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# Implications of Trends in Energy Return on Energy Invested (EROI) for Transitioning to Renewable Electricity

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ABSTRACT

Recent papers argue that the energy return on energy invested (EROI) for renewable electricity technologies and systems may be so low that the transition from fossil fuelled to renewable electricity may displace investment in other important economic sectors. For the case of large-scale electricity supply, we draw upon insights from Net Energy Analysis and renewable energy engineering to examine critically some assumptions, data and arguments in these papers, focussing on regions in which wind and solar can provide the majority of electricity. We show that the above claim is based on outdated data on EROIs, on failing to consider the energy efficiency advantages of transitioning away from fuel combustion and on overestimates of storage requirements. EROIs of wind and solar photovoltaics, which can provide the vast majority of electricity and indeed of all energy in the future, are generally high ($\geq$ 10) and increasing. The impact of storage on EROI depends on the quantities and types of storage adopted and their operational strategies. In the regions considered in this paper, the quantity of storage required to maintain generation reliability is relatively small.

## 1. Introduction

Many countries, states and towns are in the process of transitioning from fossil fuels to renewable energy (REN21, 2019; Go 100% renewable energy, n.d). The transition is driven primarily by the need to mitigate global climate change by cutting greenhouse gas (GHG) emissions (IPCC, 2018) and the lower costs of supplying bulk electricity from wind and solar energy than from new fossil and nuclear energy (DoE (Department of Energy), 2018; Fu et al., 2018; Lazard, 2019; Graham et al., 2018; Vartiainen et al., 2019). Other well-known advantages of the transition include:

- reduced air pollution, respiratory diseases, water use, water pollution, land degradation and electricity costs;
- improved long-term energy security;
- job creation; and,
- for households, small businesses and local communities, increased independence in energy supply.

Therefore, it is timely to investigate the environmental and economic impacts of the transition. Studies by Hall et al. (2014), Sers and Victor (2018) and King and van den Bergh (2018) discuss the implications for the macro-economy of the energy return on energy invested (EROI, sometimes written EROEI) of renewable energy (RE) and fossil fuels (FF). EROI is a measure of the effectiveness of energy invested by people in producing energy outputs. Each study identifies the same dilemma, arguing independently that, if the EROI of RE is substantially smaller than that of FF, then the transition to a RE system may require a large fraction of global energy use and hence will impact on economic development. White and Kramer (2019) provide a more optimistic analysis that treats both physical and economic definitions of EROI.

The present paper examines this issue critically for the case of large-scale electricity supply-demand systems in regions with high solar and/or high wind resources that could drive the transition to 100% renewable electricity either within these regions or economical transmission distance from these regions. In these regions, variable renewable energy (VRE) such as wind and/or solar provides the major proportion of annual electricity generation. These regions include, onshore, most of Australia, south-west and central USA, north-west China,

*Abbreviations:* CST, concentrated solar thermal; EROI, energy return on energy invested; $EROI_{el}$, EROI (electric); $EROI_{PE\text{-}eq}$, EROI (primary energy equivalent); ESOI, energy stored on energy invested; EV, electric vehicle; FCAS, frequency control ancillary services; FF, fossil fuel; GHG, greenhouse gas; ICE, internal combustion engine; LCOE, levelized cost of energy; NEM, National Electricity Market (of Australia); PV, photovoltaic; RE, renewable energy; VRE, variable renewable energy

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north-west South America, North Africa, and the Middle East; they also include off-shore northern Europe and north-eastern USA, which have high wind energy resources. Together these regions have the capacity to supply a large fraction of global electricity from wind and solar photovoltaics (PV) by transmission lines (Bogdanov et al., 2019, Fig. 1[1]).

Hansen et al. (2019) provide a recent overview on the status of the 100% renewables in the entire energy system. However, the present paper focuses on utility-scale renewable *electricity* generation and storage – electricity, because a future low-carbon energy system is very likely to be one in which most energy is supplied and used in the form of electricity, the easiest and cheapest form of energy to transform to renewable sources (IEA, 2017; Jacobson et al., 2015; Ram et al., 2019; Bogdanov et al., 2019). In 2016 electricity was responsible for 22% of total final energy consumption in the OECD, natural gas 20% and oil 47%; the electricity fraction has doubled since 1973 in both OECD and global data (IEA, 2018). The increase is likely to continue, driven by declining costs of renewable electricity.

