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Energy density and spatial footprints of various electrical power systems

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Abstract

Conventional and renewable power generators have been evaluated in order to determine their energy densities and spatial footprints on a life-cycle (or 'cradle-to-gate') basis. The nuclear fuel cycle (both with diffusion and centrifuge enrichment) was found to have the highest energy density, with bioenergy plants having the lowest. Onshore wind power exhibited a relatively promising energy density; being greater than that for its offshore counterpart. The energy density of the latter fell below that of solar photovoltaic (PV) arrays. Thus, renewables produce 'dilute electricity' overall with a spatial footprint that is orders-of-magnitude higher than for conventional sources, although there are many other sustainability criteria that will determine their usefulness in the transition towards a low carbon future.

Keywords: Energy densities, spatial footprints, electrical power systems, fossil-fuelled power plants, nuclear power stations, renewable energy technologies

1. Introduction

A criticism that is often made of renewable energy technologies for electricity generation [such as bioenergy plants, solar photovoltaic (PV) cell arrays, wind turbines, and the like] is that they have a low energy density in comparison with fossil fuel or nuclear power stations (see, for example, Fells [1]). Renewables are said to produce 'dilute electricity' with an energy density that is orders-of-magnitude lower than conventional sources [2]. A range of conventional and renewable power generators have therefore been evaluated in order to determine their energy densities and spatial footprints on a full life-cycle ('cradle-to-gate') basis.

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2. Methods and Materials

2.1. Life-cycle Ideas

The impacts resulting from each stage of the life-cycle of a product or activity should be considered in order to evaluate their full energy and environmental consequences. Process energy analysis on a life-cycle basis [3,4] was consequently employed here to trace the flow of energy through a system; thereby enabling the determination of the primary energy inputs needed to produce the life-time output from each power generator. The ratio of this output to the energy input or investment is known as the *energy gain ratio* (see Table 1 below). In addition, the ratio of net energy output to the total land required for the fuel supply chain represents the *energy density* of the device. The corresponding *spatial footprint* is approximately the inverse of this energy density. Detailed inventories of the materials, energy and land-use transactions were developed for each power generator. In this way, a 'life-cycle inventory' (LCI) was created [5,6] for the energy inputs and outputs associated with the fuel and material flows associated with each power system examined.

Table 1. Summary of estimated energy parameters for the nuclear and renewable power generators examined in the present study

Energy System	Energy Inputs (GWh)	Energy Outputs (GWh)	Energy Gain Ratio	Land-take (km^2)	Energy Density (GWh/km^2)
Nuclear: *Diffusion*	48,036	838,889	17.46	6.49	3233.24
Nuclear: *Centrifuge*	14,447	838,889	58.00	6.49	3370.56
Biomass	83,625,833	893,550,000	10.85	20.05	2.13
Wind:*Offshore*	485,972,480	12,940,000,000	26.63	27.50	22.64
Wind:*Onshore*	29,086,792	901,440,000	30.99	0.05	872.35
Solar PV (*mc-Si*)	7,155	45,000	6.18	0.00	61.84
Solar PV (*pc-Si*)	12,461	45,000	3.61	0.00	48.86

2.2. Defining the System Boundary

The system boundaries for the present study were set to include a comprehensive inventory for the key processes undertaken across the supply chain, and were generally representative of UK conditions. Aside from the power plant, the analysis includes the processes associated with the manufacture of materials, construction, operation, decommissioning and site restoration. In a wider context, the stages of exploration, extraction, fuel processing, and treatment of wastes, are typically included. Thus, the upstream boundary (the 'cradle') was comparable to the coal in the mine or gas in the reservoir [7], and the downstream boundary (the 'gate') was taken as the electricity output from the power plant. The primary resources associated with the construction of a wind turbine, for example, should include the materials used to fabricate the turbine. The inputs and outputs from a given fuel supply chain are influenced by the geographic locations of the various elements of the network. For example, the cultivation of energy crops should preferably be sited next to, or near to, the combustion plant in order to reduce the energy consumed in transporting a fuel of relatively low calorific value.

3. Results and Discussion

Spatial footprint values determined by Gagnon *et al.* [8] and the US Environmental Working Group (EWG) [9] were used to provide energy densities of natural gas and coal-fired power plants (see Table 2 below) for comparison purposes. A spatial footprint of 4 km^2/TWh (or an energy density of 250 GWh/km^2) is used to represent the coal fuel cycle, and a corresponding footprint of 0.09 km^2/TWh (or a density of 11,111 GWh/km^2) for the natural gas fuel cycle. It was found that the power generators examined could be ranked in descending order of energy densities (see Table 1 above and Fig. 1 below):

- Nuclear (centrifuge or diffusion); wind (onshore); solar PV [either monocrystalline silicon (mc-Si) or polycrystalline silicon (pc-Si)]; wind (offshore); biomass.