Valuation of Renewable Energy Resources in the Context of the *Changing Wealth of Nations* – Conceptual and Methodological Considerations

Draft report for consultation only, not for citation

May 6, 2021

GPS Global Program on Sustainability

THE WORLD BANK

Abstract

In this report, we review the concepts and methods associated with the *ex post* valuation of renewable energy resources and make recommendations for their application in the context of the World Bank's *Changing Wealth of Nations* reports. We find that neither the *System of National Accounts* (SNA) nor the *System of Environmental-Economic Accounting – Central Framework* (SEEA-CF) defines a complete and internally consistent approach to valuing renewable energy resources. The SNA largely disregards them and the SEEA-CF's treatment, while having *prima facie* appeal, does not stand up under examination. Its view that renewable energy resource values are captured in the value of associated land fails to adequately address renewable energy generation that 1) is not associated with land (offshore wind, solar and ocean resources); 2) exists under ownership rights clearly separated from land (most geothermal resources); or 3) is associated with land that has no economic value and does not appear in the national accounts (hydroelectric and most utility-scale solar/wind resources). We propose creation of a separate asset category for renewable energy resources within both the SNA and the SEEA-CF and partitioning of the value of the assets between their legal owners (governments) and economic owners (renewable energy companies). Valuation of these resources should proceed, as recommended in the SEEA-CF, *via* the "residual value" method (distortions in its application due to government intervention in electricity markets notwithstanding). We recommend this approach largely on practical grounds: it is widely used by countries (and in the *Changing Wealth of Nations* reports) to value other environmental assets. An alternative approach, known as the "least-cost alternative" method, is also found to be applicable, particularly in countries where electricity markets are very far from equilibrium. The report concludes with a discussion of the complex topic of *ex ante* valuation of renewable energy resources.

Table of Contents

ABSTRACT .... **I**

TABLE OF CONTENTS .... **II**

LIST OF ACRONYMS .... **III**

1 INTRODUCTION **1**
1.1 BACKGROUND AND OBJECTIVES 1

2 RENEWABLE ENERGY RESOURCES AS ASSETS **3**
2.1 RENEWABLE ENERGY ASSETS IN PHYSICAL TERMS 3
2.2 RENEWABLE ENERGY RESOURCES AS ECONOMIC ASSETS 4
2.3 SUMMARY AND RECOMMENDED TREATMENT OF RENEWABLE ENERGY RESOURCES AS ASSETS 13

3 RESOURCE RENT ARISING FROM RENEWABLE ENERGY ASSETS **17**
3.1 RENT AND RENEWABLE ENERGY RESOURCES 17
3.2 VALUING RENEWABLE ENERGY RESOURCE RENTS 18
3.3 RECOMMENDED APPROACH TO VALUING NATURAL RESOURCE ASSETS AND SPECIFIC CONSIDERATIONS 21

4 *EX ANTE* VALUATION OF RENEWABLE ENERGY ASSETS **29**
4.1 WHY UNDERTAKE *EX ANTE* ASSET VALUATION 29
4.2 REVIEW OF LITERATURE ON *EX ANTE* ASSET VALUATION 30
4.3 FACTORS INFLUENCING THE EVOLUTION OF RENEWABLE ENERGY ASSET VALUES 30
4.4 POSSIBLE METHODOLOGICAL APPROACHES 32

5 CONCLUSION **34**

REFERENCES **36**

APPENDIX 1– WILL GOVERNMENTS ASSERT PROPERTY RIGHTS TO SOLAR AND WIND RESOURCES? **42**

APPENDIX 2 – GEOTHERMAL PROPERTY RIGHTS IN MAJOR PRODUCING COUNTRIES 44

APPENDIX 3 – MAJOR RENT CONCEPTS IN ECONOMIC THEORY **45**

APPENDIX 4 – EMPIRICAL STUDIES OF RENEWABLE ENERGY ASSET VALUES **46**

APPENDIX 5 – TEMPLATE FOR *EX POST* VALUATION **49**

List of Acronyms

CWON – Changing Wealth of Nations

EU – European Union

FIT – Feed-in-tariff

GSI – Global Subsidies Initiative

GTAP – Global Trade Analysis Project

IEA – International Energy Agency

IPCC – Intergovernmental Panel on Climate Change

IRENA – International Renewable Energy Agency

kWh – kilowatt hour

LCOE – Levelized cost of electricity

NPV – Net present value

OECD – Organisation for Economic Co-operation and Development

PMR – Product Market Regulation

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

VRE – Variable renewable energy

WTO – World Trade Organization

1 Introduction[1]

1.1 Background and objectives

To date, the natural capital accounts compiled in the *Changing Wealth of Nations* reports (World Bank, 2011 and 2018) have included agricultural land, forests and protected areas, fossil fuels and minerals. Missing from the accounts have been renewable energy resources. This is unsurprising, given how few empirical studies of renewable energy resources and their value have published in the literature to date (Rothman, 2000). The studies that have been published have been hampered by data and methodological shortcomings and have not sparked much follow-on research.

Moreover, 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.*, 2008) or in the accompanying *System of Environmental-Economic Accounting 2012 – Central Framework* (SEEA-CF; United Nations *et al.*, 2014a) and its related ecosystem- and energy-specific handbooks (United Nations *et al.*, 2014b and United Nations, 2019).

The lack of attention paid to renewable energy resources is a concern. Available evidence, limited as it may be, suggests that these assets – especially hydroelectric resources – may be worth trillions of dollars worldwide. Extrapolating from findings for Canada (Gillen and Wen, 2000), Canada's hydroelectric resources alone may be worth $US380 billion in current dollars. This would make them more valuable than any other natural resource in Canada other than land (including the country's large fossil fuel reserves). Clearly, to the extent that these findings are accurate, the failure to account for renewable energy assets as part of wealth risks sending flawed signals to policy makers.

In this report, we address the question of renewable energy resources as assets by first reviewing and discussing their conceptual and methodological treatment in the SNA and the SEEA-CF. We then turn to what can be learned from existing empirical studies in terms of concepts, methods and data sources. Drawing from all this, we make recommendations – grounded in theory but also with due regard for practicality – on the most appropriate asset definition and valuation methodologies for use in measuring renewable energy resources in the natural capital accounts of the *Changing Wealth of Nations*.

Our focus is on geothermal, hydroelectric, solar and wind resources and primarily on their use to generate electricity. We realize this ignores other important benefits of these resources; for example, the use of geothermal and solar resources directly for heat. We realize as well that other renewable energy resources 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 report to a reasonable length – but also reflects the fact that there is great attention focused today on renewable electricity generation. Renewable resources offer the possibility of an emissions-free source to meet the world's

[1] The authors wish to thank Karen Wilson and Patrick O'Hagan, both formerly of Statistics Canada, for sharing their knowledge and insights regarding the national accounts and its treatment of natural resource assets. We are grateful as well to Grzegorz Peszko, Glenn-Marie Lange, Albertine Potter van Loon and Shun Chonabayashi of the World Bank for the opportunity to collaborate on this report and for their helpful direction and comments during its preparation. Any errors or omissions remain entirely our own.

growing need to provide homes, factories, communications and, increasingly, transportation networks with electricity.

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 *ex post* renewable energy resource valuation. In Section 4, we briefly discuss approaches that might be used for forward-looking (*ex ante*) modelling of renewable energy resources. Section 5 concludes with a summary. Several appendices provide additional depth on specific points.

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 begin with brief descriptions of the resources considered here in physical terms. 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 their treatments of natural resources broadly and of renewable energy resources 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 *Changing Wealth of Nations*.

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 heating water that can then be used for heating buildings or domestic hot water or for electrical generation in cases where temperatures are high enough to create the steam required to run an electric turbine (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, or rivers originating in 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.

Hydropower 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 by means of, for example, photovoltaic cells. 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 "thermal concentration" 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 face of the planet.

Wind energy has long been converted to mechanical power through the use of windmills. These have served to pump water, grind grain, power saw mills and other uses. 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 resources as economic assets

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

Assets are socially defined entities that can, and do, evolve over time. Both the asset boundary (the criteria that separate assets from non-assets) and the domains over which it extends depend on specific economic and institutional arrangements. The evolution of asset definitions is of central importance to any effort to account for renewable energy resources, because these resources are emerging as important parts of economic life across the globe. Some, like run-of-river hydropower, have been used for millennia. Others, such as geothermal, solar and wind electricity, have only emerged recently as widespread inputs to production as technology and consumer preferences change.

As the SNA asset definition (see below) makes clear, society has no interest in extending the asset boundary over unproductive resources. Conversely, when resources become productive (that is, used in human activity), they must be recognized as new types of assets in order for national accounting to continue properly informing decision-making (see, for example, the case of the radio spectrum discussed in Section 2.2.3). The emergence of newly productive economic resources is often followed by legal recognition of associated property rights, a key pre-condition for the resources to be viewed as assets. For example, Danish authorities have awarded damages to the owner of a wind energy farm due to losses caused by construction of another farm upwind, implying that the wind is a resource with benefits to which one individual's access is not to be unduly restricted by another (Diamond, 2015). In the United States, governments have begun to develop regulations to ensure access to sun and wind for the production of energy by restricting development on neighbouring properties (Diamond and Crivella, 2011; Landis, 2019).

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 approach 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, as noted above, 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, even if used over multiple periods, 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. Such entities are known in economics as "non-excludable", meaning that no economic unit may preclude others from also using them.

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 however and are not referred to as "economic" assets. Like the SNA, only assets that provide economic benefits are measured in monetary terms. For example, 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 hence be excluded from consideration as an economic asset.[2]

[2] The classic example is remote public land, such as wilderness forest, that provides no economic benefits. Such land is generally not included on national balance sheets, though Australia is an exception. 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).

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 environmental resources that are generally owned collectively rather than privately. 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 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).

When it comes to the question of ownership of natural resource assets, the SNA is clear that the general principle upon which asset ownership is to be determined is economic ownership: "assets appear on the balance sheet of the unit that is the economic owner[3]". The SNA goes on, however, to note that "when a natural resource is the subject of a resource lease, the asset continues to appear in the balance sheet of the lessor [e.g., a government] even though most of the economic risks and rewards of using the asset in production are assumed by the lessee [e.g., a resource company]" (SNA ¶13.3). There is, then, an apparent inconsistency in the SNA's approach to asset ownership; in general, ownership is attributed to the economic owner unless the asset in question is a natural resource, in which case ownership is attributed to the legal owner. The SNA justifies this by simply stating "…there is no wholly satisfactory way in which to show the value of the [natural resource] asset split between the legal owner and the

[3] The economic owner of an asset is an entity that has agreed by way of contract to accept the risks and rewards of using the asset in production in return for an agreed amount to be paid to the asset's legal owner. The legal owner is the unit entitled in law to the benefits of the asset's use (SNA ¶2.47).

extractor, [so] the whole of the resource is shown on the balance sheet of the legal owner" (SNA ¶13.50). This treatment raises two issues. Firstly, there is an explicit admission that the SNA treatment is not "wholly" satisfactory and, secondly, any rent associated with a natural resource asset would not be in line with the value of the asset on the government's balance sheet (as the legal owner) except in cases where royalty payments succeed in extracting the full resource rent from extractors.

The SEEA-CF, for its part, is not fully clear regarding ownership of natural resources. In the preface, it states that "the economic value of mineral and energy resources should be allocated between the extractor and the legal owner" (SEEA-CF preface ¶33). Later, in the chapter devoted to asset accounting, it argues that "the allocation of assets and the resulting estimates of institutional sector net worth should reflect the expected future income streams for each unit from the extraction of the resources" (SEEA-CF ¶5.223). There is no more explicit statement in the SEEA-CF regarding the recommended approach to attributing ownership of natural resource assets. Based on these two excerpts, the SEEA would seem to diverge with SNA treatment, suggesting that the value of natural resource assets should be divided between the legal and economic owners rather than being attributed wholly to the former.

A clear and explicit treatment of this issue is found in Statistics Canada (2015), which takes the position that the existence of both government and corporate sector ownership of natural resource is appropriate and that each one's share in ownership should be based on the economic returns it earns. This has, they argue, the advantage of ensuring that sectoral asset values are closely tied to sectoral income flows. Statistics Canada goes on to argue that the proper conceptualisation of the resource asset for the purpose of determining institutional ownership is as an intangible asset, on the grounds that it makes no sense conceptually to think of the physical asset (that is, the resource itself) being actually divided in any meaningful way between two sectors: "Even if there were agreement on a way to partition the value of the physical resource, this would be far removed from the actual accounting by governments and corporations. In many countries, a naturally occurring asset belongs to the nation as a whole, and can be extracted/harvested for economic reasons by corporations at the discretion of governments" (Statistics Canada, 2015, p. 7). Give this, Statistics Canada proposes sectoral claims on the stock of physical natural resources be treated as intangible assets that reflect sectoral claims on the underlying physical resources; in other words, it argues that the claims can be thought of as assets that derive their value from the claims that governments and corporations have in relation to the physical resource assets on behalf of the nation's population who are ultimate owners of these resources. To implement its approach in practice, Statistics Canada takes the government's claim on natural resource assets to be equal to the net present value of the royalty (and related) payment stream the government expects to earn from licensing resource firms to extract the nation's resources. The business sector's claim is then estimated as the total value of the physical resource asset[4] (valued using the residual value method discussed below in Section 3.2.1) less the government's claim.

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

The SNA says little regarding the treatment of 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

[4] This asset, it should be noted, is treated conceptually by Statistics Canada as a tangible, non-produced asset that is recorded on the unsectored national balance sheet for the nation as a whole.

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 signals) 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.[5] Interestingly, they argued that "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 potential 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 resources 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

> "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).[6]

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

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

[6] 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.