Jacobson et al. (2015) and Ram et al. (2019) show that most heat that is currently supplied to the industrial, commercial and residential sectors by direct combustion of FF can be provided more efficiently and with much less pollution by renewable electricity, either via heat pumps or direct electrical heating. They also show that most transportation, whether public or private, can be provided by electric vehicles. Large gains in energy conversion efficiency of vehicle operation are obtained by switching from internal combustion engine (ICE) to electric vehicles (EVs), however this does not take account of the life-cycle energy invested in batteries, which are starting to be mass produced on a very large scale. So far there are few studies comparing life-cycle energy invested per km travelled; the focus has been on the substantial reductions in $CO_2$ emissions in shifting from ICEs to EVs (ICCT, 2018).

The principal exceptions to the direct use of electricity in transportation are air and sea transport, together with long-distance rural road transport in remote areas, for which future energy is likely to be provided by synthetic fuels produced by using RE to produce hydrogen by electrolysis or thermal decomposition and then combining it with nitrogen from the air to produce ammonia. Although the efficiencies of producing these 'renewable' fuels are low, costs (and hence life-cycle energy invested) are projected to decline substantially by 2030 as the supply chain is scaled up and RE costs continue to decline (Hydrogen Council, 2020).

There are grounds for optimism regarding further reductions in life-cycle primary energy inputs to making renewable energy technologies. Several mining, minerals processing, steel and manufacturing industries are purchasing renewable electricity to power their processes (e.g. Parkinson, 2018; Vorrath, 2018; Parkinson, 2020), hence obtaining gains in energy conversion efficiencies (see Section 2.1) as well as reductions in costs and emissions.

Because of the variability of wind and solar, storage is a key issue for power systems in which wind and/or solar PV provide the majority of generation. It is generally accepted that hydro-electric systems based on large dams have high values of EROI (Hall et al., 2014; Raugei and Leccisi, 2016), mainly because of their long lifetimes. However, if they involve the flooding of densely vegetated valleys, they can be high GHG emitters (Demarty and Bastien, 2011). For power systems of interest in the present paper – where wind and/or solar PV provide the majority of electricity and where 'once through'[2] hydro-electricity can only provide at most a small fraction of generation – determining the impact of storage on system EROI is more challenging.

[1] This figure provides a macro view of the main regions of the globe favourable to different RE systems, but omits the regions of high localized wind resources including southern Australia.

[2] Defined here as a hydro system in which water flows one way from a dam through turbines; not pumped hydro in which water flows in a circuit.

The plan of the paper is as follows: Section 2 outlines method, including the conceptual framework and definitions. Section 3 exposes the incorrect assumptions and different perspectives that led to the belief that the present EROIs of wind and PV technologies are low and then reviews recent research that finds EROIs of wind and solar PV are actually high and increasing. The section discusses both the EROIs of individual RE technologies and dynamic EROI changes in a rapidly transitioning electricity system. Section 4 discusses EROIs and energy stored on energy invested (ESOIs) of storage technologies, paying attention to the quantity of storage required in power systems with high solar and wind potential and limited once-through hydro potential, taking Australia as a case study. Sections 3 and 4 combine results and specific discussions of those results. Section 5 concludes the paper and offers some general comments on the role of EROI in the transition to 100% RE.

## 2. Method, Framework and Definitions

The conceptual framework chosen is Net Energy Analysis, summarised by Raugei and Leccisi (2016)), which originally led to the concept of EROI. Within this framework, for an individual energy technology or a whole system, EROI is defined to be the energy output divided by the life-cycle primary energy invested. Thus, where $E$ represents energy:

$$\text{EROI} = E_{out}/E_{inv} \tag{1}$$

As far is possible, 'life-cycle' takes account of the energy invested *by people* in mining and processing the raw materials, construction, operation decommissioning and waste management. Thus $E_{inv}$ is the energy diverted from other possible societal uses. If the technology uses a fuel (e.g. fossil or biomass), the energy invested to mine, deliver and refine it is included in $E_{inv}$. In a topic that is vigorously debated (see below), it is a rare point of general agreement between authors who take otherwise quite different approaches that, within the framework of Net Energy Analysis, the energy in sunshine falling on a solar collector or in wind passing through a wind turbine or the thermal energy content in a fossil fuel is *not* counted in $E_{inv}$.

For electricity generation, there is debate about whether the energy output is simply the quantity of electricity generated over the lifetime of the technology/system or the primary energy equivalent of that electricity. The outcome of this debate is important, as illustrated in Fig. 1. Energy losses in the combustion process are typically about two-thirds of the chemical energy in the primary fuel, although they can range from about 60% to 80%, depending upon fuel quality and type of energy conversion technology.

