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MINERAL-WATER-ENERGY NEXUS: IMPLICATIONS OF LOCALIZED PRODUCTION AND CONSUMPTION FOR INDUSTRIAL ECOLOGY

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ABSTRACT

Urban and remote areas are increasingly using decentralised systems for renewable energy production and storage, as well as for water harvesting and recycling and to a lesser extent for product manufacture via 3D printing. This paper asks two questions – how will these developments affect (i) the end-uses of minerals, including critical minerals and (ii) the implications for industrial ecology and the development of a sound materials cycle society. We find a trade-off between using higher-performance critical minerals in low concentrations which are complex to recycle, and unalloyed, standardised materials for increased effectiveness across multiple reuse cycles. Design and operational challenges for managing decentralised infrastructure are also discussed as their uptake approaches a tipping point.

1 INTRODUCTION

Decentralised energy systems – specifically renewable energy-based systems – are becoming more prevalent in rural areas (where they may have a competitive advantage over fuel-based systems that require storage and import of fuels) and in urban areas where policy and incentives have been making such systems more affordable to households. From the perspective of the environmental impacts of energy systems, this is generally an important and useful investment by society. However, when considered from the perspective of a sound materials cycle – in which a very high percentage of materials is captured and recycled at end-of-life – there are a number of competing priorities that may drive the overall environmental impact in different directions under decentralised energy futures. This paper examines some of these issues.

Materials in Decentralised Generation (DG)

The development of new advanced electronics and energy devices has become highly dependent on a variety of functional materials that were largely unused, unheard-of or unavailable until the last 40 – 50 years. Examples include: rare earth metals (permanent magnets for electric motors and generators; and in fuel cells), platinum group metals (catalysts for fuel reforming and electrodes for fuel cells), by-product metals (thin film solar cells) [1]. In addition to these, a range of seemingly common materials are also listed as “critical” in different countries according to their economic, geographic and geological availability, importance to society and risk of supply-chain disruption [2]. While many of these materials are not currently scarce, increasing global demand and competition for materials in emerging economies and the lack of current investment in expansion of capacity may at some point in the future put pressure on supply. Recycling of such materials is a valuable activity from the perspective of maintaining resource security, the inherent value in the material and the reduction of a potential waste stream, however, in many cases the existing infrastructure is insufficient to domestically recycle at high rates of recovery or with economically feasible costs – particularly in developed countries. Moreover, the recycling of materials is often not much less energy-intensive than the extraction of primary metals.

Due to the high price and relatively low production rates of functional materials such as Indium, Gallium, Germanium, Selenium and Tellurium, the design of electronics and energy technologies that rely on them (e.g. photovoltaics) has focused on reducing the amount of material used in a given product to produce the requisite service. For example, thin-film solar cells use material layers of a few microns at most, bonded to each other and sandwiched among other bulk materials. This makes separation of the materials particularly difficult, and the technologies are most certainly not “designed for disassembly” at this level. Thus a trend that makes the product cheaper and more environmentally benign in the earlier stages of the lifecycle is conversely making end-of-life processing more difficult.

Distributed energy systems benefit from the electricity generation and usage being in close proximity (and thereby minimising loss in transmission). However, the nature of such systems being “distributed” creates a dispersion of the contained material that is not the case in centralised systems. The level of impact of such dispersion will vary according to the geographical situation – particularly the proximity to urban centres and recycling facilities. It is considered that such dispersion of materials may impact on the collection rate and the cost and energy required to collect the materials and transport them to the recycling centre.

2 OBJECTIVES/METHODOLOGY/SCOPE

In the case of identifying the critical minerals utilised in renewable or clean energy technologies for distributed or centralised generation, the methodology undertaken was as follows:

1. Literature (particularly LCA studies) and technical documentation was reviewed to identify the critical minerals utilised and a first-order estimate of the quantities of these materials for distributed energy systems
2. Existing equipment and installations were reviewed to obtain key parameters – such as the spatial density of the plant and contained metals.
3. Estimations of residential-scale spatial density or distribution of distributed energy were undertaken using sample population densities from Brisbane, Australia and a simplified model of a city as concentric circles of increasing population density.
4. Value of the specific materials utilised was obtained and was applied to understand the spatial value density in different configurations.
5. Interactions with decentralised water and production systems were then discussed together with implications for pursuing a sound material cycle society.

