$4,950	($2,823)	$138	$5,079	$4,078	$10,111	($3,356)	$54,356	$123	$237	$5,524	$72,702
2006	($434)	($1,179)	$6,832	($5,451)	$555	$7,419	$275	$13,942	($7,347)	$58,447	$658	$346	$9,768	$98,611
2007	$12	$377	$8,569	($9,657)	$3,796	$38,154	$13,627	$20,967	($4,725)	$49,383	($28)	$1,307	$13,542	$121,882
2008	($507)	$1,275	$6,670	($17,701)	$2,971	$47,528	$14,785	$26,660	($2,882)	$70,750	$2,573	$2,275	$14,263	$205,116
2009	($1,046)	($581)	$8,868	($33,543)	$3,193	$16,605	$8,728	$30,557	$1,126	$71,808	$441	$1,446	$12,454	$58,783
2010	$1,974	($936)	$14,747	($38,330)	$1,063	$20,720	$4,648	$43,672	$3,238	$81,680	$2,356	$4,425	$12,233	$106,628
2011	$4,286	($4,855)	$13,973	($70,090)	$5,561	$58,168	$3,545	$46,378	$10,377	$83,330	$6,131	$8,638	$30,083	$59,951
2012	$11,176	($5,612)	$12,476	($65,725)	$7,629	$41,380	($3,197)	$60,510	$11,293	$90,913	($197)	$8,753	$26,538	$16,348
2013	$7,993	($5,433)	$25,475	($44,455)	$10,717	$36,484	($12,976)	$75,014	$7,237	$121,841	$6,420	$11,236	$55,947	$120,540
2014	$7,734	($12,212)	$22,054	($73,047)	$17,614	$28,394	($28,692)	$78,064	$5,117	$111,712	$3,366	$6,483	$55,265	$169,004
2015	$10,093	($12,953)	$9,680	($153,900)	$15,725	$24,280	($29,833)	$46,542	$3,777	$73,902	$541	$5,279	$71,223	($77,372)
2016	$9,445	($13,366)	$192	($145,452)	$12,182	$10,786	($36,841)	$28,171	$6,626	$73,970	$481	$5,985	$37,703	($107,170)
2017	$9,367	($5,662)	($13,496)	($110,555)	$14,654	$53,495	($20,968)	$28,904	$5,449	$86,470	$5,212	$2,202	$51,565	($98,067)

Source: Author's calculations.

Table A4 – Combined onshore and offshore wind electricity asset value per unit of electricity generated, social resource rent

	Australia	Brazil	Canada	China	France	Germany	India	Italy	Japan	Spain	Sweden	Turkey	United Kingdom	United States
1990							$3,063	$3,141		$3,107	-$7,693		-$4,258	$3,510
1991					-$990	-$1,809	$1,082	$2,573		$3,070	-$4,450		-$5,243	$3,469
1992			$2,865		-$1,165	-$2,697	$1,986	-$10,975		$3,517	-$2,114		-$5,293	$3,432
1993			$2,934		-$7,627	-$584	-$457	-$21,520	-$31	$2,652	-$2,000		-$583	$3,709
1994	-$249		$2,691		-$1,173	$453	$4,118	-$11,532	-$4,590	$2,888	-$1,510		$669	$4,217
1995	$1,682		$2,724		-$712	$51	$3,904	-$7,625	-$3,923	$2,534	-$1,869		$526	$4,067
1996	$1,985		$2,796	-$2,624	-$2,058	-$344	-$3,449	$1,432	-$14,433	$1,047	-$2,049		$763	$4,345
1997	$1,847		$2,781	-$2,540	-$964	-$58	-$2,728	$1,032	-$43,687	$870	-$1,429		$1,099	$4,310
1998	$522		$2,553	-$2,342	-$1,705	$381	-$2,958	$2,692	-$11,198	$533	-$1,028		$1,826	$4,004
1999	$592		$1,848	-$2,032	-$28	-$492	-$1,314	$3,246	-$7,302	$709	-$1,008		$1,585	$4,663
2000	-$1,494	-$190,444	$2,425	-$1,531	-$1,341	-$591	$600	$2,192	-$6,945	$940	-$832		$1,386	$4,993
2001	-$503	-$4,095	$2,182	-$946	-$113	-$1,548	-$4,064	$2,569	-$4,136	$781	-$1,421		$945	$4,509
2002	$160	-$1,547	$2,115	-$780	$97	-$1,025	-$1,091	$2,999	-$3,163	$1,040	-$742		$1,592	$4,408
2003	$656	-$1,866	$2,586	-$581	$475	-$560	-$2,239	$3,963	-$1,686	$1,950	-$371		$1,133	$3,325
2004	-$1,145	-$1,602	$2,669	-$667	$564	$355	-$1,093	$4,656	-$833	$2,258	$22		$2,162	$3,609
2005	-$3,423	-$240	$3,159	-$1,765	$143	$187	$733	$4,315	-$1,916	$2,567	$131	$4,020	$1,902	$4,066
2006	-$253	-$4,971	$2,763	-$1,947	$254	$242	$40	$4,693	-$3,390	$2,509	$666	$2,732	$2,312	$3,697
2007	$5	$569	$2,850	-$1,694	$933	$961	$1,452	$5,197	-$1,808	$1,791	-$20	$3,681	$2,568	$3,522
2008	-$164	$1,078	$1,761	$0	$522	$1,171	$1,249	$5,484	-$980	$2,147	$1,289	$2,686	$2,003	$3,683
2009	-$274	-$469	$1,335	-$1,347	$404	$430	$598	$4,670	$312	$1,884	$177	$967	$1,342	$792
2010	$391	-$430	$1,690	-$781	$107	$548	$289	$4,786	$806	$1,845	$673	$1,517	$1,189	$1,121
2011	$704	-$1,795	$1,372	-$978	$459	$1,190	$182	$4,705	$2,219	$1,942	$1,009	$1,829	$1,885	$496
2012	$1,603	-$1,111	$1,103	-$638	$509	$817	-$139	$4,513	$2,334	$1,838	-$27	$1,494	$1,337	$115
2013	$1,004	-$826	$1,418	-$321	$665	$706	-$527	$5,036	$1,395	$2,190	$652	$1,487	$1,970	$710
2014	$754	-$1,000	$979	-$456	$1,017	$495	-$1,053	$5,143	$981	$2,148	$300	$761	$1,729	$919
2015	$880	-$599	$366	-$828	$738	$307	-$936	$3,135	$677	$1,498	$33	$453	$1,768	-$401
2016	$774	-$399	$6	-$600	$567	$137	-$1,016	$1,593	$1,075	$1,513	$31	$386	$1,012	-$467
2017	$744	-$134	-$469	-$362	$593	$506	-$440	$1,629	$840	$1,760	$296	$123	$1,031	-$381

Source: Author's calculations