In electricity generation, most of the greenhouse gas emissions and other pollutants result from the combustion of primary fuels. Therefore, saving one unit of final or end-use energy in the form of fossil electricity, either by efficient energy use or by substituting renewable electricity, can save typically three units (range two to four) of FF and their emissions. Hence, it is argued by one school of thought that, in transitioning to renewable electricity in order to reduce the emissions from fossil fuelled electricity, energy output in Eq. (1) should be the primary energy equivalent of the electricity generated, because it represents how much primary energy is preserved for alternative uses per unit of primary energy invested in renewable energy (Raugei et al., 2012, 2015). Hereinafter, the primary energy equivalent EROI is written as '$\text{EROI}_{\text{PE-eq}}$', while the traditional version of EROI in which the energy output is just the electricity generated is written as '$\text{EROI}_{\text{el}}$'. EROI without subscripts covers both definitions. It is emphasized that for some perspectives, such as the comparison of EROIs of FF at the point of extraction with EROIs of RE at the point of capture, it is valid to use $\text{EROI}_{\text{el}}$. It all depends on the choice of perspective and system boundaries.

Our method of calculating primary energy equivalent differs slightly from that of Raugei et al. (2012), which converts $\text{EROI}_{\text{el}}$ to $\text{EROI}_{\text{PE-eq}}$, by

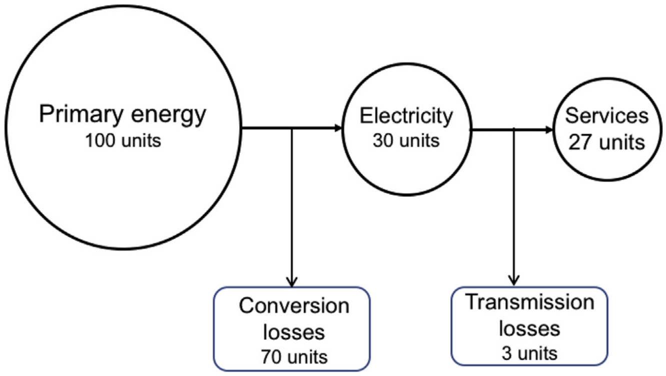


**Fig. 1.** Typical flow diagram for electricity generation from fossil fuels.

dividing by $\eta_{grid} \approx 0.3$, which is an average for a whole fossil fuelled power system. Instead, within the present context of an energy transition for the purpose of climate mitigation, we consider that the substitution of each individual FF power station by RE power stations is justified by its climate benefits in receiving a factor η representing the efficiency of energy conversion of that FF power station. This applies to each substitution until 100% RE is achieved. This method reflects the large differences in η between power stations: e.g. $\eta \approx 0.2$ for brown coal (lignite), and $\eta \approx 0.55$ for combined cycle gas. However, the main problem with using $\eta_{grid}$ is that, as RE penetration ➔ 100%, $\eta_{grid}$ ➔ 1 and so $EROI_{PE\text{-}eq}$ ➔ $EROI_{el}$, which is inappropriate in the present context.

The net energy gain NEG is defined to be:

$$NEG = E_{out} - E_{inv} \quad (2)$$

Dividing NEG by $E_{out}$ gives the net to gross energy ratio NTG:

$$NTG = NEG/E_{out} = 1\text{–}1/EROI \quad (3)$$

This non-linear relationship between NTG and EROI gives the well-known 'energy cliff' (e.g. Sers and Victor, 2018, Fig. 1): as EROI decreases to 1, NTG tends to zero, an outcome to be avoided for an energy supply system. For EROI = 10, NTG = 0.9, 90% of its maximum possible value, so energy technologies or systems with EROI greater 10 (or even eight) should not be of concern to macro-economists. This paper refers to EROI values ≥10 as 'high' and values < 10 as 'low'.

The method for determining EROIs of VRE technologies in Section 3 is a critical analysis of the literature, identifying studies based on errors, inconsistencies and inappropriate or outdated data, and identifying studies with consistent, well-defined methods. The method for discussing the impact of storage on system EROI in Section 4 is based on knowledge from electric power engineering and analysis of the results of two published case studies from Australia, which is typical of regions with high solar and/or wind resources. For individual storage technologies that are not net generators of electricity, the indicator 'energy stored on energy invested' (ESOI) is used.

## 3. EROIs of Renewable and Fossil Fuelled Electricity Generation

Sections 3.1 and 3.2 discuss EROIs of key individual electricity generation technologies. As technologies evolve or fuel inputs become scarcer, these EROIs change. Section 3.3 discusses the dynamic EROIs of electricity systems transitioning rapidly from FF to RE.