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).[7] 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, the assumptions underlying it deserve further examination.

The SEEA-CF's argument seems predicated[8] on the standard economic notion that if two parcels of otherwise identical land differ only in their capacity to generate renewable energy, their market price should reflect this difference (with the one with higher renewable energy potential being the more highly valued). Sites for renewable energy production are not infinite in supply, especially not for geothermal and hydroelectric resources (both of which depend on specific attributes of the earth's crust or its hydrologic features). Thus, it would be reasonable to expect areas of land with high geothermal or hydroelectric potential to command relatively higher prices than those without, other things equal. Sites suitable for solar and wind production are also in limited supply, even if the sun shines and the wind blows everywhere. Variations in both the degree of sunshine/wind speed and the physical characteristics of sites (angle to the sun or wind, obstructions, prohibitions, existing land uses) impact suitability – and therefore value – for solar/wind production.[9]

Several assumptions are implicit in the SEEA-CF's argument around renewable energy resources as assets:

- markets for renewable energy production are in something close to long-term competitive equilibrium
- property rights to land include the rights to the economic benefits flowing from any associated renewable energy generation, and

[7] For its part, the specialized SEEA-Energy handbook devoted to accounting for energy resources (United Nations, 2019) states that "the sun and the wind are not considered to be environmental assets" for its purposes (¶2.24) and repeats the SEEA-CF position that renewable energy resource values should be captured in the value of the associated land (¶2.50).

[8] We say "seems" predicated because the basis for the SEEA-CF's argument is not spelled out explicitly anywhere in the text.

[9] Arguably, this is not true in the case of nations, like Saudi Arabia, with vast areas of desert with largely undifferentiated potential for solar power production and no other meaningful potential for economic use. Even in such cases, however, the principles of valuation would apply – but the supply of suitable land would so far outstrip demand that no opportunity cost would arise.

- land associated with renewable energy production has a positive and measurable economic value and that this value is captured, at least in principle, in the national accounts.

Each of these assumptions is considered in turn below.

2.2.4.1 Renewable energy markets are close to equilibrium

For the value of land to reflect the value of any associated renewable energy assets, markets for renewable energy must be in something close to long-term competitive equilibrium. Buyers and sellers of land require clear and reliable information, and the ability to properly use that information, on a variety of points in order to account for renewable energy production potential in their assessments of land value. These include:

- the physical potential of the land in question for renewable energy production
- how the use of the land for renewable energy production might affect its value for other purposes (e.g., how installation of a wind turbine on farmland might affect its value as potential residential development site)
- the current and future demand for different forms of renewable energy
- the legal and regulatory frameworks for renewable energy, including property rights to the economic benefits of renewable energy production, government support for renewable energy production and capture of the associated resource rent, and
- the capital and operating costs of renewable energy production.

It is not clear to what extent reliable information on these points is actually available to investors. Moreover, this availability likely differs considerably from country to country. In jurisdictions with relatively long histories of renewable energy production, such as Denmark and Holland, it may be the case that there is sufficient certainty on the above points for land transactions to reflect the value of renewable energy production. In jurisdictions where renewable energy production is newer and/or markets are in rapid evolution (which includes most of the world), it seems likely that uncertainty exists on many of these points, meaning that the economic benefits of renewable energy resources will be, at best, imperfectly factored into land prices. As an example of the uncertainty investors face, public perception of the desirability of renewable energy infrastructure – especially wind turbines and solar panels – is fickle. While citizens in many countries support renewable energy (PEW Research, 2018; European Commission, 2017), they can also object when projects are developed “in their backyards”. Opposition is driven by socioeconomic concerns, visual and sound impacts and environmental concerns (Bidwell, 2016; Enevoldsen and Sovacool, 2016) and has resulted in planned developments being scrapped, such as the Cape Wind project in Nantucket Sound, Massachusetts (Smith, 2007).

Uncertainty regarding legal and regulatory environments can create considerable distortions in markets. A rational investor would want clarity regarding the allocation of the economic benefits of renewable energy production before making a large land purchase. Since those benefits would be expected to play out over decades, the challenges posed for the investor by uncertainties are multiplied. In another example, a solar energy investor in California had its panels blocked by neighbouring redwood trees. After a lengthy lawsuit, the owner of the solar array won out and the trees had to be removed (Borenstein, 2011). This suggests that property rights to renewable energy resources are still not firmly established, even in California with its long history of production. Appendix 1 explores another source of uncertainty – what governments might do in the long run regarding solar and wind property rights.

As discussed in Section 3.2.1 below, renewable electricity markets – and electricity markets more generally – have moved in recent years toward long-run competitive equilibrium. Thus, the foregoing is not intended to suggest that investors in renewable energy markets operate in a “wild west” setting. Rather, the point is simply that enough uncertainty remains in those markets to question whether the, theoretically correct, assertion that land prices will capture renewable energy resource rents is valid in practice. Our view is that it may be in some instances but likely not in all.

2.2.4.2 Property rights and renewable energy resources

For the value of land to reflect the value of any associated renewable energy assets, it must be the case that the land owner also owns the rights to the economic benefits associated with the renewable energy resources. The only case in which this would seem to be unambiguously true is that of solar/wind electricity production on privately owned land. When a farmer erects a wind turbine on his farm or a homeowner installs solar panels on her roof, the economic benefits of the energy production will be conferred on him/her simply by the fact of his/her ownership of the associated land.

In the case of solar/wind and hydroelectric production on public land/water, it is also true that the rights to both the land/water and the economic benefits of the energy production vest in the same unit (in this case, the government on behalf of the public). However, as we argue next, in those cases the land/water in question is likely not traded in markets and has no economic value (at least, no value that is observed within the national accounts). There is, therefore, no value that renewable energy production on public land might influence, even if the property rights to the resource are clear in this case.

The case of geothermal resources is the most problematic from the perspective of property rights, as rights to these resources in most countries – as with the rights to sub-soil resources in general – are assumed not by the owner of the land above them but by the government on behalf of all citizens (see Appendix 2). The United States is something of an exception to this, as sub-soil resource rights there are legally conferred by default on the owners of the associated surface land. However, it is common in the United States for rights to the surface and mineral estates to have been severed at some point in the past, meaning that the rights to the two are frequently owned by different parties today. Thus, in most countries, including the United States, it is not clear that the presence of geothermal resources on or under a given piece of land would have any positive impact on the value of the land. Indeed, a case could be made that the opposite is true to the extent that geothermal energy production disrupts surface land uses and/or raises concern for groundwater quality. In such cases, the exploitation of geothermal resources could cause land values to fall, not rise.[10]

2.2.4.3 Land value is already captured in the national accounts

For the value of land to reflect the value of any associated renewable energy assets, it goes without saying that the land in question must have a non-zero economic value in the absence of renewable energy production and that its value must be captured, at least in principle, in the national accounts. Otherwise, there is no observed land value for renewable energy assets to impact. This has implications for renewable energy production on land with no other practical

[10] Note that the argument here pertains to large-scale exploitation of geothermal resources and not to their small-scale use for heating/cooling purposes in residential- or commercial-building ground-source geothermal systems. The property rights to this energy likely do accrue to the land owner. Though here again it seems unlikely that the value of the land on which the building is sited will rise simply because the owner decides to install a ground-source geothermal system. Land below essentially any building can be used as a source of heat/cooling, so neither differential rent nor scarcity rent could be expected to arise.

use and for production that occurs in the absence of land (for example, off-shore wind farms). Only in the case of renewable energy production on privately owned land does an observable land value exist that could be plausibly influenced by the presence of renewable energy assets. Privately owned land always has a value because it has, by definition, at least one economic use.[11] The value of all private land is captured in the national accounts and markets should be able to "price in" its value for renewable energy production (notwithstanding the issues associated with property rights and market equilibria just noted).[12]

Publicly owned land is different, especially public land that is found in its "natural" state (*e.g.*, forests, rivers or deserts) and has no practical economic use. Such land is not considered an asset in the context of the national accounts, as no value can be observed for it.[13] The argument that renewable energy asset values will captured in land values is not plausible, then, for production that occurs on public land with no other practical use. This includes essentially all rivers used for hydroelectricity production and any public lands used exclusively for solar, wind or geothermal production. In the absence of renewable energy production, these areas have no economic value and, therefore, renewable energy production cannot influence their value. In such cases, the SEEA-CF notes "the value of the land will, in theory, be equal to the net present value of the future income stream [from the renewable energy production]" (SEEA-CF ¶5.229). This recognition that land used only for renewable energy production is equal in value to the value of the renewable energy resources themselves[14] is simply another way of stating that such land has no economic value unto itself; all its value arises from its use to produce renewable energy.

Why the value that arises from renewable energy production on otherwise valueless land should be attributed to the land rather than to the renewable energy assets themselves is not clear and the SEEA-CF offers no explicit justification. It is the equivalent of attributing the value of standing timber resources to the land on which the trees grow and not to the trees themselves, something the SEEA-CF recommends against. Rather, the SEEA-CF recommends that timber resources (in fact, all natural resources other than renewable energy) be recognized as assets in and of themselves. Thus, the approach suggested for renewable energy assets would seem inconsistent with the main thrust of the SEEA-CF's arguments regarding natural resource valuation.[15] This issue is of considerable practical importance, since renewable energy

[11] Even private land that is not actively used in any kind of production process nearly always has an economic use as a store of value for its owner. An exception to this might be very remote areas of land held privately for the purposes of ecological preservation. The economic value of such areas, even as a store of value, may be zero. For the present purposes, such areas can be ignored.

[12] An interesting case (not discussed in the SEEA-CF) is that of speculation in land with no obvious economic value other than renewable energy production. It may be the case that private entrepreneurs, anticipating future growth in demand for solar or wind energy, will purchase large tracts of public land in remote areas with high potential for renewable energy production but no other apparent economic value (such as deserts). The value of such land would, in principle, appear in the national accounts. The extent of such speculation is unknown, but it seems unlikely to be widespread given the large areas in question (renewable energy farms in remote areas can be tens of kilometres squared in size). Governments may be reluctant to sell off large areas of public land to speculators unless plans for a renewable energy farm have already been put in place and approved, in which case the land would likely be sold to the firm developing the farm rather than to a speculator and it would be quickly brought into production rather than lying "fallow" waiting for a farm to be proposed.

[13] Public land with buildings or other major public infrastructure (bridges, roads, ports) on it does have a positive economic value and is recorded in national accounts.

[14] The valuation of natural resource assets by measuring the present value of the future rent they generate is the standard approach in the SEEA-CF. It is recommended for the valuing of fossil fuel, mineral, timber and other natural resource assets.

[15] Section 5.8.4 of the SEEA-CF discusses valuation of timber resources. There the asset of economic significance is considered the timber itself and not the land on which the trees grow, though it is recognized that timber rent may include a small share that should be attributed to the land on which the timber stands. The SEEA-CF recommends

production is often sited on land that has no alternative use. Large solar energy farms (utility-scale projects), which account for most of the growth in the world's installed capacity (IEA, 2017) and can be tens of square kilometres in size, tend to be built in inhospitable areas such as deserts. If the SEEA-CF renewable energy resource recommendations are followed, the value of these large farms would be attributed to land in the national accounts.[16] If the main SEEA-CF approach to valuing natural resources were followed instead, they would be attributed to a separate solar energy asset.

A final concern with the SEEA-CF's argument around renewable energy assets comes in the case of off-shore production, such as the off-shore wind farms that are of growing importance.[17] As with most publicly owned territory, no economic value is attributed to off-shore areas in the national accounts and, therefore, there is no possibility that the value of off-shore renewable energy production could be captured in the value of a country's off-shore territory. Recognizing this, the SEEA-CF states that "by convention, the value of income streams from [off-shore] sources are attributed to the value of land" (SEEA-CF ¶5.231). Again, it is unclear why this should be the case and the argument seems somewhat arbitrary. As noted above, the "convention" elsewhere in the SEEA-CF would suggest just the opposite: assigning the value of off-shore renewable energy resource to the resources themselves and recording them as assets in the national accounts, as the SEEA-CF argues should be done in the cases of timber and other renewable resources (not to mention non-renewable resources).

2.3 Summary and recommended treatment of renewable energy resources as assets

To summarize, the SEEA-CF's argument that solar, wind, geothermal and hydroelectric energy asset values are captured in the value of the associated land, while having *prima facie* appeal, 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 the 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.

With respect to the most important contemporary renewable energy resource, 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 rivers that have no other

---

that this share be estimated and deducted for the purpose of deriving the estimate of resource rent on timber resources. It does not, however, recommend that the entire timber rent be considered to arise from the land asset, as it does in the case of renewable energy resources.

[16] It is worth noting that the value of such inhospitable land for solar energy production might, in fact, be zero according to standard economic theory, as the opportunity cost of its use for solar farms may be zero.

[17] Denmark saw its share of off-shore wind power capacity increase from just 2% of total capacity in 2000 to 32% in 2016 (Danish Energy Agency, 2018).

economic value. There is no possibility that the value of hydroelectric resources could be captured by measuring the (non-existent) value of these public waterbodies. The SEEA-CF's recommendation that the public waterbodies be given a value equal to calculated value of the hydroelectric resources themselves (SEEA-CF ¶5.491) is, thus, inconsistent with its recommended approach to valuation of other natural resource assets.

For their part, geothermal resources are considered public assets in most countries, with property rights separate from the land found above them. There is no reason, given this, to expect the value of the land above the resources to 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 resources risks missing much of the value of these increasingly important resources. For example, none of the value of the 56% of Canada's total electricity generating capacity that was accounted for by hydroelectric resources in 2016[18] would be captured in any existing land (or water) value on Canada's national balance sheet. The only way for this value to be included in Canada's national accounts would be for it to be explicitly calculated as the present value of the future stream of rent from the resource and added to the asset values already present on the balance sheet. In fairness, the SEEA-CF acknowledges as much, but then goes on to argue that this calculated value is really the value of water and not of the hydroelectric resource itself, a view that is clearly out of line with its approach to other natural resource assets.

