Energy 84 (2015) 36–44

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Beyond carbon: Quantifying environmental externalities as energy for hydroelectric and nuclear power

Seth Sheldon [a], [*], Saeed Hadian [b], Ory Zik [a]

[a] Lux Research Inc., 100 Franklin St., 8th Floor, Boston, MA 02110, USA
[b] Anderson School of Management, University of California, Los Angeles, Los Angeles, CA 90024, USA

ARTICLE INFO

Article history:
Received 8 October 2014
Received in revised form
27 December 2014
Accepted 26 January 2015
Available online 1 April 2015

Keywords:
Life cycle assessment
Externalities
Nuclear power
Hydroelectricity
Environmental impact

ABSTRACT

Together, hydroelectric and nuclear power account for roughly 30% of all electricity generated on earth. Both technologies are often presented as answers to the dual challenge of meeting ever-increasing global energy demand while meeting stricter GHG (greenhouse gas) emissions targets. Indeed, the last two decades have witnessed a great deal of research on the life cycle GHG emissions of these technologies. On the basis of carbon intensity, the general consensus is that these technologies are more efficient than all other technologies of similar scale (e.g. coal, natural gas). However, hydroelectric and nuclear power come with environmental costs that sit outside the boundaries of traditional energy-based accounting methods, including water consumption, land change, and waste generation. We provide a novel framework that integrates energy and environmental life cycle assessment techniques so that dissimilar impacts can be more equitably assessed. The analysis considers diffusion- and centrifuge-based nuclear technologies, as well as reservoir and run-of-river hydropower. Results suggest that these resources are substantially less efficient (in our examples, anywhere from 5 to 85%) when key externalities are included. In the conclusion, we reflect on the benefits of using a physics-based method of measuring the externalities of power generation.

1. Introduction

The following paper offers a novel framework for assessing the life cycle energy requirements for the two most significant non-fossil fuel sources of electrical energy globally: hydroelectricity and nuclear power. Together, these two energy generation technologies account for 88 percent of all non-fossil fuel power generation, and about 30 percent of the electricity produced worldwide [13].

Generally regarded as low-carbon alternatives to coal, natural gas, and petroleum energy feedstocks, hydroelectric and nuclear power have technology life cycles which continue to be studied extensively from both energy and environmental perspectives. Van Leeuwen & Smith (2005) provide a rigorous accounting of typical cradle-to-grave primary energy consumption and resultant GHG (greenhouse gas) emissions for nuclear power, which is used in our analysis, although several more recent studies are available that provide similar insights [52–54]. As with nuclear, life cycle energy and GHG emissions are well studied for hydropower [2,8,9], although a great deal of attention is also given to non-GHG environmental effects [11,56,57]. Interestingly, much of the information available on nuclear power's impacts focus on risk analysis theory [58] and the health effects of direct radionuclide exposure [59], rather than the other non-negligible energy and environmental effects of ordinary operations [21,55].

As these and many other studies highlight, nuclear and hydropower technologies are not without environmental externalities.[1] Additionally, CO_2 and other GHGs are often treated as the sole quantifiable externality of concern—an approach that is ill-suited for non-combustible resources. Moreover, traditional life cycle energy and carbon accounting can underestimate the significance of such impacts by 1) assuming that the best available technologies presently in use fully internalize environmental burdens, and/or 2) setting them outside of the target system's boundaries.[2]

---

* Corresponding author. Tel.: +1 321 695 5575.
E-mail addresses: seth.sheldon@luxresearchinc.com (S. Sheldon), saeed.hadian@ucla.edu (S. Hadian), ory.zik@luxresearchinc.com (O. Zik).

[1] By “externalities” we specifically mean the set of environmental impacts which have not been mitigated (i.e., internalized) by the power generator. Note that many harmful impacts are avoided on a regular basis by power generators while they operate in accordance with federal and state environmental regulations.

[2] Moomaw et al. (2011, p. 976) [51] neatly outline the three most common methods of estimating “primary energy” consumed in electricity production by non-fossil fuel-based technologies: the *physical energy content* method, the *substitution* method, and the *direct equivalent* method. We rely instead on the EROEI (energy return on energy investment) method adopted by Fernando (2010) [3], and Van Leeuwen & Smith (2005) [20]. Our approach limits the definition of primary energy input to raw fossil fuels.

http://dx.doi.org/10.1016/j.energy.2015.01.116
0360-5442/

We argue that energy and environmental LCA (life cycle assessment) methods can be systematically integrated to better understand the diverse set of time- and location- dependent impacts of society's energy generation choices. We do so by way of a plain analysis of the life cycle energy requirements of nuclear power and hydropower when additional externalities are included. The major externalities associated with both technology types are GHG (greenhouse gas) emissions, water consumption, and land use.[3] Nuclear power also necessitates long term waste storage and consideration of statistically unlikely, but highly impactful catastrophic events.