### 3.1. Errors in Traditional Estimates of EROIs of Technologies

The calculation of EROIs of technologies and systems has inherent uncertainties that require subjective judgements, for example, choosing the boundaries of the system and the circumstances under which electricity output or primary energy equivalent is used for $E_{out}$. These inherent uncertainties must be distinguished from incorrect and internally inconsistent methods.

A major source of incorrect low EROI results for RE is the use of outdated data for technologies that have been evolving rapidly. Sers and Victor (2018) base their statement that EROIs of VRE technologies are 'substantially lower than conventional fossil fuels' on the meta-analysis of Hall et al. (2014), who 'calculated the mean EROI value using data from 45 separate publications *spanning several decades*' (our emphasis). Averaging over several decades is invalid for solar PV and wind, because they have experienced huge improvements in technologies and supply chains, demonstrated by very large reductions in their respective prices as well as direct evidence. The invalidity in using old data is confirmed by Palmer and Floyd (2017), Fig. 2), who plotted data from 1997 to 2014 published by Louwen et al. (2016) and found a reduction in Cumulative Energy Demand ($E_{inv}$ + solar energy input) of PV by up to an order of magnitude, and by Görig and Breyer (2016), as discussed in more detail in Section 3.2.

In choosing 'optimistic' and 'pessimistic' values of EROIs of energy technologies, King and van den Bergh (2018) cited as one of their sources the invalid results of Hall et al. (2014). Furthermore, the former's Table 1 of EROI values fails to specify the type of PV cell or the location of the PV and wind technologies, which determine $E_{out}$. The paper stated that its 'pessimistic' values for wind and solar allow for storage, but this seems to have been done in an arbitrary manner. Hence their chosen EROI values (even high 'optimistic' values) are poorly based. This kind of modelling is potentially valuable, so it's hoped that King and van den Bergh (2018) and Sers and Victor (2018) will redo their respective models with more realistic data.

A paper by Ferroni and Hopkirk (2016) estimates that EROI of PV in Switzerland, a country of low insolation, is 0.82, i.e. a net consumer of energy. However, a detailed analysis by Raugei et al. (2017) finds methodological inconsistencies involving choice of system boundaries, calculation errors and the use of outdated data (the latter involved taking a 10-year average over a rapidly improving technology). By correcting these shortcomings, Raugei et al. (2017) obtain an EROI that is an order of magnitude larger.

**Table 1**
LCOE and capital cost of the principal new renewable electricity technologies, 2010 and 2018

| Technology | LCOE 2010 (USD/MWh) | LCOE 2018 (USD/MWh) | Δ (%) | Capital cost 2010 (USD/kW) | Capital cost 2018 (USD/kW) | Δ (%) |
|---|---|---|---|---|---|---|
| Solar PV | 0.371 | 0.085 | 77 | 4621 | 1389 | 70 |
| Onshore wind | 0.085 | 0.056 | 34 | 1913 | 1497 | 22 |
| Offshore wind (limited data) | 0.159 | 0.127 | 20 | 4572 | 4353 | 5 |
| CST (limited data)) | 0.341 | 0.185 | 46 | 8829 | 5204 | 41 |

Source: Figs. S1 & S2 of IRENA (2019).
Notes: All values are real, i.e. corrected for inflation, expressed in USD 2018 and are global-weighted averages. The IRENA database comprises about 17,000 projects, commissioned by the end of 2018, corresponding to a capacity of about 1700 GW. Only utility scale projects are given in this table. The values are actually prices rather than costs. However, long-term price trends, as opposed to year-to-year variations, can be a good indicator of cost trends (IRENA, 2019). PV is photovoltaics; CST is concentrated solar thermal; Δ denotes percentage reduction.

### 3.2. Actual EROIs of Technologies

Raugei and Leccisi (2016) found that, for the UK, which has low average annual insolation, $EROI_{PE\text{-}eq}$ is much greater than 10 for wind and Cd−Te solar PV, and equal to 10 for multi- and single crystalline silicon. Leccisi et al. (2016) examined $EROI_{PE\text{-}eq}$ of PV at three levels of insolation (1000, 1700 and 2300 kWh/m$^2$/yr), and found, for four different types of PV panel, that $EROI_{PE\text{-}eq} \geq 10$, even for the lowest level of insolation.

For coal-fired electricity in the UK, Raugei and Leccisi (2016) found $EROI_{el} = 3.6$, less than $EROI_{el}$ values they and Leccisi et al. (2016) found for wind and most PV types.[3] Brockway et al. (2019) found that most high values of EROI reported for FF are calculated at the primary energy stage, i.e. where the fuels are extracted from the ground. They calculated global averages for fossil fuelled (coal and gas) *electricity* and obtained $EROI_{el} \approx 4$ and declining.[4]

To the best of our knowledge, there is no published evidence that the EROIs of wind or solar PV per se are declining over time. The empirical evidence that their EROIs are increasing is manifold: falling prices; increasing energy conversion efficiencies and increasing capacity factors for both wind and PV; and rapid energy learning rates for PV. Each of these is now examined.