2.3.1 Recommended approach to renewable energy resources as assets

The approach recommended for treatment of renewable energy resources as asset in the *Changing Wealth of Nations* (CWON from here forward) is to adopt the SEEA-CF's standard approach for 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 the addition of a new category of natural resource assets to both the SNA and SEEA-CF asset classifications (Table 1) and, ideally, paying attention to possible confusion with existing terminology; for example, both classifications already include "mineral and energy" assets that 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*

[18] Statistics Canada, Table 25-10-0022-01, *Installed plants, annual generating capacity by type of electricity generation.* Available here.

	Other biological resources
	Water resources

Note: Suggested additions shown in green.

Implicit in our suggested approach is the claim that renewable energy resources meet the criteria necessary to be defined as assets. We feel justified in this claim in part because the treatment given renewable energy resources in the SEEA-CF itself amounts to acknowledgement that these resources have value as assets and that this value can be measured by calculating the net present value of future rent derived from their use (especially SEEA-CF ¶5.229 and ¶5.491).

The approach recommended here has two advantages. Firstly, it ensures consistency in the accounting for all natural resource assets, including renewable energy resources. Secondly, it ensures the full value of all types of renewable energy resources will be captured in the national accounts.

A potential disadvantage of our approach is that it could lead to double counting of some renewable energy resources. 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 resources 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 resource 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 resources. 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.

With regard to the ownership of renewable energy resource assets, we recommend the approach adopted by Statistics Canada (2015) in its national balance sheet accounts (see the discussion earlier in Section 2.2.2). In this approach, ownership of natural resource assets is partitioned between governments and resource companies according to the economic benefit each receives from their use, with government benefits taken to be equal to the net present value of future royalty streams. In the case of renewable energy resources, since governments do not today generally extract royalty payments for their use, the entire asset value would be attributed to the business sector following this approach. This seems to us appropriate, as it reflects the fact that governments – for now anyway – operate as though it is necessary to relinquish all of their benefits from renewable energy resource use to encourage renewable energy companies to take on the risk of exploiting the resources. Whether governments will forever relinquish their benefits from use of these assets is a matter we address further below (see Section 3.3.1 and Appendix 1).

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 methods to use in placing values on the resources.

3 Resource rent arising from renewable energy assets

The nature of economic 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 benefits accruing to a factor of production over and above what is required to maintain that factor in the productive process, though they highlight different circumstances by which these payments come about. A review of basic rent concepts is provided in Appendix 3.

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." The SNA explicitly considers that "two particular cases of resource rent are considered, rent on land and rent on subsoil resources. Resource rent on other natural resources follows the pattern laid out by these two instances." (SNA ¶7.154). Where recorded payments arise from a combination of rent and other sources, for example land hire, the SNA stipulates a majority allocation rule, classifying the payment as rent or "other sources" based on whichever is the greater share (SNA ¶7.155-¶7.158). The arbitrary social definition of assets is specifically considered with regards to the treatment of rent on subsoil assets, with ownership recognized to "[depend] upon the way in which property rights are defined by law and also on international agreements" and a variety of payment structures being acceptable (SNA ¶7.159 and ¶7.160).

3.1 Rent and renewable energy resources

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 rent and its distribution among factors of production. For example, Ricardian/differential and scarcity/absolute rents are based upon the supposition of market equilibrium. Where markets are not in equilibrium such rents cannot exist, strictly speaking. By contrast Marshallian quasi-rents are features of markets that are not in long-run equilibrium.

An additional challenge is that the inexhaustible nature of renewable energy resources poses challenges to theories of value and thus to theories of rent.[19] 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. As noted in Section 3.3.1, governments may choose to do this in the future, as they have done in the case of the radio spectrum.

[19] A related measurement problem arises when the supply of resources is increasing over time (or total expenditures are growing): a declining cost share of the resource is equated with declining productivity in growth accounting, producing a biased view of the contribution to economic growth over time. Santos *et al.* (2016) explore this issue with regards to structural changes in the energy supply in Portugal.

3.1.1 Hydroelectric resource rent

Hydropower is an ancient 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. Where equilibrium can reasonably be assumed, quasi-rents should not exist. 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 (see Section 3.2).

3.1.2 Geothermal resource rent

Rights to subsoil resources are generally recognized (and assumed by governments) and markets often exist in which such rights are traded and priced. Sites for geothermal power generation are both heterogeneously distributed and scarce.[20] The technology for geothermal power production is relatively well-established. Under these circumstances, both Ricardian and scarcity rents should accrue.

3.1.3 Solar and wind resource rent

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. In the short-run, opportunities for entrepreneurial and quasi-rents exist. Because solar and wind energy markets are not in equilibrium today, they should not be generating Ricardian or scarcity rents. However, they may currently yield quasi-rents.

3.2 Valuing renewable energy resource rents

Where rent does arise from the use of renewable energy resources,[21] 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.[22]

[20] 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.

[21] Recall that the focus of this study is on the use of renewable energy resources in the context of electricity generation. Rent likely arises from their use to generate heat as well but that is not discussed here.

[22] Specific subsidies and taxes are those directly related to the production of renewable energy. For example, a concessionary loan received by a solar electricity producer to finance purchase of solar panels would be considered a specific subsidy. A subsidy received for the purpose of employing workers of a specific type (those from disadvantaged populations, for example) would not. Regarding taxes, specific taxes would include any royalties or other fees paid on energy production. Normal taxes paid on corporate profits are excluded.

Calculating rent in this way requires an estimate of the value of the produced capital employed in the renewable electricity process, along with an estimate of the rate of return to that produced capital. If the value of wind energy rent is being estimated, for example, then it is the value of the wind turbines and any other produced capital used by wind energy producers, as well as an estimate of the rate of return to the capital that are required. If detailed capital stock data are available from the national accounts, the required estimate of the value of produced capital may be available there. If not, the figure will have to be compiled using data available from other sources; for example, corporate reports of wind energy companies. For the rate of return, the SEEA-CF recommends using an economy-wide figure based on government bond rates where these exist (SEEA-CF ¶5.144). The data necessary to estimate such a rate of return should be available from the national accounts so long as an economy-wide estimate of capital stock is compiled.

Section 3.3 discusses the methodological details of the residual value method in further detail.

3.2.1 The residual value method and its applicability to renewable energy resources

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).

The OECD's Product Market Regulation (PMR) indicators measure the competitiveness of a number of markets, including electricity and natural gas. In compiling the PMR indicators, the OECD considers a number of factors, including market entry barriers, public ownership, vertical integration and retail price regulation. Based on this, a measure from 0 to 6 is calculated for all OECD and several non-OECD countries, with 0 reflecting the most competitive markets and 6 the least. In 2018, the average PMR value for electricity markets for OECD countries was 1.63, with a range from 0 (United Kingdom) to 2.89 (South Korea); the equivalent figures for natural gas markets were 1.65, 0 (United Kingdom) and 4.63 (Switzerland). These results suggest, perhaps surprisingly given electricity's notoriety as a highly subsidized commodity, that electricity markets are more broadly competitive than natural gas markets today in OECD countries. The results for the non-OECD countries considered (2.93 for electricity and 2.60 for natural gas on average)[23] suggest that electricity markets are slightly less competitive than natural gas markets in these countries and that both markets are less competitive than those in OECD countries.

[23] Argentina, Brazil, Kazakhstan and South Africa.

Taking a more qualitative approach, a World Bank review (Jamasb, *et al*. 2015) considered the state of electricity market reform in developing countries. It found that many developing countries have undertaken electricity market reform, but the progress varies between countries and most remain in transition. Reforms were found to have improved the efficiency and productivity in the electricity sector, though the gains may not always benefit energy consumers. Independent regulatory bodies and strict regulation, which do not exist everywhere, are necessary to ensure efficiency gains do not benefit only producers and governments.

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 would seem reasonable to suggest – the concerns raised earlier in Section 2.2.4.1 above notwithstanding – that application of the RVM to estimation of renewable electricity rents 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) programs of some kind 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). See Section 3.3.1 for further discussion of subsidies.

At the same time, the nature of government support for solar and wind energy is different than it was in the electricity market's past. For one, solar and wind energy producers in many countries today 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[24], 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.

3.2.2 An alternative to residual valuation: The least-cost alternative method

An alternative approach to the RVM exists when the economic conditions required for that method to apply do not exist, as would have been the case for renewable energy in the past when government intervention in electricity markets was broad and deep and as is likely still the case today in countries where market deregulation has not advanced significantly. This approach – known as the least-cost alternative method – rests on the principle that the rent on a given asset can be identified in any activity by evaluating the difference in cost of the activity when using the asset and when using its least-cost alternative. This difference can be taken as the rent attributable to the asset. The method has been most often examined in the estimation of the rent on hydroelectric resources. It was used with considerable sophistication, for example, in two early studies of hydroelectric rents in Canada, as discussed in Appendix 4.

[24] 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, 2018).

The advantage of the least-cost alternative method is that it requires no information regarding revenues. Only information on costs is needed. In instances where revenue data are unreliable because of market distortions, this is helpful, as correcting revenue data for market imperfections is complex. Doing so for anything other than a trivial activity would require remodeling of the entire economy to estimate equilibrium prices in the absence of the market distortions. Cost data, on the other hand, are relatively easily corrected, since the inputs used in one activity are frequently used in others. For example, wages paid in highly regulated industries (like electric power was in the 1980s) can be inflated above market rates. Labour is used as an input in most activities, however, so adjusting inflated wages so they reflect market norms is relatively straightforward.

The disadvantage of the method is its complexity. Applied fully, the method requires simulation of two hypothetical worlds, one in which the activity takes place including the asset of interest but in which all input cost data have been adjusted to eliminate distortions caused by market interventions and a second in which the activity takes place with the least-cost alternative to the asset (also with all cost data corrected). Needless to say, for any real-world activity, this is a large undertaking. 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 potential disadvantage of the method is that it may result in an estimate of what renewable energy rent *should* be, rather than what rent *is*. This is because, in its full application, the approach compares hypothetical least costs of energy production with and without the renewable source. If actual costs are far from hypothetical costs – because, for example, the electric power system is highly regulated and/or poorly managed – the hypothetical rent may be quite different from actual rent. Of course, it is not hypothetical rent that should be included on national balance sheets, but actual rent, if policy makers are to receive appropriate signals from the valuation of renewable energy resources. This shortcoming can be avoided by applying the method in a more limited way, comparing actual costs against hypothetical costs.

Simple applications of the least-cost alternative method have been used to achieve "back-of-the envelope" calculations of renewable energy resource rents. Typically, observed market prices of electricity are compared against the cost of generation from a renewable energy project. For example, the average cost of importing electricity from a neighboring jurisdiction offers a straightforward way of evaluating the least-cost alternative in the case of hydroelectric production (Gillen and Wen, 2000; Hreinsson, 2008a; Hreinsson, 2008b; Wandji, 2018). This approach avoids the need to model the hypothetical alternative world in detail but has the drawback that the "alternative" cost employed is in fact partly determined by the supply of renewable energy. It is this endogeneity that more complex counterfactual modelling seeks to overcome. In practice, the relative economic importance of the renewable energy assets being valued (that is, their price-making power) may serve as a yardstick to judge whether back-of-the envelope approaches are valid or whether more complexity is called for. For example, the simple approach of adopting imports as the least-cost alternative might be justified for a small renewable energy sector in a country that imports sizeable quantities of electricity from a regional market.

3.3 Recommended approach to valuing natural resource assets and specific considerations

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 resources in the CWON. We also acknowledge that the least-cost alternative method is worthy of consideration, especially in cases where subsidies remain significant and markets are likely still far from long-term equilibrium (mainly for solar and wind energy assets). RVM has several advantages over the least-cost alternative approach that lead us to propose it as our preferred approach. Firstly, its use would promote consistency in the methodological approach to the valuation of natural resources, as the RVM is already recommended by the SEEA-CF – and widely used – for valuation of fossil fuels, minerals, timber and aquatic resources. Secondly, its use would be consistent with practice by the few national statistical offices that have attempted valuation of renewable energy assets (see the review of empirical studies in Appendix 4). Finally, its use is consistent with existing practice in the CWON.

Below we discuss some of the considerations in applying the RVM. Additional information regarding data needs and potential sources associated with the method is provided in Appendix 5.

3.3.1 Subsidies and taxes

Applying the RVM requires data on subsidies paid to and taxes paid by producers of renewable energy. Subsidies come in two forms: what are called in the SNA “subsidies on products” and “subsidies on production”. The former are subsidies paid to producers directly on the sales of their products, such as a premium on solar or wind electricity paid through a FIT program. The latter are subsidies paid in relation to the production process, such as a subsidy paid on capital acquisition *via* a concessionary loan. The value of both kinds of subsidies must be estimated and subtracted from the value of renewable electricity sales[25] in arriving at an estimate of resource rent *via* the RVM. It is worth noting in this regard, however, that it is not common practice among national statistical offices to adjust estimates of fossil fuel resource rent for any subsidies paid to the fossil fuel industry when applying the RVM to non-renewable energy resource valuation. This is in spite of the fact that fossil fuels are also heavily subsidized globally.

A complementary approach that may be worth considering in the CWON would involve applying the notion of social resource rent promoted by Statistics Netherlands (see the discussion in Appendix 4). It is not recommended that social resource rent be used as the central estimate of rent for renewable energy resources in the CWON, as this would introduce conceptual inconsistency into the natural capital accounts. However, consideration could be given to presenting social rents as an addendum item alongside normally calculated rents.