3 RESULTS

Critical Materials in Decentralised Energy

The review of LCA literature [3] and other technical documentation provided initial estimates of the range of materials and the quantities required per kilowatt of installed capacity. This review also identified the typical scale of individual units and power plant scale installations, building on other recent estimates [4]. Table 1 shows the key critical materials, their function within technologies, the range of reported densities of materials per unit generating capacity and typical scale. While details on wind turbine technologies are readily widely available, the specific quantities and ratios of photo-active materials (PVA) in photovoltaics is often unclear. The estimates here are based on a USGS [5] study as well as the reported total PVA in various LCA studies.

Table 1: Density of some critical functional materials in distributed energy technologies

Technology	Critical materials	Function	Density (kg / kW)	Typical scale (kW)
Wind turbines	Dysprosium, Neodymium,	Permanent magnets	0.15-0.2 (Dy and Nd combined)	1500 – 5000 (turbines) 15,000 – >1,000,000 (wind farm)
	Copper	Generator windings and wiring	1.2 (turbine only – onshore) 2-5 (windfarm averages onshore) 6-12 (windfarm averages offshore)	
Photovoltaics	Indium, Gallium, Selenium, Tellurium	Photo-active materials (total PVA reported)	0.4 – 1.4 (various LCA studies) 2-3 (USGS)	1 – 5 (residential) 10,000 – 550,000 (solar farm)
	Copper	Electrical connections and power electronics	0.25 (various LCA studies)	
Fuel cells	Platinum	Electrodes / catalysts (PEM FC)	0.0001 – 0.001 (various)	5 - >350,000
	Yttrium, Lanthanum	Electrolyte and electrode materials (SOFC)	0.02-0.2 (Yttrium) (various)	

**note battery storage technology has not been considered in this analysis*

Utilising the figures in Table 1 and incorporating historical prices from the United States Geological Survey for 2012 [6, 7], Table 2 gives an estimated range of the valuable materials contained in typical distributed energy technologies with renewable or clean energy focus. It should be noted that these are at a relatively high price point, and that there is still a considerable uncertainty in the quantity and specific material quality requirements for some of these technologies.

Table 2: Estimated range of potential value in contained metals at 2012 prices

Technology	Critical materials	Average value per unit capacity ($ / kW)	Total value of contained metals	
			Unit scale ($US)	Power plant scale (Million $US)
Wind turbines	Dysprosium, Neodymium,	44.6	$ 57,000 – 255,000	$ 0.57 – 51
	Copper	10.9 (unit) 28.4 (onshore) 72.9 (offshore)	$ 15,000 – 61,000	(onshore) $ 0.24 – 40.5
				(offshore) $ 0.73 – 97
Photovoltaics	Indium, Gallium, Selenium, Tellurium	555.3	$ 130 – 4,900	$ 1.3 – 539
	Copper	2.0	$ 2 - 10.1	$ 0.02 – 1.1
Fuel cells	Platinum	27.5	$ 25 - 250	$ 1.75 – 17.5
	Yttrium	24.3	$ 22.1 - 221	$ 1.5 – 15.5

With regards to recovery of valuable materials, there are a number of factors that should be considered, including:

- Total value and concentration of contained material
- Spatial density of material in operating conditions (t / km^2) – including effective spatial density with consideration of probability of individual unit failures and replacement rate
- Number of units requiring to be disassembled for cost-offset
- Effectiveness and cost of recovery of materials from products
- Physical and chemical composition of materials in products, for example, relatively pure or relatively complex material streams (impacting on cost and effectiveness)

From Table 2 it can be observed that the valuable materials on the unit of capacity is highest in PV, however the size of such units ranges widely – typical residential scale units are smaller, therefore the total contained content in such units is small, whereas wind turbines are more prevalent at megawatt scales, therefore total content is higher while value per kilowatt may be lower.