In general, falling prices of technologies go hand in hand with falling energy investments into the technologies. As real costs decrease, so does the embodied energy of spending on materials, goods, services, labor and investments. In the period from 2000 to 2014, an increasing number of countries decoupled their total energy footprint in relative terms, i.e. their total use of direct and indirect energy increased more slowly than GDP increased (Akizu-Gardoki et al., 2018). This means that the energy intensity (total energy consumed per dollar) has been falling in the same period, both in these countries and also globally (Chang et al., 2019). Hence the average total energy (invested) per dollar spent has decreased. Together with reduced spending, these two factors drive down energy investments and therefore increase EROIs.

The Renewable Cost Database of the International Renewable Energy Agency documents huge reductions in global weighted-average Levelized Costs of Energy (LCOE) and capital costs of solar PV and large reductions in LCOE and capital costs of onshore wind between 2010 and 2018 (IRENA, 2019), see Table 1. Improvements in wind turbine design and some of the causes of increased capacity factors (higher tower; longer blades) entail decreasing inputs of materials and energy per kWh. Increasing capacity factors also result in declining operation and maintenance costs per kWh (IRENA, 2019, p.42). Table 2 shows the increases in capacity factors for wind and solar technologies.

For solar PV, IRENA (2019) reports that lower module prices, ongoing reductions in balance of system costs and increases in capacity factors are the main drivers of reductions in LCOE. Dale and Benson (2013) find that the rate of decrease in the Cumulative Energy Demand (defined above) of solar PV is comparable with that of financial cost and that improvements in EROI result from increased energy efficiency and reduced material requirements of PV modules. Kavlak et al. (2018) identify increasing module energy efficiency as the largest contributor to cost reductions over 1980–2001, while increasing size of manufacturing plant was the largest contributor over 2001–2012. All these improvements entail reduced energy invested and increased energy output. Increased manufacturing plant size entails scale economies through shared infrastructure, reduced labor requirements and better quality control, resulting in reduced energy invested.

Görig and Breyer (2016) derived energy learning rates, i.e. how energy invested decreases with the doubling of the cumulative capacity, for solar PV. From a database of 73 publications published between 1976 and 2010, and using a market weighted mix of technologies and volumes, they found an energy learning rate of 17% for PV modules and 14% for PV systems. With medium-level annual irradiation of 1700 kWh/m$^2$ on six different rooftop PV systems, they found EROIs in 2010 ranging from 10 to 25 and projected EROIs in 2020 of 20 to 60. It is unclear whether they calculated primary energy equivalent or electric EROIs.

Improvements in PV technology continue: among monocrystalline silicon solar cells, the passivated emitter and rear cell (PERC), which is gaining share in the world market, has a lower energy payback time (i.e. higher EROI) compared with the current industry standard, the screen-printed aluminium back surface field (Al-BSF) cell (Lunardi et al., 2018).

**Table 2**
Changes in global weighted average capacity factor of wind and solar technologies, 2010–2018.

| Technology | Capacity factor 2010 (%) | Capacity factor 2018 (%) | Increase (%) |
|---|---|---|---|
| Solar PV | 14 | 18 | 29 |
| Onshore wind | 27 | 34 | 26 |
| Offshore wind (small database) | 38 | 43 | 13 |
| CST (small database) | 30 | 45 | 50 |

Source: Figs S.4–S.7 of IRENA (2019).
Note: PV is photovoltaics; CST is concentrated solar thermal.

### 3.3. Dynamic EROIs in Transitioning Electricity Systems

Dynamic effects of the transition from FF to RE systems involve the 'energy-emissions trap' (Sers and Victor, 2018), a trade-off between rapid mitigation of GHG and a temporary increase in system EROI as new RE technologies are built more rapidly than they can generate power to compensate for the energy invested. Dale and Benson (2013) find that the global PV industry was in energy debt prior to 2010, but was energy positive in recent years as capacity factors increase and energy invested decreases. Carbajales-Dale et al. (2014) include storage in their dynamic modelling and find that.

> both on-shore and offshore wind can support the deployment of a very large amount of storage, over 300 h of geologic storage in the case of on-shore wind. On the other hand, solar PV, which is already energetically expensive compared to wind power, can only 'afford' about 24 h of storage before the industry operates at an energy deficit.