The subsidies discussed above are both “explicit”, where payments are made directly to producers in relation to specific aspects of their activities. Subsidies can also be implicit; for example, support provided to producers by government organizations whose function is to import equipment and then sell its at lower prices domestically (SNA ¶7.101). In principle both explicit and implicit subsidies are important and should be taken into consideration in the RVM. **Doing so for implicit subsidies in the CWON would, however likely not be practical given the detailed country-level data that would be required. It is not recommended at this point; accounting only for explicit subsidies is recommended and even that may be hampered by lack of data.**

Subsidies to energy producers are not the only form of government support to the renewable energy industry today. In countries where the equipment used to generate renewable energy is manufactured (solar panels and wind turbines, for example), it is also common for governments

[25] Note that sales are to be valued *including* any subsidies on products. Thus, if a FIT is in place for a given producer, its electricity output should be valued at the raid paid through the tariff and not at the prevailing market price for electricity. The difference between the tariff rate and the market rate is the value of the product subsidy that must subsequently be deducted in the rent calculation.

to subsidize the manufacturers. Depending on the impact of these subsidies on manufacturing firms' behaviour, it may be that this subsidization impacts the cost structure of renewable energy producers. If, for example, wind turbine manufacturers sell turbines at prices below what their competitive market price would be in the absence of subsidization, wind energy companies face relatively lower capital costs than other firms, distorting their financial incentives.

The question of what a wind turbine would be worth in a fully competitive market is obviously difficult. From one perspective, it would be reasonable to expect manufacturers to take advantage of their subsidies to sell at lower prices than they would have to otherwise. On the other hand, firms may be price-takers and will understand that subsidies are typically temporary. Thus in competitive markets, and over the long run, market forces will tend to push manufacturers toward charging fair market value. The ability of firms to set prices is limited given the highly traded nature of modern manufactured goods. Furthermore, international trade laws explicitly prohibit countries from using subsidies to undercut their foreign competitors (Text Box 1).

Text Box 1 – World Trade Organization rules and solar energy subsidies

The dispute mechanism of the World Trade Organization (WTO) has been used to challenge renewable energy subsidies supporting develop local manufacturing capacity. In a dispute over the Government of Ontario's (Canada) FIT program, the WTO's Appellate Body condemned the program's local-content requirements, though not the program as a whole (De Beivre, Poletti, and Espa, 2016).

China is the largest manufacturer of both wind turbines and solar panels (Zhang *et al.*, 2013; Bougette and Chalier, 2013). Renewable energy manufacturing in China has historically been supported with a number of subsidy programs, including financial support for research and development; import tax exemptions for equipment and parts necessary for the manufacture process; and loans and credit provided by state banks. China also had a local content requirement until 2009, when the program was cancelled due to scrutiny from the WTO (Zhang *et al.*, 2013). In 2013, the EU placed anti-dumping duties on solar panels produced in China as a response to Chinese subsidies and pressure from European manufacturers. The United States also imposed protective measures. While the EU also had renewable energy subsidies, its programs were designed to increase the price paid for renewable electricity by consumers rather than to support manufacturers (Bougette and Chalier, 2017). The anti-dumping measures were removed in 2018, as the European Commission felt that the support measures in China had decreased and import prices were coming into line with world prices (Blenkinsop, 2018)

Subsidies to the renewable energy industry are far from the only ones offered by governments. Industries across the economy, from agriculture, forestry and mining through manufacturing, transportation and construction benefit from various kinds and degrees of support in most countries. Given the ubiquity of subsidies, cost structures everywhere can be expected to be distorted away from their long-run competitive equilibrium positions. According to the International Energy Agency (IEA, no date), direct fossil fuel subsides worldwide alone amounted to about $US400 billion in 2018. The OECD reports that agricultural subsidies in its member countries came to $US317 billion on average from 2015 to 2017. Global subsidies for renewable energy, in contrast, amounted to $US150 billion in 2015 according to the IEA. Clearly, though large, government support of the renewable energy industry is not the largest category of subsidies in absolute terms.

Given the above, there does not seem to be a case for including manufacturing subsidies for solar and wind energy equipment among those considered in the CWON. Market forces will tend to ensure that renewable energy producers pay fair market value for their equipment and these subsidies are not especially large in the global context. Cost structures of renewable energy producers are not likely to be any more distorted by manufacturing subsidies than are the structures of any capital-intensive sector of the economy, including fossil fuels, mining, forestry and non-renewable electricity production. **Thus, the only subsidies that must be accounted for in the CWON are those on renewable energy products (for example, FIT on solar and wind electricity) and on renewable energy production (for example, concessionary loans for capital acquisition).**

Turning briefly to taxes, the RVM requires that specific taxes paid by producers of renewable energy be added to the value of sales in the estimation of rent. Specific taxes would include any royalties paid on renewable energy production, as well as other fees to the extent they are clearly related to energy production and not to general business operations; a fee paid for a wind farm operator's license would be considered a specific tax, while a normal business licence fee that would be paid by any operating entity would not.

Royalties, which are common in the cases of fossil fuels, minerals and timber, are not generally collected by governments on renewable energy production, with the exception of hydroelectricity. Governments today are mainly interested in supporting nascent geothermal, solar and wind industries – and regularly do so in the form of subsidies – so there is no broad collection of royalties on these resources. As discussed in Appendix 1, this may change in the future as these industries mature, subsidies are reduced and governments begin to view the resources as public assets from which rent can, and should, be captured through royalties and other payments. **For the purposes of the CWON, we recommend that no special effort be made to measure the few specific taxes that may be paid on geothermal, solar and wind resources today but that consideration be given to how these payments might evolve in the future and what that might mean for future patterns of rent (see Section 3.3.3.3). For hydroelectric resources, we recommend that royalties and other specific taxes paid on production be accounted for in the calculation of rent.**

3.3.2 The costs of intermittency – Grid integration costs of variable renewable energy resources

Other than hydroelectric resources, which have been around for decades and are well integrated into existing national energy systems, renewable electricity sources are relative newcomers. They are also, at least in the case of solar and wind resources, quite different from existing electricity system components. The nature of traditional electricity generation technologies is such that they can 1) operate nearly continually; 2) vary their level of output according to demand; 3) be easily integrated with one another in a national grid. This is true of fossil fuel and nuclear generation, largely true of hydroelectric generation and also true of geothermal generation where it exists. Solar and wind – or variable renewable energy (VRE) – resources are different.

Due to their nature, VRE resources are not as predictable as other sources of electricity. Put simply, the sun does not always shine and the wind does not always blow. "Capacity credit" is the term used to reflect the contribution of VRE resources to overall electrical system security. It can be estimated by determining the capacity of conventional plants displaced by solar and wind resources while maintaining the same degree of system security; that is, an unchanged probability of failure to meet the reliability criteria for the system. Alternatively, it is estimated by determining the additional load that the system can carry when wind power is added while maintaining the same reliability level (European Wind Energy Association, 2010).

Reliability is not the only issue in integrating VRE resources into existing electricity systems. Upgrades may be needed to national transmission and distribution grids as well. In order to connect remote production sites, such as offshore or desert wind farms, new trunk powerlines may be needed. To take advantage of internationally distributed production sites to "smooth" production and increase system security, cross-border transmission lines will be required (European Wind Energy Association, 2010).

Under conditions of long-term competitive equilibrium, in which renewable and non-renewable electricity sources are fully integrated into the same national system, the reliability and grid connection costs of the various sources would be factored into the prices of their outputs. Rent on solar and wind resources would therefore reflect the lower reliability of wind and solar and any higher costs associated with their transmission *vis à vis* other sources.

It is clear, however, that solar and wind energy resource markets are not in long-term competitive equilibrium, especially not in developing countries. However, as argued above, in many developed countries they operate in an industry that has moved toward equilibrium in recent decades (Text Box 2). Moreover, VRE resources remain relatively small players in what is a massive global electricity market. At low levels of market penetration, VRE grid integration costs can be expected to be modest (European Wind Energy Association, 2010). The International Energy Agency (IEA, 2018) describes four stages of VRE deployment. Only in the third phase, when VRE resources represent from 10-25% of electricity generation, do significant grid integration challenges emerge. Only a few countries were considered to be at Phase 3 or higher as of 2018.[26]

Text Box 2 - Progress on eliminating vertical integration in electricity production and distribution

One of the main issues preventing electricity markets from achieving long-term competitive equilibrium in the past was vertical integration of electricity production and transmission/distribution. Large public utilities not only owned and operated all the generating capacity, but they did the same for the powerlines and other infrastructure necessary to get electricity from the generating station to consumers. Eliminating the monopoly power imparted to these massive, integrated companies has been a major effort of market reforms. The OECD's PMR indicators (see description in Section 3.2.1) consider vertical integration in the electricity industry on a scale of 0 (complete integration) to 6 (complete separation of ownership). Between 2000 and 2018, the OECD average for the vertical integration indicator dropped from 5.19 to 2.3, suggesting considerable progress toward independence among producers and transmitters/distributors of electricity, even if work remains to separate them entirely.

As noted above (Section 3.2.1), the theoretical applicability of the RVM to renewable energy resources is less than ideal due to distortions in renewable energy markets. Failure to internalize the full costs of VRE grid integration would certainly be among them and could be considered an implicit subsidy. At this initial stage in the development of the renewable energy accounts for the CWON, however, it is not clear that this particular distortion, among the others, deserves special treatment. We would, therefore, **not recommend that VRE grid integration costs be considered when estimating renewable energy resource rents**.

3.3.3 Estimating revenues and costs in the future

No matter what method is used to determine renewable energy resource rent (RVM, least-cost alternative or something else), the need to estimate future revenues and costs cannot be avoided. This is because the final step in estimating the value of the resource as an economic

[26] Phase 3 (10-25% VRE generation): Italy, the United Kingdom, Greece, Spain, Portugal, Germany and parts of the United States and Japan; Phase 4 (>25% VRE generation): Ireland and Denmark.

asset is to calculate the net present value (NPV) of a stream of annual rent flows over the lifetime of the resource.[27]

The SEEA-CF recommends that "in the absence of…information on expected future price changes…estimates of [future] resource rent should be set based on current estimates of resource rent, thus assuming no price changes beyond the general level of inflation" (SEEA-CF ¶5.133). This is the approach already adopted in the natural capital accounts of the CWON and also used by most statistical offices in the valuation of natural resource assets. In the case of the natural resource assets that have been valued to date – mainly those that are bought and sold in long-standing, relative stable and predictable markets (fossil fuels, minerals and timber) – the assumption of constant future rents is defensible. It likely is as well for hydroelectric resources, which are well established economically and technologically.[28] In the cases of the rapidly evolving markets for geothermal, solar and wind energy, however, it is not. The state of play in these markets in terms of the costs of technologies (solar panels, for example), the prices for electricity (including the possibility of widespread carbon pricing in the future) and uncertainty around the future of subsidies is simply too fluid to make an assumption of constant rent realistic.

This means that research will be required to determine reasonable future trajectories for, on the one hand, revenues from renewable production and, on the other, the cost of that production.

3.3.3.1 Future revenues

Revenues are a function of the quantities of renewable energy produced and the price renewable energy commands in the market. A general starting point for production forecasts is the International Energy Agency's annual *World Energy Outlook*, which provides multi-decade projections of most variables of importance for energy markets, though without a great deal of regional or temporal detail. The 2016 edition of the report contains a special focus on renewable energy resources and the 2018 edition does so for electricity in general.

Regarding prices, there is an overwhelming amount of information available on possible future trajectories (Weron and Zator, 2014). Thus, the problem is not finding a price forecast but choosing among the various alternatives available (see, for example, Joint Research Centre, 2018 and IEA, no date). In general, any model of the energy sector will include a future price path, though the researchers may not make the path available in their results. The paths are "endogenous" to the models and typically what users are interested in is the outcome – how much does each sector grow or, in today's world, what changes will result in global carbon levels. Thus, the modelling literature may not be a good source of information regarding future electricity prices. A useful strategy may be to partner with the International Energy Agency or another agency involved in large-scale energy modelling to obtain price forecasts. Private corporations like Shell and British Petroleum also have energy models that may be sources of information.

[27] Neoclassical economic theory provides the rationale for this: the value of any asset is assumed to be equal to the discounted present value of the stream of benefits it will provide its owner over its useful lifetime. In most instances, this value is determined through transactions in assets between buyers and seller in the marketplace; the values of both bulldozers and laptop computers are determined this way. In the instance of natural resources, markets are either very thin (few transactions) or absent entirely. Thus, national accountants must estimate the value of these resources indirectly by calculating the net present value of their lifetime benefits, which is taken to be the stream of rent they generate over their lifetimes.

[28] It should be noted, however, that the assumption of constant future rents has the effect of embedding the volatility of resource commodity prices into natural asset valuations. Research into alternative versions of the NPV calculation to deal with such volatility has been undertaken by the United Nations Expert Advisory Group on National Accounts (2014).

A simple approach to projecting future prices may be to assume they will be equal to long-term averages of historical prices (Advisory Expert Group on National Accounts, 2016).

3.3.3.2 Future costs

In terms of future production costs, a promising source of both data and methods is research into the "levelized cost of electricity" (LCOE). LCOE is widely used to compare the cost-effectiveness of competing technologies and guide investment decisions (Branker *et al.* 2011). It reports the NPV of production costs (both capital and operating) on a per-unit-output basis ($/kWh) and can include various capital depreciation profiles. This, in principle, provides all that is needed in the RVM in terms of cost inputs. The advantage to CWON of looking to this literature for data and methods is that the area is both active and mainstream. The International Energy Agency, for example, presents estimates of LCOE in its publications. Use of LCOE estimates from an agency like the International Energy Agency would lend credibility to renewable energy resource valuation in the CWON. One concern with LCOE values is that they underestimate the cost of VRE resources because they do not consider capacity credits.