Considering the spatial density in the case of a power plant scale operation, of the technologies compared, fuel cells present the most compact unit, and therefore the most spatially dense. Wind turbines have typical spacings of 300m – 1.5km, while photovoltaics are typically closely spaced for individual units, but have significant overall land area coverage, therefore a designed with sufficient space for maintenance vehicles to pass between. Estimates based on site maps and data indicate that Sakai solar power station in Japan has approximately 49 MW / km^2 rated capacity without considering any buffer zone. On the other hand, residential solar in a city is likely to have a much lower energy density (we estimate at high levels of uptake ~1 MW / km^2 in a modelled Australian city). The Wattle Point wind farm in South Australia has an overall spatial energy density of around 5 MW / km^2, while the theoretical energy density for wind turbines with the pseudo-industry-standard spacing of 7 times the diameter of the turbine [8] is around 33 MW / km^2. Some of the largest fuel cell installations in the world have approximately 2800 MW / km^2 spatial energy density, although these could theoretically be increased by multi-level vertical installation (unlike PV). Residential scale fuel cells, although currently small scale, are likely to present a similar spatial density to residential solar. Likewise, although the feasibility in urban areas is unclear, for the sake of comparison we will apply the residential spatial density of PV to wind power. Given these estimated spatial densities, and including the previously presented data, Table 3 presents some indicative material and value spatial densities.

Table 3: Estimated range of potential material and value density

Technology	**Critical materials**	**Mass density of contained metals (t / km^2)**		**Value density of contained metals ($US million / km^2)**	
		Residential scale	**Power plant scale**	**Residential scale**	**Power plant scale**
Wind turbines	Dy, Nd	0.24	6	0.06	1.5
	Cu	1.8	117 (onshore)	0.01	0.9 (onshore)
			300 (offshore)		2.4 (offshore)
Photovoltaics	In, Ga, Se, Te	2.3	83	0.76	27.1
	Cu	0.34	12	0.003	0.1
Fuel cells	Pt	0.001	2	0.04	77.4
	Ytt	0.15	309	0.03	68.4

Table 3 indicates that fuel cells and photovoltaics have the best power plant scale spatial value density. Due to the high spatial power density of fuel cells, they have a very high spatial value density – whereas photovoltaic installations have a high per kilowatt value of materials but a low spatial power density. On the unit scale, wind turbines have a very high value density, but as they are widely distributed across the landscape, the spatial value density is diminished.

With regards to the extraction of the valuable material, in the case of rare earth magnets in wind turbines, this is a relatively straightforward activity – assuming that the material is to be reused for the same or similar purpose. If a separation of the materials is required, this can require significant thermal energy and is technically challenging. However, this is still likely to be comparatively effective and less process-intensive than the recycling of valuable components in fuel cells or especially in PV panels. In both of these technologies thin-films of materials are used to reduce the cost and to optimise properties such as mass transfer (fuel cells). The recovery of such diffuse and intermixed materials of micron-scale films is complex.

Considering the failure rates of individual units, the high value density in a single wind turbine mean that the extraction of value from a single failed unit would be relatively more attractive than the failure of a smaller PV of fuel cell unit. This may offset the lower spatial value density of wind turbines in a windfarm.

4 DISCUSSION

The density, potential range and material value density of materials contained in DG equipment also needs to be considered in the wider socio-political context in which the materials exist. This includes; the types and locations of firms and organisations that participate in the primary production of DG products, and associated service activities; organisations involved in the collection and reprocessing of materials and; the supply chain customers for any recycled materials. Each of these organisations will have an impact on the realisable value (and hence viability) at the economy level of recycling, rather than the potential value at the physical material level. The political and policy context that the firms and organisations operate in can also provide a push or pull tension for all of these activities.

The firms involved in the production of renewable energy equipment are large national and multinational firms that compete on per unit cost, and therefore have competitive advantage in the scaled up production of DG equipment. These firms by and large are innovative and research intensive but are largely focused on incremental performance improvements to existing products and process innovations to enhance competitive advantage in production.