However, capacity factors of wind and solar are greater nowadays than those used by Dale and Benson (2013) and Carbajales-Dale et al. (2014) – see Section 3.1.

The 'energy-emissions trap' applies to all power generation technologies, especially to the other commercially available low-carbon option, nuclear power, which has high up-front energy invested (Lenzen, 2008), reflected in very high up-front economic costs (Lazard, 2019). In the USA, nuclear power stations take on average several years to plan plus nine years to construct (Koomey and Hultman, 2007), while wind and solar farms can be planned and built in 2–3 years; residential rooftop solar systems are mass produced and can be installed in one day. The rapid construction plus installation times of wind and solar more than compensate for the higher capacity factor of nuclear, while the latter's long lifetime is irrelevant to the system dynamic dilemma. If we accept the need for rapid, substantial climate mitigation (IPCC, 2018), then we may have to accept a temporary increase in system EROI during the period of rapid growth of RE. Updating to 1 January 2020 the global carbon budget for 1.5 °C target reported by IPCC (2018), the 7.7 billion people on this planet have about 340 Gt of

[3] It doesn't seem meaningful to compare $EROI_{PE\text{-}eq}$ of electricity from FF and RE. In this case $EROI_{el}$ is relevant.

[4] This number has been adjusted for their different definition of EROI: they used net instead of gross EROI.

remaining $CO_2$ emissions to be shared or 44 t per person on average. At the current rate of $CO_2$ emissions of about 37.5 Gt p.a., nine years remain. Hence there is a case for giving investment in climate mitigation a very high priority.

## 4. EROIs of Systems with Storage Technologies

The problem of incorporating storage into the evaluation of EROI of whole electricity systems has been discussed previously from various perspectives by Carbajales-Dale et al. (2014), Pellow et al. (2015), Sternberg and Bardow (2015), Palmer (2017a), Raugei et al. (2017) and Solomon et al. (2018). A comprehensive review of pre-2017 literature is given by Palmer (2017b).

### 4.1. Roles and Types of Storage

Storage in generating systems with high penetrations[5] of VRE permits generation reliability[6] to be maintained by filling troughs in supply and reducing peaks in demand. Storage can also provide frequency control ancillary services (FCAS) (Parkinson, 2019). Some forms of storage (e.g. batteries) improve security[7] by providing very rapid response to a disturbance resulting from, for example, the unexpected failure of a power station, the physical collapse or overloading of a major transmission line, or a sudden change in demand. Storage also provides greater utilisation of transmission and distribution lines, thus reducing the need for augmentation.

For 100% RE systems, in which most annual generation is supplied by VRE, there is likely to be a mix of storage technologies playing these different roles: batteries with energy storage capacities of a few hours at most[8]; possibly concentrated solar thermal (CST) with overnight thermal storage if the region has plenty of direct sunlight; off-river pumped hydro (discussed in Section 4.2) with storage of days to weeks; and, if seasonal storage is needed, compressed air and/or conventional hydro in locations where geological caverns or the hydro resource respectively are available.

There is a nexus between the penetration of VRE into the power system, storage capacity and the amount of curtailment (Solomon et al., 2018). As the cost of wind and solar electricity continues to fall, it becomes economically viable to increase the penetration of variable renewable power capacity, to curtail power output additional to demand and to reduce the amount of energy storage, without loss of reliability.

We distinguish between two types of storage, both of which can play valuable roles in power systems with high VRE penetration:

1. Storage that's integrated into a net generator of electricity: e.g. CST with thermal storage; once-through hydro with dam; open-cycle gas turbine with chemical storage in fuel tank or pipeline. These technologies may have high EROIs if their life-time operation is high and round-trip losses are small.
2. Storage that's a net user of electricity: e.g. battery; pumped hydro; compressed air. EROI is inappropriate for this type of storage, however energy stored on energy invested (ESOI) is useful:

$$\mathrm{ESOI_{el}} = E_{st}/E_{inv} \tag{4}$$

where $E_{st}$ is energy stored over the lifetime of the technology (Barnhart and Benson, 2013). While Barnhart and Benson (2013) found $\mathrm{ESOI_{el}} > 200$ for on-river pumped hydro and compressed air storage, several types of battery had $\mathrm{ESOI_{el}}$ between two and 10. Although batteries are generally charged and discharged (partially) on an almost daily basis, their lifetimes are much shorter than hydro or compressed air and so their $E_{st}$ is relatively low. Since Barnhart and Benson used LCA to estimate $E_{inv}$, RE input to the battery must have been included, thus decreasing their ESOI results. However, in NEA framework it would be excluded when the electricity input to the battery is supplied by excess RE that would otherwise be curtailed.