3.3.3.3 Future subsidies and taxes

Regarding subsidies, which can affect both the revenue and cost side of renewable energy production, the Netherlands recently announced the world's first subsidy-free wind project. It appears that China, the world's largest solar electricity producer, is moving toward some subsidy-free projects as well (Reuters, 2019). Researchers are already reporting solar and wind energy LCOE values – in the absence of subsidies – that are competitive with traditional fossil fuel and nuclear electricity (Lazard, 2018). The International Renewable Energy Association (IRENA and CPI, 2018) argues that "electricity from renewables will soon be consistently cheaper than from most fossil fuels. By 2020, all the renewable power generation technologies that are now in commercial use are expected to fall within the fossil fuel-fired cost range, with most at the lower end or undercutting fossil fuels." Thus, though renewable energy rents will to continue to be impacted by subsidies for some time to come, subsidies will likely diminish – or even disappear – over the kind of lifetimes recommended for NPV calculations for renewable energy resources. Given this, projecting the future path of subsidies in valuing renewable energy for the CWON may be as simple as assuming a linear decline from their current level to some diminished level (or zero) over a reasonable time horizon. A potential source of data is the International Institute for Sustainable Development's Global Subsidies Initiative (GSI), which has data for renewable energy subsidies by technology type, though only in Europe. The GSI data are, in turn, based on data from the Council of European Regulators (CEER, 2013). The GSI also provides data for some non-European countries; for example, China and India.

Consideration must also be given to future patterns of specific taxes on renewable energy resources. Though royalties and other such taxes are negligible today on geothermal, solar and wind (but not on hydroelectric) resources, they may not remain so forever. A reasonable guide to how geothermal, solar and wind resources may be treated in the future would be the treatment rent from other natural resources is given by governments. Evidence from Statistics Canada's national balance sheet – the only one in the world to apportion the value of natural resource assets between the government and corporate sectors – suggests that Canadian governments collect about 25% of rent on fossil fuel, mineral and timber resources. An approach to incorporating future royalty payments on geothermal, solar and wind resources in the CWON might be, then, to assume a gradual ramping up of royalties from zero to 25% over the same time horizon over which subsidies are assumed to diminish.

3.3.3.4 Resource life

In terms of choosing the “lifetime” for renewable energy resources, standard practice in accounting for renewable natural resources would suggest the use of a very long (50 year[29]) lifetime in the NPV calculation. Given the uncertainties around revenues and costs, it may be more appropriate to use a finite lifetime in the NPV calculation for renewable energy resources; a 25-year horizon would be reasonable for resources with highly uncertain future revenues and costs like solar and wind electricity. This is long enough to meaningfully capture the value of the asset while minimizing the impact of any uncertainties in the rent estimate on the asset value. It is also approximately equal to the expected lifespan of renewable energy generation equipment, after which equipment may be “repowered” (for example, replacement of the generators or blades in a wind turbine). Thus, use of a 25-year horizon may eliminate the need to factor repowering costs into revenue and cost projections. A longer time horizon (50 years) could be used in the case of hydroelectric resources, for which more stable future costs and revenues can be assumed.

We do not recommend preparing detailed forecasts of all of the above variables in the context of the CWON. Doing so would add considerable complexity to the estimation of renewable energy resource values for little gain in accuracy, given the uncertainty in the underlying data and assumptions. **Rather, for now, we suggest developing one or two realistic scenarios for each and testing the sensitivity of the estimates to different assumptions around the trajectories of key variables.** This should be sufficient to determine which variables have enough impact on the estimates to require more detailed modelling in future editions of the report.

We discuss the questions around estimation of future prices, generation, subsidies and costs in more detail in the next section of the paper on *ex ante* modelling.

[29] Use of lifetimes beyond 50 years in NPV calculations has little effect on the resulting values, since the effect of discounting is to greatly reduce the present value of rent flows in the distant future.

4 *Ex ante* valuation of renewable energy assets

At the end of the preceding section, we discussed the approach that might be used in deriving renewable energy resource values in an *ex post* accounting context. As noted, because the market rarely values environmental assets directly, this requires assumptions about future trajectories of revenues and costs related to renewable energy production for use in indirect valuation *via* NPV calculations. In keeping with the practice of environmental asset valuation, the approaches proposed above to projecting revenues and costs are not sophisticated. Whenever possible, national accountants make the simplifying assumption that current-period rent will continue unchanged into the future, avoiding the need to make any explicit decisions about how revenues and costs will evolve; this is the approach routinely used, for example, when national accountants value fossil fuel, mineral and timber resources. When such an assumption is not legitimate, as in the case of rapidly evolving markets for solar and wind energy, the approaches suggested for use in *ex post* accounting remain simple; reliance on projections of prices, production levels and costs made by third-party organizations, such as the International Energy Agency, for example.

In this section, we turn to the valuation of renewable energy resources in an *ex ante* context. This is a more sophisticated task that rests on the modeller undertaking his/her own detailed assessment of the future and how renewable energy resources and their value might evolve in it. We do nothing more than scratch the surface of this topic – which is broad and deep – in what follows.

4.1 Why undertake *ex ante* asset valuation

National accounting provides a detailed framework for tracking changes in wealth that have occurred in the past. This *ex post* approach, which employs a minimum of theoretical structure to interpret real observations of the world[30], provides a valuable record of past events from which to learn. However, public policy is inherently forward-looking. As such, *ex ante* techniques to assess the future value of assets are an important complement to the learning-from-the-past enabled by the national accounts. Estimation of future national wealth (given particular assumptions) through *ex ante* asset valuation facilitates the analysis of proposed policies or actions, allows the evaluation of trade-offs and provides a critical guide to better economic decision-making.

4.1.1 The difference between *ex post* and *ex ante* valuation

Ex post and *ex ante* valuation approaches are distinguished by their temporal viewpoints. The former use observations on past states of the world to construct measures of past or current value.[31] The latter seek instead to value states of the world that have not yet occurred, introducing a fundamental element of uncertainty *via* assumptions about the future. This uncertainty divides the backwards-looking accounting procedures of the SNA from the forward-

[30] The SNA is designed in light of the neoclassical theory of production and neoclassical assumptions (for example, perfectly competitive markets) justify its core accounting identities. Though markets are rarely, if ever, perfectly competitive in reality, the SNA nonetheless provides a valuable factual description of economic activity that is much used in policy design and evaluation.

[31] The fact that valuation of some environmental assets requires projections of future rent streams notwithstanding. Such projections are one of the few instances in which the national accounts do not rest entirely on past observations. National accountants do all they can to limit the degree to which they must make assumptions about the future in valuing environmental assets.

looking modelling approaches required for *ex ante* valuation. Because of this uncertainty, the results of models should be interpreted with caution, based on a thorough technical review of the method employed. In the best case, *ex ante* models are “signposts” to the future, guiding policy makers along optimal paths. It is important to emphasize that *ex ante* valuation is always undertaken for purposes other than the estimation of accounting values. National accounts must not rely on *ex ante* valuation of resource assets, as to do so would be inconsistent with the conceptual (*ex post*) basis of all other values in the accounts.

4.2 Review of literature on *ex ante* asset valuation

Despite widespread interest in modelling the future economic role of renewable energy, little attention has been paid to the explicit *ex ante* valuation of the associated assets. The few forward-looking studies addressing renewable energy asset valuation have all done so using the least-cost alternative method (see Section 3.2.2). Shrestha and Abeygunwardana (2009) provide an accessible review of the methodology. Such studies can be differentiated by the realism of their treatment of future least-cost alternatives.

In the simplest cases, prices for the least-cost alternatives are taken as exogenous to the modelling exercise; for example, estimated from simple extrapolations of current price trends or from most-likely price scenarios. For example, Hreinsson *et al.* (2013) evaluate future hydropower rents in Iceland by comparing engineering estimates of generating costs against a selection of reference prices to estimate net present values of (differential) rent per project. While tractable, this approach is not theoretically grounded: future prices will clearly be determined by the supply of electricity from the hypothetical project being evaluated. An “ideal” approach to least-cost evaluation should recognize this fact, modelling the entire equilibrium system within which future prices are endogenously determined (Zucker and Jenkins, 1984). Wandjii and Bhattacharyya (2018) take this approach, valuing national hydropower rent for Cameroon as the difference between the optimized total costs of a hypothetical future system that includes hydropower and one excluding it.[32] Hybrid approaches are also possible; for example, Boungnong and Phoneko (2012) attempt to model rents per hydropower project under various assumptions about least-cost alternative energy sources.

4.3 Factors influencing the evolution of renewable energy asset values

Any *ex ante* valuation method depends on projections of the future demand for and supply of renewable energy resources. Uncertainty in these projections can be profound due to the coincidence of rapidly evolving technologies and a volatile regulatory environment. *Ex ante* modelling of renewable energy resource values benefits from relatively stable biophysical variables (with a few important exceptions) and fairly well characterized trends in economic variables. It is the evolution of psycho-social preferences, driving consumption choices and public policy, that represents the greatest challenge. The future course of these critical variables is essentially unpredictable and should be handled *via* scenario analysis (see below).

The fundamental biophysical drivers of future renewable resource values, on the demand side, are relatively well known: the global population is steadily growing, becoming wealthier and consuming more energy. The International Energy Agency’s Current Policies Scenario

[32] The Long-range Energy Alternatives Planning system software (LEAP) used in this this analysis is widely used and distributed free of charge by the Stockholm Environment Institute. As such, it is a credible and viable tool for undertaking country-level *ex ante* valuation studies.

projection from the 2018 *World Energy Outlook* estimates an almost 40% increase in global energy demand from 2017 to 2040 (IEA, 2018). How this demand will translate into increased demand for renewables is less certain, because statistical estimates of key economic parameters (such as income elasticities of demand) must rely on historical data – and tastes are changing. On the supply side, the physical abundance of most renewable energy resources (hydroelectric, solar and wind energy) is well-known (for example, Jacobson and Delucchi, 2011), while geothermal are less well characterized. Many of the spatial datasets needed to model the future biophysical abundance of renewable energy assets under various assumptions about generation efficiency, energy prices, and transportation costs are readily available. However, it is important to remember that solar, wind and hydroelectric energy all depend on aspects of an earth system that is rapidly changing as the climate warms (for example, cloud-free days, global circulation patterns, rainfall and oceanic circulation).

Individual trends in economic variables are amenable to forecasting, while general-equilibrium variables (for example, market prices for energy) are emergent properties that require far more data and assumptions to predict. Simple implementations of technology learning curves,[33] such as Moore's law, appear to accurately describe the development of solar and wind generation technologies in particular (Farmer and Trancik, 2007; Farmer and Lafond, 2016) and the ability to quantify associated uncertainty is growing (for example, Lafond *et al.*, 2018). Renewable energy technologies may improve significantly in the coming years. Enhanced geothermal systems are under development, for example, which would allow exploitation of geothermal energy almost anywhere on the planet (REN21, 2018). Solar photovoltaic technology efficiency is advancing rapidly and research into photosynthetic energy flow could lead to even greater advances in efficiency (Kabir *et al.*, 2018).

As is well known, generation technologies are only one aspect of the problem; storage and transmission infrastructure are equally important. The development of energy storage technologies (batteries) is the subject of intense effort (for example, Nykvist and Nilsson, 2015). Lithium-ion battery technology, in particular, could see significant improvements as production grows, materials improve and supply chains become more competitive as the mass production needed to meet the demand for electric vehicles ramps up (IRENA, 2017) – but hard-to-predict technological breakthroughs may well be the source of future technical improvements (Schlachter, 2013). While storage technology is easily traded and can be modelled at global scale, transmission infrastructure is fixed per country and requires more detailed spatial modelling. Transmission systems themselves will change as smart grid technology and distributed energy systems are put into place. Such systems can help reduce the grid integration costs of VRE (see Section 3.3.2), as imbalances between supply and demand are reduced (REN21, 2018; Kempener, Komor and Hoke, 2013).

The modelling of consumption choices represents the greatest challenge to the *ex ante* valuation of renewable energy resources. As discussed in sections 2 and 3, energy markets in general can be distorted by government market interventions, especially in the developing world. The extent of these distortions depends on political and social choices that are not amenable to quantitative forecasting. Prediction of consumption preferences, too, is intractable: global demand for renewables is growing (REN21, 2018) but how it will evolve as the impacts of global warming become more apparent is not known.

[33] A technology learning curve relates the unit cost of production to (cumulative) production volume, typically with a constant factor.

4.4 Possible methodological approaches

Following the framework outlined in sections 2 and 3, *ex ante* valuation of renewable energy resources should proceed *via* a calculation of the NPV of rents accruing to the resources expected to be present in future states of the world (estimated *via* the RVM or least-cost alternative method). For consistency with the national accounts, any such NPV valuation for a given year should include only those resources that fall within the asset boundary in that year.[34] Similarly, the value of proven but not producing renewable energy assets should not be included in *ex ante* valuation – as in the SNA, proven assets must be economically beneficial to be counted as assets. In a modelling context, only assets modelled as "in production" given prices and technology available in a given year should be counted.