There are a number of drivers influencing the firms that manufacture DG to be involved in the collection and recycling of end-of-life product. Product Stewardship programs such as PV Cycle in Europe is one such example of DG equipment manufacturers closed loop management of materials. The PV Cycle association includes product manufacturers of 80% of the European solar market and is a voluntary agreement to take-back and recycle post 1990 end-of-life PV systems (see http://www.pvcycle.org/). The Association has a target of collecting 65% of PV systems installed after 1990 and the recycling 85% on the contained materials.

The Association was established in 2007 [9] with the motivation for members to join the association are related to corporate governance commitments to sustainability rather than to obtain new inputs from recycled products. Given the 20-25 year lifespan of PV systems, joining PV Cycle also represented an ambition rather than reality for most of the Association members. As of 2010 only two of the 40 members [10] had actual take-back schemes and recycling facilities in place (German based Deutsche Solar AG and US based First Solar). This year (2015) marks 25 years since the base year of 1990, but as the exponential growth of PV installed generation occurred after 2000, there is still time for the industry to establish and trial take-back schemes before volumes increase. The availability of time is positive in the sense that schemes can be in place by the time volumes increase, but is a negative in that recycling activities will lack critical mass, and therefore lack the incentives for innovation that will be required to cost-effectively take back, recycle and re-use materials.

For some Solar PV firms, end-of-life take back and recycling of products is part of firm strategy. For example First Solar operates product stewardship of all their products globally (not just in Europe with PV Cycle) and have done since 2002. First Solar has a specific commitment to the environmental sustainability of their products including end-of-life. This allows the company to claim they have the lowest carbon footprint of available PV technologies [9]. With the sale of each model First Solar sets aside funds for the estimated future costs of collection and recycling of the unit. The funding is kept in a separate trust account and independently audited annually [9]. Again here the motivation for recycling is not capturing the value of the materials in products but rather avoiding the costs (both financial and reputational) of end-of-life product contributing to waste streams.

Whilst not quantified in the same level of detail, the remainder of this discussion section considers the interaction of decentralised energy with other distributed infrastructure, including water provision and recycling and also product manufacture as shown in Table 4.

Table 4: Nexus between energy, water and minerals

Technology	Energy	Water	Minerals
Decentralised energy	Decentralised energy systems should have higher efficiencies as there are limited transmission losses	Demand for water is reduced as decentralised energy systems do not require water cooling systems of large power stations, however solar farms require water for cleaning	Need for a wider range of speciality and expensive metals and minerals for decentralised energy systems (e.g. battery storage)
Decentralised water - **raintanks** - **onsite recycling**	Decentralised water systems typically need decentralised energy system (e.g. local pumps) for transporting water	Decentralised water systems may require higher levels of maintenance for delivering water security	Decentralised water systems typically do not require speciality or expensive minerals or metals
Decentralised production, e.g via additive manufacturing	Decentralised production can be energy intensive, innovative designs are required to overcome	Although not essential, decentralised production can benefit from decentralised water systems	Decentralised production requires smaller units which can require speciality or expensive minerals or metals, in theory less materials can be used through clever design

Considerations for sound material cycle society: a checklist

There are several key factors that should occur for sound and resilient material circular society at the intersection of the material-energy-water nexus. These include:

- Need for reliable (often smaller scale) technologies that are economic to purchase and operate
- Holistic thinking across ‘value chain’ encouraging stronger product stewardship measures

- Smarter and more innovative design approaches that value ‘design for remanufacturing, recycling and re-use’
- Policy and regulatory frameworks that fosters efforts towards dematerialisation
- Reliable data and information across all parts of circular ‘value chain’ to allow new and emerging business to conduct the relevant business cases with confidence
- Supporting infrastructure to help encourage the appropriate producer/consumer behaviour to enable the circular ‘value chain’
- Setting of suitable targets for remote and urban areas to track performance over time, not only for one indicator (energy or waste), but of the material-energy-water nexus

The above characteristics are relevant for the nexus between energy, water and minerals. Such an example is the use of higher-performance critical minerals in low concentrations which are complex to recycle but are essential for decentralised energy and water systems, compared with unalloyed, standardised materials which can be used widely and can be effectively recycled or re-use across multiple cycles, such as materials used in centralised energy and water systems.

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