### 4.2. Quantity of Storage – Australian Case Study

As mentioned in the introduction, Australia can be considered typical of regions with high solar and/or wind resources and low once-through hydro resources. In Australia, electricity is responsible for 33% of GHG emissions and all energy 82% of emissions (DEE, 2019, Table 3). As a case study, we consider two simulation modelling studies of the operation of Australian National Electricity Market (NEM) with 100% RE. Simulation modelling has been well established over the past decade with scores of studies carried out globally, most in Europe, the USA and Australia (Hansen et al., 2019). Studies address multiple scenarios and are validated by sensitivity analysis, increasingly by practical experience in regions with high VRE penetrations, e.g. Scotland, Denmark, South Australia, Germany and several US states, and by the regular successful use over several decades of simulation models for planning and operation of actual large-scale electricity systems. The simulation models' qualitative result, that reliability can be achieved with high penetrations of variable RE, is supported by the statement from Energinet that 'in 2016, Danish wind turbines produced more than the total electricity consumption for 317 hours of the year' (Jørgensen, 2017); Denmark has one of the most electricity reliable systems in Europe.

In 2018, NEM generating capacity was 60 GW and annual generation in FY 2018–19 was 205 TWh, of which coal supplied 70%, wind 10%, gas 9%, hydro 8% and solar PV 3% (AER (Australian Energy Regulator), 2019). One case study utilises storage in the form of dispatchable[9] RE technologies that are net generators of electricity (Type 1 storage), while the other utilises existing once-through hydro together with Type 2 storage.

Elliston et al. (2016) took storage in the form of dispatchable renewables having net generation, comprising existing hydro supplemented by CST with thermal storage and open cycle gas turbines using renewable fuels. Renewable energy penetration was increased in steps of 10% above the level of existing hydro; the economic optimal mix of technologies was determined at each step. A reliable 100% RE generation system was achieved with an optimal mix comprising 78% of annual energy generation provided by the VRE sources (wind + PV) and 22% by the dispatchable renewables. In transitioning from zero additional penetration of renewable energy to 80%, the increase required in generating capacity and annual energy generation from dispatchable RE was very small, see Fig. 2. However, in going from 80% to 100% renewables, the capacity and generation of dispatchable renewables required an increase by a factor of approximately three, with dispatchable power capacity reaching 26 GW and annual generation of 47 TWh (Elliston et al., 2016, Tables A.10 & B.13).[10] Fig. 2 is similar to Fig. 9 of Solomon et al. (2018), after rotating the axes and replacing total RE penetration by VRE penetration.

[5] 'Penetration' of VRE is defined to be the percentage of annual electrical energy demand supplied by direct VRE generation plus storage discharge.

[6] In power engineering, 'generation reliability' is a measure of the ability of generation by the whole system to meet demand. It is measured by e.g. Loss of Load Probability (average probability that supply fails to meet demand) or proportion of unserved energy demand over a year. It should not be confused with concepts of reliability in other branches of engineering.

[7] In power engineering, 'security' denotes the ability of the power system to tolerate disturbances and hence maintain electricity supply to consumers.

[8] If the costs of flow batteries decline, they could provide overnight storage on a utility scale. Their costs increase more slowly with increasing energy capacity than Lithium batteries.

[9] i.e. can supply power promptly on demand

[10] In their Tables B.11 to B.13, the units should be TWh, not GWh.

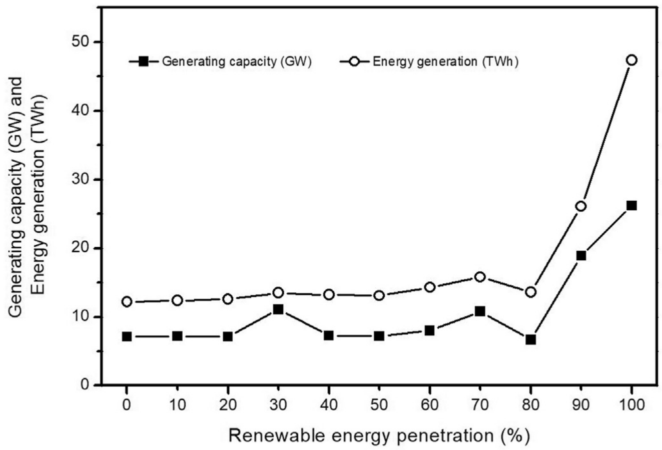


**Fig. 2.** Generating capacity and annual energy generation of Type 1 storage as a function of total RE penetration into the NEM system.
Source: Data from Elliston et al. (2016).
Notes: RE is renewable energy; VRE is variable renewable energy; NEM is Australian National Electricity Market. Each step of 10% RE penetration is an economic optimal mix. At 100% RE, VRE has penetration of 78% and dispatchable RE 22%.