The NPV of rents from renewable energy assets may be calculated using either the RVM or the least-cost alternative method. Identified examples of ex ante valuation all use the latter, using a variety of approaches. At the country level, case-by-case least-cost alternative valuation using assumed or observed output costs is clearly unsatisfactory, as it is difficult to imagine a scenario in which country-level exploitation of renewable energy assets does not move output (energy) prices. In contrast, rents may be modelled as residual values through use of producers' surplus estimates from computable partial- or general-equilibrium models, due to the equivalence between producers' surplus and differential plus scarcity rents (Hartwick and Olewiler, 1991).[35] Because of the centrality of energy supply to the economy at large, the use of partial equilibrium models (with price and demand paths beyond the energy sector taken as exogenous) for this is purpose is subject to criticism. However, the growing interest in modelling the global energy sector since the oil crisis of the 1970s has led to the development of several large-scale computable general-equilibrium models that may be useful. For example, the Global Trade Analysis Project (GTAP) model of the global economy now has an extended database that disaggregates the electricity sector, with hydroelectric, wind and solar resources individually modelled (Peters, 2016). Among energy-specific models, the International Energy Agency's World *Energy Model* is another leading example. Incorporating future changes to the biophysical availability of renewable resources, as well as their heterogenous distribution between countries and the differential productivity of specific sites, is simply a matter of modelling effort. This may be done in an aspatial framework (for example, as in GTAP) or *via* a spatially explicit representation of resources.[36]

Any effort to forecast renewable energy resource values must accommodate substantial uncertainty. The core methods available are scenario analysis (an arbitrary delineation of representative cases to explore the future state space); Monte Carlo analysis and allied methods (combinatorial explorations of the future state space); and sensitivity analysis (characterizing the role of key model parameters in defining the state space). These approaches serve fundamentally different roles. Scenario analyses are required where uncertainty is high and a meaningful "forecast" is not possible. Instead, a subset of possible cases is modelled. Among the key factors listed in the preceding section, the evolution of consumption preferences

[34] In contrast, Kahn (2017) compares national wealth accounts in which the value of assets is only included from the year of their discovery into the future against those in which values in past years are updated to include assets that, while not in use for production, still existed.

[35] Note that, in a partial- or general-equilibrium modelling context, the problems in applying the Ricardian or "differential" rent concept noted in Section 3.1 do not arise; markets in these models are in equilibrium by construction.

[36] For example, Tian *et al.* (2016) couple a biophysical model of forest growth (driven by outputs from IPCC global climate models) to a partial-equilibrium model of the global forest sector. Such efforts, while costly, are increasingly feasible due to the widespread availability of geospatial data.

and public policy will require scenario analysis in most cases, as these depend on the complexity of collective psychology, which has no generally accepted forecasting method. When uncertainty exists but is relatively low, combinatorial methods may be used to simulate the distribution of key parameters for analysis. For example, prices per kilowatt hour for renewable electricity resources can be modelled as a function of underlying technologies – but prudent forecasts will iterate such forecasts many times, varying independent parameters to estimate a confidence interval around predicted values[37]. Sensitivity analysis, by contrast, is most useful to demonstrate the influence of model structure on results. The *de facto* standard for forecasting future prices, for example, is a (dynamic) computable general-equilibrium model. Such models are complex, but are sensitive to key parameters (for example, elasticities of substitution between renewable and non-renewable energy sources) and assumptions (for example, transmission costs and trade structure). Prudent use of such models requires sensitivity analysis, often using combinatorial methods, to approximate the uncertainty in results.

Where resources allow, detailed modelling of future national supply is the preferred option. LEAP software (see Footnote 32) could be used to do this on a country-by-country basis or a partnership could be established with a global general-equilibrium modelling team. Beginning with geospatial information on the global distribution of renewable energy resources, those considered likely to provide economic benefits could be defined using projections of electricity prices, levelized costs of electricity, demand and transmission costs. Such an approach would imply a major, resource-intensive project with heavy reliance on geospatial data.

An alternative would be to accept less accurate “back-of-the-envelope” calculations based on approaches like that of Hreinsson *et al.* (2013). Such approaches should be undertaken within a scenario-analysis framework as discussed above.

[37] In the simplest case of fitting a standard linear model to past data, as is done for technology learning curves, confidence intervals can be fit from the distribution of past observations.

5 Conclusion

Valuing renewable energy resources 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. This report reviews the associated concepts and methods and makes several recommendations for their application in the context of the World Bank's *Changing Wealth of Nations* reports. These recommendations are rooted in both the theory and practice of national economic and environmental accounting as laid out in the SNA and the SEEA-CF. Where best practices are unclear or simply unrealistic, our recommendations are guided by the need to provide practical, useful information to allow management of a country's natural resource assets.

Neither the SNA nor the SEEA-CF defines a complete and internally consistent approach to valuing renewable energy resources. The SNA largely disregards them but implies they do not qualify as economic assets because ownership rights cannot be enforced. The SEEA-CF treats them in detail, considering their value to be captured in associated land, but fails to adequately address renewable energy generation that 1) is not associated with land (offshore wind, solar and ocean resources); 2) exists under ownership rights clearly separated from land (most geothermal resources); or 3) is associated with land that has no economic value and does not appear in the national accounts (hydroelectric and most utility-scale solar/wind resources). In the few cases where renewable energy resources are in fact bundled with land that is both owned and valued in the national accounts (for example, wind turbines on agricultural land), the SEEA-CF's approach assumes that land markets have accurately "priced in" the value of associated resources. While the SEEA-CF's argument has *prima facie* appeal, we find the assumptions underlying it do not stand up under examination. We propose instead that a separate asset category for renewable energy resources be created within both the SNA and the SEEA-CF and that the value of these assets be partitioned between their legal owners (governments) and economic owners (renewable energy companies). We consider the risk of double counting between the existing land asset and this new asset category and find it to be low on both economic and accounting grounds; specifically, land markets today likely fail to completely internalize renewable energy resource values (where such resources are bundled with land) and national accountants employ practical means in compiling national balance sheets that permit the avoidance of double counting.

Within the national accounts, natural resource assets are to be valued as the net present value of their associated rents. Little attention has been paid to the estimation of rents arising from renewable energy resources. We consider this subject at length and find, as in the SEEA-CF, that a "residual value" method (that is, rent measured as resource revenues less associated production costs) is appropriate. The validity of this method rests on an assumption of renewable energy markets approximating long-run competitive equilibrium. While we acknowledge that markets in many countries – especially in the developing world – do not meet this standard, data from the OECD suggest considerable movement toward competitiveness since deregulation of electricity markets began, at least in developed countries. Heavy subsidization of renewable energy production and consumption remains, however, and this poses a clear theoretical challenge to the residual valuation method. An alternative approach, known as the "least-cost alternative" method, attempts to identify rents by comparing the cost of electricity generation with and without renewable resources. This technique has been applied with varying sophistication to the valuation of hydroelectric resources.

Despite the theoretical challenge to the residual value method posed by market imperfections, we recommend it for the valuation of renewable energy resources. Our primary rationale is consistency: the residual value method is widely applied in country practice (and in the *Changing Wealth of Nations* reports) to other environmental assets that policy-makers must evaluate against renewable energy resources. We consider the potential pitfalls of applying this approach, notably the payment of subsidies on renewable energy production, consumption and equipment manufacture. While care must be taken, heavy subsidization is not unique to the renewable energy sector.

Finally, reviewing the small (and largely experimental) literature on *ex ante* valuation of renewable energy resources, we note that many factors must be considered and suggest a range of approaches for such forward-looking valuation.

References

Bernard, J.T., Bridges, G.E., and A. Scott. 1982. "An evaluation of potential Canadian hydro electric rents." Resources Paper No. 78. Vancouver: University of British Columbia.

Bidwell, D. 2016. "The Effects of Information on Public Attitudes Toward Renewable Energy." *Environment and Behaviour*48(6): 743-768.

Blenkinsop. 2018. "EU ends trade controls on Chinese solar panels." Reuters. Retrieved August 31, 2018. https://www.reuters.com/article/us-eu-china-trade/eu-ends-trade-controls-on-chinese-solar-panels-idUSKCN1LG1QM

Borenstein, S. 2011. "The private and public economics of renewable electricity generation*."* Working paper 17695, National Bureau of Economic Research. https://www.nber.org/papers/w17695 .

Bougette, P. and C. Charlier. 2017. "Anti-dumping and Feed-in Tariffs as Good as Buddies? Modeling the EU-China Solar Panel Dispute." GREDEG Working Paper no. 2017-17. https://ideas.repec.org/p/gre/wpaper/2017-17.html

Boungnong, C. and D. Phonekeo. 2012. "Economic Rent from Hydropower Development in the Case of Lao PDR." *GMSARN International Journal 6.2*: 35-44.

Branker, K., Pathak, M.J.M., and J.M. Pearce. 2011. "A Review of Solar Photovoltaic Levelized Cost of Electricity." *Renewable & Sustainable Energy Reviews* 15: 4470-4482.

Cadogan-Cowper, A. and P. Comisari. 2009. Recording land in the national balance sheet. Information paper for the London Group Meeting, Wiesbaden, 30 November-4 December 2009. https://unstats.un.org/unsd/envaccounting/londongroup/meeting15/LG15_11_1a.pdf

CEER (Council of European Energy Regulators). 2013. S*tatus Review of Renewable and Energy Efficiency Support Schemes in Europe*. 52 pages.

Da Silva., E.A. 2018. "Absolute Rent". In Macmillan Publishers Ltd (eds). *The New Palgrave Dictionary of Economics*. London: Palgrave Macmillan.

De Beivre, D., Poletti, A. and Espa, I. 2016. "Actual and potential WTO disputes on subsidies for fossil and renewable energy." Paper for the international conference *Global Public Goods, Global Commons and Democracy: An Interdisciplinary Perspective.* KU Leuven. https://ghum.kuleuven.be/ggs/events/2016/international-conference-global-commons-global-public-goods-and-global-democracy-leuven/de-bievre-espa-poletti-actual-and-potential-wto.pdf

Diamond, K.E. 2015. "Wake Effects, Wind Rights, and Wind Turbines: Why Science, Constitutional Rights, and Public Policy Issues Play a Crucial Role." *William & Mary Environmental Law and Policy Review* 40(3): 813-847. https://scholarship.law.wm.edu/cgi/viewcontent.cgi?article=1658&context=wmelpr

Diamond, K.E. and E.J. Crivella. 2011. "Wind Turbine Wakes, Wake Effect Impacts, and Wind Leases: Using Solar Access Laws as the Model for Capitalizing on Wind Rights During the Evolution of Wind Policy Standards." *Duke Environmental Law & Policy Forum* 22: 195-244.

Danish Energy Agency. 2018. "Energy Statistics 2016". https://ens.dk/sites/ens.dk/files/Statistik/energy_statistics_2016.pdf .

Enevoldsen, P. and D. Sovacool. 2016. "Examining the Social Acceptance of Wind Energy: Practical Guidelines for Onshore Wind Project Development in France." *Renewable & Sustainable Energy Reviews* 53: 178-184

European Commission. 2017. "Citizen support for climate action". *Energy, Climate change, Environment.* https://ec.europa.eu/clima/citizens/support_en .

European Commission, International Monetary Fund, Organisation for Economic Co-operation and Development, United Nations and World Bank. 2009. *System of National Accounts 2008.* Washington, DC: World Bank. Retrieved from http://documents.worldbank.org/curated/en/417501468164641001/System-of-national-accounts-2008

Eurostat and OECD. 2015. "Eurostat-OECD compilation guide on land estimation. Luxembourg: Publications Office of the European Union. https://ec.europa.eu/eurostat/documents/3859598/6893405/KS-GQ-14-012-EN-N.pdf

European Wind Energy Association. 2010. "powering Europe: wind Energy and the electricity grid." http://www.ewea.org/grids2010/fileadmin/documents/reports/grids_report.pdf

Farmer, J.D., and F. Lafond. 2016. "How predictable is technological progress?"*Research Policy*, 45: 657-665.

Farmer, J.D., and J. Trancik. 2007. "Dynamics of technological development in the energy sector". *London Accord*. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.465.3841&rep=rep1&type=pdf

Fine, B. 1982. "Royalty and Rent". *Land Economics* 58(3): 338-350.

Gillen, D. and J-F. Wen. 2000. "Taxing Hydroelectricity in Ontario." *Canadian Public Policy 26(1)*: 35-49.

Hartwick, J.M. and N.D. Olewiler. 1999. *The Economic of Natural Resource Use*. 2nd Edition. Reading, Mass.:Addison-Wesley.

Hreinsson, E.B. 2008a. "Renewable Energy Resources in Iceland – Environmental Policy and Economic Value." *Nordic Conference on Production and Use of Renewable Energy.* Vaasa, Finland.

Hreinsson, E.B. 2008b. "The Economic Rent in Hydro and Geothermal Resources in Iceland with Reference to International Energy Markets and Resource Cost Structure." *Working Group on European Electricity Infrastructure.* Paper 08GM0965.

Hreinsson, E.B, Jonassson, K. and G.G. Petursson. 2013. "Discounted value of economic rent in hydro and geothermal expansion planning in Iceland." 48th International Universities Power Engineering Conference (UPEC).

Hyland, M. 2015. "Restructuring European electricity markets: A Panel data analysis." *ESRI Working Paper No. 504.* Dublin: The Economic and Social Research Institute (ESRI).