We first outline the typical life cycle primary energy needs of the two most common technology types for both hydroelectricity generation and nuclear power generation and show their apparent EF (efficiency factors)—the ratio of the electrical energy output to the amount of primary energy input. We then outline typical unmitigated life cycle environmental impacts for each technology, and follow it with an assessment of the energy needed for reasonably deployable mitigation technologies (i.e., off-the-shelf, low cost and low energy intensity options). Through this experimental synthesis of contemporary LCA methods, we are able to provide updated efficiency factors that are based on additional mitigative energy needs. In the conclusion, we summarize the results and consider the decision support benefits of a unified, non-monetary quantification of the material impacts of power generation.

2. Methods and data

2.1. Hydroelectric power

Hydropower is the most common renewable energy source on the global scale and is responsible for meeting 19 percent of total energy demand worldwide [1]. As a renewable resource, hydroelectric energy is generally believed to be a more environmentally friendly alternative to fossil fuel combustion in terms of emissions and other ecosystem impacts. But construction and operation of hydropower plants requires a substantial investment of material, energy, land, and financial resources. In this study, the efficiency factor of this energy technology is investigated from life cycle energy and environmental perspectives.

The EF of hydropower technology is largely dependent on the type of technology used. Two types of hydropower plants (reservoir and run-of-river) are studied here to elucidate life cycle energy costs and to reconcile these figures with additional measurable externalities.[4]

Reservoir and run-of-river hydroelectric power generation occurs in five major stages, each requiring energy and material inputs:

1. *Preliminary investigation and river diversion.*
2. *Major civil works of dam construction.*
3. *Operation and regular maintenance.*
4. *Refurbishment and replacement of major components.*
5. *Plant decommissioning.*

Table 1
Life cycle energy requirements of reservoir and run-of-river hydropower plants, assuming an operational lifetime of 75 years.

Input, output	Process	Terajoules (10^{12} J)	
		Reservoir	Run-of-river
Input	Preliminary investigation	7	0.5
Input	Construction materials of river diversion	186	12
Input	Other processes of river diversion	89	5.9
Input	Major civil works (construction, materials, equipment)	24,380	1566
Input	Operation and maintenance (for 75 years)	31.88	4.13
Input	Refurbishment and replacement (for 75 years)	192	24
Input	Plant decommissioning	112	43
Input	Total (thermal)	24,998	1656
Output	Total (electrical)	598,050	72,750
Output/Input	Efficiency Factor	23.92	43.93

Table 1 shows the typical energy inputs for different stages of the hydropower energy production cycle as well as the energy output for reservoir and run-of-river technologies [3].[5,6]

We assume a modest 75 year operational lifespan and typical operational capacities of 540 MW and 183.9 MW for reservoir and run-of-river plants, respectively. Notional reservoir hydroelectric power output is equal to 2215 GWh/yr (7.974×10^{15} J/yr) and notional run-of-river power output is equal to 270 GWh/yr (9.72×10^{14} J/yr). The resulting efficiency factors (output/input) are 23.92 for reservoir hydro and 43.93 for run-of-river hydro. While Kumar et al. (2011) provide first order validation for the EFs shown in Table 1 by citing studies which have found efficiency factors from 50 to 30 and even lower [8], researchers should always exercise caution in this regard. . EFs can change significantly when the areal extent, location and capacity of a hydropower plant differ from those assumed in this study. Additionally, the lifetime of hydropower plants is another important factor. Assuming a useful lifetime of 150 years, for example, effectively doubles the projected EF. Indeed, Gagnon (2008) provides estimates of efficiency factors for well-performing hydropower facilities of each type as high as 205–280 for reservoir technologies and 170–267 for run-of-river technologies [4].

2.2. Life cycle externalities – hydroelectry

Hydroelectric power produces a variety of environmental externalities that are recognized and quantifiable. These externalities are rarely included in life cycle energy studies,[7] which describe only those energetic processes that have or are likely to have occurred. Accounting of detrimental environmental impacts has instead fallen within the domain of life cycle environmental impact assessment. The three most significant negative externalities associated with hydroelectric power are GHG emissions, water consumption, and land use.

2.2.1. Emissions

For the notional 540 MW reservoir hydroelectric facility considered here, the following CO_2 and CO_2e emission rates and

---

[3] Certain high profile externalities such as loss of human life, loss of biodiversity, loss of recreational value, changes to planetary rotational speed [49] and others are recognizable, but difficult or impractical to quantify as energy at this time. We therefore exclude them from this study.

[4] “Pumped storage” and “in-stream technology” are other forms of hydropower technology [2] that are less common compared to “reservoir hydropower” and “run-of-river hydropower.” These technologies are excluded from this white paper because of lack of data.

[5] All data in this table are calculated based on an input–output (I/O) method.

[6] No accurate data were found for the preliminary investigation, river manipulation, and other processes of river diversion stages for run-of-river hydropower plants. Hence, the overall energy loss for these is considered to be proportional to the total input for run-of-river to reservoir hydro, or 6.6% [3].

[7] A notable exception to this is Fernando (2010) [3], in which the author considers energy needs associated with land reclamation and carbon capture.