IEA (International Energy Agency). 2017. "Renewables 2017: Analysis and Forecasts to 2022". https://www.oecd-ilibrary.org/energy/renewables-2017_re_mar-2017-en

IEA (International Energy Agency). 2018. System Integration of Renewables: An Update on Best Practice. https://www.iea.org/publications/insights/insightpublications/SystemIntegrationofRenewables.pdf

IEA (International Energy Agency). No date. Fossil-fuel subsidies (webpage). https://www.iea.org/weo/energysubsidies/

IPCC (Intergovernmental Panel on Climate Change). 2011. *Renewable Energy Sources and Climate Change Mitigation.* O. Edenhofer, R.P Madruga and Y. Sokona (Eds). New York: Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/03/SRREN_FD_SPM_final-1.pdf

Ingelson, A. 2018. "Wind Energy Development on Public Lands in Alberta: A Missed Opportunity". *University of Calgary Faculty of Law Blog.* *https://ablawg.ca/2018/06/14/wind-energy-development-on-public-lands-in-alberta-a-missed-opportunity/comment-page-1/*

IRENA (International Renewable Energy Agency). 2017. Electricity Storage and Renewables: Costs and Markets to 2030. Abu Dhabi: International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

IRENA (International Renewable Energy Agency) and CPI (Climate Policy Initiative). 2018. Global Landscape of Renewable Energy Finance. Abu Dhabi: International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_Global_landscape_RE_finance_2018.pdf

Jamasb, T. Nepal, R. And G.R. Timilisina. 2015. "A Quarter Century Effort Yet to Come of Age." *Policy Research Working Paper 7730.* Washington DC.: World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/22211/A0quarter0cent0developing0countries.pdf?sequence=1

Jacobson, M., and M. Delucchi. 2011. "Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials." *Energy Policy*, 39: 1154-1169.

Jilani, S.A. 2015. "Spectrum Allocation Methods: Studying Allocation through Auctions." *Journal of Economics, Business and Management* 3(7): 742-745.

Kabir, E., Kumar, P., Kumar, S., Adelodun, A.A., and K. Kim.2018. "Solar Energy: Potential and Future Prospects." *Renewable and Sustainable Energy Reviews* 82:894-900.

Kahn, E. 2017. "Questions on valuation of natural capital: evidence from Canada, 1970-2011." M.Sc. Thesis (June 2017). Supervisor: Thomas Picketty.

Kempener, R., Komor, P., & Hoke, A. 2013. "Smart Grids and Renewables: A Guide for Effective Deployment." Abu Dhabi: International Renewable Energy Agency. https://www.irena.org/documentdownloads/publications/smart_grids.pdf .

Lafond, F., Bailey, A., Bakker, J., Rebois, D., Zadourian, R., McSharry, P., and J. Farmer. 2018. "How well do experience curves predict technological progress? A method for making distributional forecasts." *Technological Forecasting and Social Change* 128: 104-117.

Landis, J.B. 2019. "Sunny and Share: Balancing Airspace Entitlement Rights Between Solar Energy Adopters and Their Neighbours." *Vanderbilt Law Review* 72(3): 1075-1114.

Lazard. 2018. "Levelized Cost of Energy Analysis." https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf

Levine, A. L. and Young, K. R. 2018. "Efforts to streamline permitting of geothermal projects in the United States." *Rocky Mountain Mineral Law Foundation Journal* 55(1).

Limbu, T.R. and R.M. Shrestha. 2004. "Evaluation of Economic Rent of Hydropower: A Case of Nepal." *Australasian Universities Power Engineering Conference.* Brisbane.

Malinowski, M., Leon, J.I. and H. Abu-Rub. 2017. "Solar Photovoltaic and Thermal Energy Systems: Current Technology and Future Trends." *Proceedings of the IEEE* 105(11). https://ieeexplore.ieee.org/abstract/document/7914744

Nykvist, B., and M. Nillson. 2015. Rapidly falling costs of battery packs for electric vehicles. *Nature Climate Change*, 5: 329-332.

OECD, United Nations, European Union, The World Bank and Food and Agriculture Organization of the United Nations. 2014. *System of Environmental Economic Accounting 2012: Experimental Ecosystems Accounting.* New York: UN. https://doi.org/10.1787/9789210562850-en.

Orkustofnun (National Energy Authority). no date. "Legal Framework". *Geothermal.* https://nea.is/geothermal/legal-and-regulatory-framework/nr/102 .

Peters, J. 2016. "The GTAP-Power data base: disaggregating the electricity sector in the GTAP data base." *Journal of Global Economic Analysis*, 1(1): 209-250.

Pew Research Center. 2018. *Majorities See Government Efforts to Protect the Environment as Insufficient. "*Strong public support for more solar and wind power". https://www.pewinternet.org/2018/05/14/majorities-see-government-efforts-to-protect-the-environment-as-insufficient/ps-05-10-18_report-07/ .

Pineau, P-O., Tranchecoste, L., and Y. Vega-Cardenas. 2017. "Hydropower royalties: A comparative analysis of major producing countries (China, Brazil, Canada, and the United States)." *Water* 9(287).

Radowitz, B. 2019. "Vestas exec: Nordics show how all countries will become subsidy-free." *Wind Europe Conference and Exhibition. https://windeurope.org/confex2019/files/media-and-press/Recharge-Day-one.pdf*

Rai, K. and B. Van Campen. 2015. "Geothermal policy and regulation: cases from Chile, Kenya, New Zealand and the Philippines." IRENA.

REN21. 2018. Renewables 2018: Global Status Report. Paris: REN21 Secretariat. http://www.ren21.net/gsr-2018/

Reuters. 2019. "China to give Priority to subsidy-free renewable projects in new plan." April 12, 2019. https://uk.reuters.com/article/us-china-renewables-subsidy/china-to-give-priority-to-subsidy-free-renewable-projects-in-new-plan-idUKKCN1RO1HG

Rothman, M. 2000 "Measuring and Apportioning Rents from Hydroelectric Power Developments." *World Bank Discussion Paper no. 419*. Washington DC: World Bank. https://elibrary.worldbank.org/doi/abs/10.1596/0-8213-4798-5

Santos, J., Domingos, T., Sousa, T., and M. St. Aubyn. 2016. “Does a small cost share reflect a negligible role for energy in economic production?” MPRA Paper No. 70850 (working paper). https://mpra.ub.uni-muenchen.de/70850/.

Schlachter, F. 2013. “No Moore’s Law for batteries.” *Proceedings of the National Academy of Sciences of the United States of America*, 110(14): 5273.

Shrestha, R. M. and A.M.A.K Abeygunawardana. 2000. “Evaluation of economic rent of hydro power projects.” *Energy Policy 37*: 1886-1897.

Sinner, J. and J. Scherzer. 2007. “The Public Interest in Resource Rent.” *New Zealand Journal of Environmental Law* 11: 279-295.

Smith, E. 2007. “Wind Energy: Siting Controversies and Rights in Wind.” *Environmental & Energy Law & Policy Journal.*

Statistics Canada, 2015, “Natural resource wealth statistics in the National Balance Sheet Accounts”, in *Latest Developments in the Canadian Economic Accounts*, Catalogue No. 13-605-x, Ottawa: Statistics Canada. https://www150.statcan.gc.ca/n1/en/pub/13-605-x/2015009/article/14239-eng.pdf?st=w5qiZ4fb

Statistics Netherlands. 2011. “Environmental Accounts of the Netherlands 2010.” The Hague: Statistics Netherlands. https://www.wavespartnership.org/sites/waves/files/images/Netherlands%20env%20accts%202010.pdf

Statistics New Zealand. no date. “Energy Monetary Stock Account 1987-2001”. http://unstats.un.org/unsd/envaccounting/ceea/archive/Energy/EnergyMonetaryStockAccount_NewZealand.PDF

Tian, X., Sohngen, B., Kim, J., Ohrel, S., and J. Cole. 2016. “Global climate change impacts on forests and markets.” *Environmental Research Letters*, 11(3): 035011.

UK Office for National Statistics (UK ONS). 2016. “UK natural capital: monetary estimates, 2016.” *Statistical Bulletin.https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/uknaturalcapital/monetaryestimates2016*

UK Office for National Statistics (UK ONS). 2019. “Scottish natural capital: ecosystem Service Accounts, 2019.” *Experimental Statistics. https://www.ons.gov.uk/releases/scottishnaturalcapitalecosystemserviceaccounts*

United Nations, European Union, Food and Agriculture Organization of the United Nations, International Monetary Fund, Organization for Economic Co-operation and Development and World Bank. 2014. *System of Environmental-Economic Accounting 2012 - Central Framework.* New York: United Nations. https://unstats.un.org/unsd/envaccounting/SEEA-CFRev/SEEA-CF_CF_Final_en.pdf

United Nations. 2019. *System of Environmental-Economic Accounting for Energy.* New York: UN. https://SEEA-CF.un.org/sites/SEEA-CF.un.org/files/SEEA-CF-energy_en.pdf

Van Campen., B. 2015. “Comparison of Geothermal regulation between Chile, Philippines and New Zealand.” Melbourne: Proceedings World Geothermal Congress.

Wandji, Y.F. and S.C. Bhattacharyya. 2018. “Evaluation of economic rent from hydroelectric power developments: Evidence from Cameroon.” *The Energy and Development Journal. https://dora.dmu.ac.uk/handle/2086/14494*

Wessel, R.H. 1967. “A Note on Economic Rent.” *The American Economic Review* 57(5): 1221-1226.

Weron, R. and M. Zator. 2014. “Revisiting the relationship between spot and future prices in the Nord Pool electricity market.” *Energy Economics* 44: 178-190.

Winters, M. S. and Cawvey, M. 2015. “Governance obstacles to geothermal energy development in Indonesia.” *Journal of Current Southeast Asian Affairs* 34(1): 27-56.

World Bank. 2011. *The Changing Wealth of Nations: Measuring Sustainable Development in the New Millennium.* Washington, DC: World Bank. http://documents.worldbank.org/curated/en/630181468339656734/The-changing-wealth-of-nations-measuring-sustainable-development-in-the-new-millennium

World Bank. 2018. *The Changing Wealth of Nations: Building a Sustainable Future.* Washington, DC: World Bank. http://documents.worldbank.org/curated/en/727941517825869310/The-changing-wealth-of-nations-2018-building-a-sustainable-future

Young, R.A. and J.B. Loomis. 2014. *Determining the Economic Value of Water: Concepts and Methods.* New York: Routledge.

Zhang, S. Andrews-Speed, P. Zhao, X. and He, Y. 2013. “Interactions between renewable energy policy and renewable energy industrial policy: A critical analysis of China’s policy approach to renewable energies.” *Energy Policy* 62: 342-353.

Zuker, Richard C. and Glenn P. Jenkins. 1984. “Blue Gold: Hydro-Electric Rent in Canada.” Development Discussion Papers 1984-01, JDI Programs.

Appendix 1– Will governments assert property rights to solar and wind resources?

A relevant question is whether governments in the future will cede solar and wind property rights to private individuals just because they happen to own the land that underlies the sun and wind. A plausible case can be made that such resources are public – as no individual had anything to do with their creation – and, therefore, that any economic benefits arising from their use should flow to the government on behalf of all citizens. Governments may one day choose to realize those benefits – even if they mainly do not today – through legislation asserting public property rights. Indeed, some have already begun to do so in a limited way. In Canada, for example, the province of British Columbia charges royalties based on revenue for wind power development on crown lands. The province of Ontario uses a competitive bidding process for wind power developments on crown land (Ingelson, 2018).

Another reason governments may eventually exercise property rights over solar and wind resources is the clear and long-standing practice of doing so in the case of the most important renewable energy resource worldwide today, hydroelectric resources. Governments in many countries ensure that the economic benefits of hydroelectric resources flow to citizens by controlling the resources through publicly owned hydro utilities. This allows them to sell hydroelectricity at prices below competitive market rates, effectively distributing resource rent to consumers.[38] Even in countries with privatized electricity systems, governments charge considerable royalties on the use of water in hydroelectricity production in an effort to capture the associated rent (Pineau *et al.*, 2017).

The similarly clear and long-standing government practice of capturing rent on fossil fuel and mineral exploitation provides another reason why rent capture on renewable energy resources may be taken more seriously by governments in the future. Certainly, in the case of geothermal resources, which share much in common with other sub-soil resources, it seems likely that governments will eventually apply the kind of royalty schemes already applied to fossil fuels and minerals. Indeed, some already do. That more will eventually do so seems all the more likely since governments in most countries claim the rights to geothermal resources (see Appendix 1).

There is more recent precedent in the case of the radio spectrum, which shares much in common solar and wind resources. All three are intangible, associated in some way with the atmosphere and difficult for any unit other than a government to assert property rights over. Governments have regulated access to the spectrum since the early 1900s. However, the economic value of the spectrum was not realized until the 1990s, when governments began to allocate spectrum to cellular telephone operators through competitive auctions. Spectrum auctions from 1994 to 1996 in the United States netted the government nearly $20 billion dollars (Jilani, 2015). Governments realized at that point that the spectrum was a public asset with substantial value. They may well eventually see the same to be true of solar and wind resources. It would be relatively simple for them to assert, as they did with the spectrum, their rights to the ownership of sun and wind energy within their jurisdiction.

Moreover, as growth in solar, wind and other renewables gradually permits a shift away from fossil fuels, governments in fossil fuel-producing jurisdictions may have little choice but to begin capturing rent on renewable energy. They may face substantial and unaffordable declines in

[38] Of course, some of these consumers are corporations, so not all the economic benefits end up flowing directly to households.

revenues otherwise. In the Netherlands, for example, an average 6.6% of national government revenues came from corporate payments of natural gas royalties from 2003 to 2016.[39] Over that same period, the country's natural gas reserves declined by nearly 50% in physical terms. This physical depletion coupled with economic pressures on the fossil fuel sector in general mean that the Dutch government cannot count on substantial revenues from its natural gas resources forever.[40] Given this, it is reasonable to suggest the government may, at some point, decide to collect royalties on its growing wind power resources.

[39] Author's calculations based on data from the Netherlands' Central Bureau of Statistics.

[40] In addition to the general economic pressures on the fossil fuel industry, the Dutch government is also facing public demands to end natural gas extraction in the North Sea's Groningen Field due to earthquakes caused by settling of the sea bed in the area of extraction (Oil Change International, 2018). The government has committed to ending production in the field by 2030 as a result (van den Berg, 2018).

Appendix 2 – Geothermal property rights in major producing countries

The globally installed capacity of geothermal power was 12.8 GW by the end of 2017, with the United States owning the largest share (2.5 MW). Other major producers include the Philippines, Indonesia and New Zealand, all found along the Pacific Ring of Fire. Turkey, Italy and Iceland are the largest producers in Europe and Kenya is the only significant producer in Africa (REN21, 2018).

In many countries, geothermal resources are owned by the state; this includes the Philippines, Indonesia, Kenya, and Chile. The Philippines collects royalty payments of up to 1.5 percent of gross energy earnings, with the proceeds being split 60:40 between national and local governments (Van Campen, 2015). Past geothermal development in Indonesia was primarily pursued by the state oil and gas company, but a competitive bidding process for exploitation permits has been implemented (Winters and Cawvey, 2015). Development of geothermal resources in Kenya has also been primarily pursued by state companies, although the licensing process is open to private companies (Van Campen, 2015). Chile opened South America's first geothermal plant only in 2017 (REN21, 2018), but as home to about 10 percent of the world's volcanoes, the country has large untapped potential. Chile enacted a geothermal law in 2000 to allow private companies to explore and exploit resources in the country (Rai and Van Campen, 2015).

Ownership of geothermal resources in New Zealand is contentious. As with mineral and water resources, geothermal resources are held separately from land. However, many geothermal resources are subject to ownership claims by Maori peoples. In practice, geothermal resources are regulated by the Resource Management Act and overseen by regional governments (Van Campen, 2015).

Geothermal ownership in the United States varies by jurisdiction. On federal lands, geothermal resources are treated as mineral rights and are held by the government. Some states, including California, also treat geothermal resources as minerals and separate the rights to them from land. Other states, particularly arid Midwestern states, treat geothermal resources as water resources, subject to permitting by state authorities. Yet others, such as Maryland and Oregon, have hybrid systems that regulate geothermal resources as either mineral or water resources, depending on the temperature and depth of the resource (Levine and Young, 2018).

Ownership of geothermal resources in Iceland is attached to land. Geothermal resources on public land are property of the state. Exploration and exploitation of resources requires a permit from the National Energy Authority, regardless of where the resource is located (Orkustfnun, no date.)

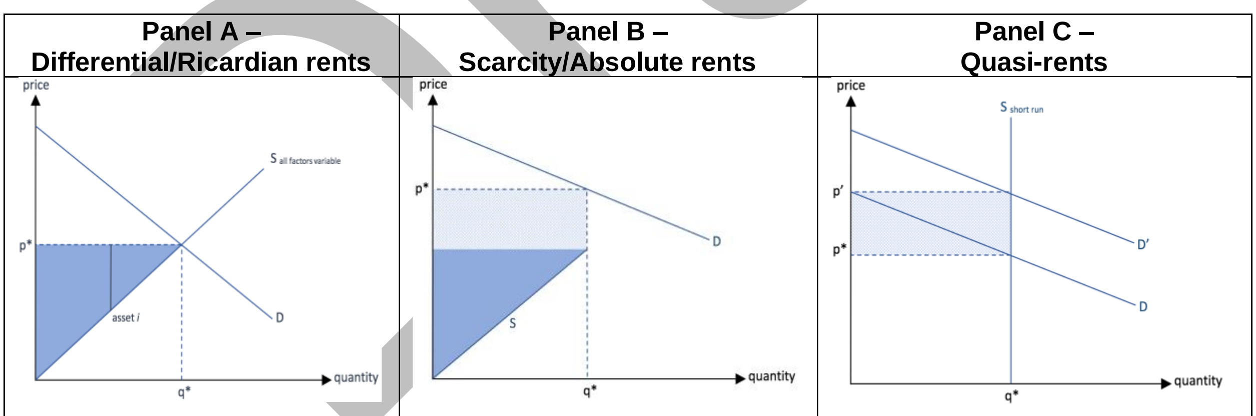
Appendix 3 – Major rent concepts in economic theory

Rent concepts can be roughly categorized as follows (Sinner and Scherzer, 2007):

- **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 (fixed 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). Such “scarcity” rents are also known as “absolute” rents within Marxian economics (da Silva, 2018).
- **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.

In all cases, the fundamental source of rent is scarcity. Thus, Wessel (1967, p. 1222) considers that Ricardian rent is “in essence” the same as scarcity rent, as it is the scarcity of more-productive factors that allows them to earn differential rents. If scarcity is not permanent, Marshall’s “quasi-rents” emerge until long-run equilibrium is reached. Figure 1 summarizes the various concepts.

Figure 1 – Rent concepts



Renewable energy resources can generate several types of rents. Differential or Ricardian rents (shaded area in Panel A) arise from productivity differences between producers. The intersection of market demand and supply determines the equilibrium price and quantity (p* and q*), which is also the price at which the least-productive asset will produce. The i^{th} asset earns rent equal to the difference between market price and its marginal cost of production (which lies on the market supply curve). Scarcity or absolute rents (light shaded area in Panel B) arise from demand exceeding supply in the long run. Here, supply cannot exceed q*, but market demand bids the price to p*. All assets earn scarcity rents. As before, more productive assets also earn differential rents. Finally, quasi-rents (shaded area in Panel C) are rents that arise in the short-term only. In the short term, the supply of assets is fixed at q*, with demand curve D and equilibrium price and quantity p* and q*. Suppose demand shifts outward to D', bidding price up to p'. Assets then earn a form of scarcity rent, which persists until demand falls or more producers enter the market (not shown).

Appendix 4 – Empirical studies of renewable energy asset values

Though hydroelectric resources account for more of the installed global capacity of renewable electricity resources than all other sources combined (IEA, 2017), few efforts have been made at measuring their value. Writing in 2000, Rothman noted that “very little has been written…on how to measure economic rent from hydroelectric development.” Only a handful of empirical studies having been published in the peer reviewed or grey literatures in the time since (Wen and Gillen, 2000; Limbu and Shrestha, 2004; Hreinsson, 2008a; Hreinsson, 2008b; Statistics Netherlands, 2011; Boungnong and Phonekeo, 2012; UK Office for National Statistics, 2016; Statistics New Zealand, 2017; Wandji and Bhattcharyya, 2018). The more relevant of these studies are reviewed briefly below.

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 set of researchers concluded that the RVM was suitable. 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 government intervention. Instead, both studies adopted the least-cost alternative approach (see Section 3.2.2). Bernard, Bridges and Scott compared actual capital and operating costs of hydroelectricity resources against those of the least-cost mix of coal, heavy oil, natural gas and nuclear generation needed to replace them; non-hydroelectric portions of the existing system were not remodelled. Load duration curves were used to determine the cheapest method of replacing hydroelectric resources for different types of load (base, intermediate and peak). Attempts were made to calculate differences in transmission costs for hydroelectric versus other resources given the need for hydroelectricity to be transmitted over long distances. Transformation, distribution and administration costs were assumed to be the same. Zuker and Jenkins’s approach was similar, though rather than modelling just the replacement of hydroelectric resources with the least-cost alternative, they compared the overall cost of Canada’s existing electricity system (including hydro) with the cost of a completely remodelled, least-cost system based on coal, heavy oil, natural gas and nuclear resources.

Gillen and Wen (2000) proposed a method for estimating hydroelectric resource rent in the Canadian province of Ontario (which has substantial hydroelectric resources) using the cost of electricity imports as the least-cost alternative. Their interest was to assess whether the provincial government’s water charges collected from hydroelectric energy producers were an effective mechanism for rent capture. They found that rents in 1995 were $CDN1.3 billion, ten times as much as the province collected in water charges. This led them to conclude that the province substantially under-taxed hydroelectric rent.

As an aside, Gillen and Wen’s rent estimates suggest that Ontario’s hydroelectric assets were worth about $CDN29 billion in 1995, or about $CDN 45 billion in current dollars.[41] The province’s hydro assets have grown by something like 15% since 1995, suggesting a value of around $CDN 50 billion for its current assets. Given that Ontario is currently home to about 11% of Canada’s hydroelectric assets, this would suggest a very rough value of $CDN 500 billion ($US380 billion) for the country’s existing hydroelectric assets. This figure is larger than

[41] Assuming a 3.8% discount rate and a 50-year lifetime for the resource.

Statistics Canada's 2017 estimated value of any natural asset other than land.[42] While Gillen and Wen's estimates are to be used with caution[43], they do illustrate the importance of a complete accounting of the wealth associated with natural resources in revealing Canada's true national wealth. The same would be true of other countries, such as China, Brazil and the United States, with large hydroelectric energy resources.

Statistics Netherlands (2011, p. 138), noting that when national balance sheets "are restricted only to non-renewable energy resources…serious underestimation of a country's available energy resources" is possible, undertook a study of the value of the Netherlands' wind energy resources using the RVM. This method was chosen because "like any other natural resource, renewable energy resources provide capital services to their owner and their remuneration [resource rent] should be an element in the gross operating surplus of the energy producer" (p. 139). Given this, the RVM should reveal the value of the wind energy rent. A nominal discount rate of 6% was applied and the resource was assumed to be available into the infinite future. An interesting feature of the study is development of what the authors call a "social resource rent", which they define as resource rent normally calculated (or market-based resource rent) as per the RVM but without the adjustment for specific subsidies on production. The intuition behind the social resource rent is that it reflects the value of the resource taking societal preferences (in the form of subsidies) into account. The "social preferences" referred to here are those of the public for emissions-free energy generation, as expressed through political support for government subsidies to carbon-free wind energy. The authors find that, while market-based resource rent on wind energy resources was negative in every year from 1990-2010 (implying a zero economic value for the resource), social rent is consistently positive after 2004. Valued using social rent, Dutch wind energy resources were estimated to be worth more than 5 billion euros in 2010 – a substantial sum, but still only 3% of the estimated value of the Netherlands' natural gas resources in that year.

The United Kingdom Office for National Statistics has prepared two different estimates of the value of the United Kingdom's renewable energy resources, one (UK ONS, 2016) for hydroelectric and wind energy resources for the whole of the United Kingdom and the other for all renewable resources[44] but just for Scotland (UK ONS, 2019). Both studies use the RVM. Data on revenues and costs for the UK-wide study were sourced from annual corporate reports. Due to data limitations, no account was taken of subsidies provided to the industry. This, the authors recognize, means the estimated asset values are likely overstated. The combined value of hydroelectric and wind energy resources (assuming a 3% to 3.5% discount[45] rate over 50 years) was 54.5 billion UK pounds in 2014. The Scottish study estimated renewable energy resource "rent" by assuming it was equal to the renewable share of the electricity generation industry's gross value added.[46] The authors acknowledge that this is not a valid estimate of rent

[42] The natural resource assets currently included on Canada's national balance sheet are fossil fuels, minerals, timber and land (commercial, residential and agricultural). Statistics Canada, Table 38-10-0006-01, *Value of selected natural resource reserves*. Available here.

[43] Gillen and Wen note that their rent estimates are similar to those found by Zuker and Jenkins but considerably more than Bernard, Bridges and Scott's value.

[44] Hydroelectric, solar, wind, tidal, wave, landfill/sewage gas and other bioenergy resources.

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

[46] Differential levelized costs of production between conventional and renewable electricity generation, weighted by the physical quantities of electricity generated from different sources, were applied to total electric power generation gross value added to estimate the gross value added of electricity from renewable sources.

but use it in any case in the RVM to calculate an “asset value” for Scottish renewable energy resources, which they give as about 24 billion UK pounds (2017 prices) for the year 2015.[47]

[47] The RVM calculation uses a 100-year asset life with a 3.5% discount rate during the first 30 years, a 3% discount rate thereafter up to 75 years and a 2.5% rate after 75 years.

Appendix 5 – Template for *ex post* valuation

Renewable energy resource	**Recommended approach to rent estimation**	**Expected pattern of future rents**	**Assumed resource lifetime**	**Data requirements**		
				Revenues	**Costs**	**Specific subsidies and taxes**
Geothermal	Residual value method in countries where electricity markets can be assumed to be close to long-term competitive equilibrium Least-cost alternative method can be considered for countries where electricity markets remain distorted by government intervention	Variable – depends on future revenues and costs	25 years	Electricity price per kWh in base year; projections of annual electricity prices over resource lifetime Electricity production (kWh) in base year; projections of annual electricity production over resource lifetime	Cost of materials and supplies in base year; projections of annual costs over resource lifetime[1] Labour costs in base year; projections of annual costs over resource lifetime[1] Value of fixed capital used in production in base year;[2] projections of annual fixed capital stocks over resource lifetime	Value of subsidies paid on products (such as FIT) in base year; projections of product subsidies over resource lifetime Value of subsidies paid on production (such as concessionary loans) in base year; projections of production subsidies over resource lifetime Value of royalties and other specific taxes (such as generator operating licenses) in base year; projections of specific taxes over resource lifetime
Hydro electric	See geothermal	Constant	50 years	Electricity price per kWh in base year Electricity production (kWh) in base year	Cost of materials and supplies in base year Labour costs in base year Value of fixed capital used in production in base year[2]	Value of subsidies paid on products (such as FIT) in base year Value of subsidies paid on production (such as concessionary loans) in base year Value of royalties and other specific taxes (such as generator operating licenses) in base year
Solar	See geothermal					
Wind	See geothermal					

Notes:
1. A reasonable simplifying assumption may be constant costs over the resource lifetime for materials/supplies and labour.
2. Fixed capital stocks include all assets used in renewable electricity generation, including wells and heat-exchange equipment (geothermal), dams (hydroelectric), panel arrays (solar), turbines (wind) and generating equipment (all).