Gas turbines are mass-produced and generally have low capital costs in dollars per kilowatt and hence low values of energy invested. However, in the simulations by Elliston et al. (2016), both gas turbines and CST with thermal storage have low capacity factors (i.e. are used infrequently) and have low life-time energy outputs. Therefore, if operated this way, they may have low EROIs. However, in some regions, CST with thermal storage can be operated 24/7 with high capacity factor for most of the year and so could credibly have high EROI, as estimated by Whitaker et al. (2013). Note that CST with storage does not necessarily have a lower EROI or higher LCOE than CST without storage, because the higher capacity factor resulting from storage can offset both the energy and monetary costs of storage.

The simulations of the NEM by Blakers et al. (2017) assumed a baseline system in which VRE supplied 92% of annual electricity generation. To maintain generation reliability at the standard, they supplemented existing hydro storage (8% of annual generation) with additional small off-river pumped hydro plants, charged by VRE generation that would otherwise have been curtailed. The modelled pumped off-river hydro technologies are small closed-loop systems with energy storage capacities of days to weeks. Seasonal storage in addition to the existing Snowy Hydro scheme was found to be unnecessary. (Incidentally, a proposed new large pumped hydro plant (called Snowy 2.0) would not help VRE until it had operated for several years, because most of the pumping would initially be done by coal power.) A reliable generating system was achieved with off-river pumped hydro generating capacities of 16–28 GW for various scenarios, similar in magnitude to that of Elliston et al. (2016) with smaller VRE penetration (78%). The total energy storage capacities required for reliability at 100% RE were 470–490 GWh or 0.22–0.24% of annual generation. Although they appear to be remarkably small, they are used many times per year. Demand response was also used during a few critical peaks.

These two detailed simulation models each show that, for 100% renewable electricity systems with high solar and/or wind penetrations, the quantity of storage required, both in terms of generating capacity and stored energy, depends on the penetration of VRE generation and is generally small for energy penetrations less than about 40%.

For pumped hydro, a long lifetime and frequent use of the storage entail that the energy output is high. Furthermore, some off-river (closed loop) pumped hydro systems (Blakers et al., 2017; Lu et al., 2018), e.g. those with the bottom reservoir a mineshaft or the ocean and with short pipeline distances, may have quite low values of energy invested as well as high energy outputs. These authors have identified 616,000 potentially feasible off-river pumped hydro sites with total storage potential of about 23 million GWh by using geographic information system analysis. They estimate this is about 100 times greater than required to support a 100% global renewable electricity system (Blakers et al., n.d., website), which provides a large buffer for environmental, social and economic constraints on siting.

The amount of storage needed for maintaining reliability can be reduced by geographic dispersion of wind and solar farms (given adequate transmission links), diversity of types of RE resources, choice of particular storage technologies, increasing RE capacity and accepting increased curtailment, sector coupling, new transmission links, reformed market structure/rules, and demand response. Because demand response has very low energy invested (mainly 'smart' meters and switches) and potentially frequent operation, it would have negligible adverse impacts on system EROI. A diversity of VRE, with different statistical properties, can also reduce storage amount; e.g. in many regions, wind speeds are higher at night. Therefore, assigning various amounts of storage to individual RE technologies (e.g. Weissbach et al., 2013) will overestimate the storage requirement of the whole system. Furthermore, during the transition to 100% RE, Type 1 storage, in the form of reserve base-load and peak-load FF generators, can also serve quite large penetrations of VRE, as shown in Fig. 2.

### *4.3. Summary on Storage*

In regions with high wind and/or solar resources and low once-through hydro-electric potential, the amount of storage required for generation reliability in 100% RE power systems is small. It depends on the many factors listed in the previous paragraph. The impact of storage on system EROI is not just a property of the technology, but also depends on the operating strategy applied to the storage technologies. Some forms and uses of storage may have low ESOIs and may significantly reduce the EROI of power systems with high penetrations of VRE: e.g. Lithium batteries with high energy capacity used to fill troughs in VRE supply; CST and gas turbines with infrequent use. Other forms of storage may have high ESOIs and may not reduce system EROI significantly: e.g. once-through hydro; pumped hydro (both on-river and off-river); compressed air; CST with thermal storage and gas turbines used frequently; batteries with low energy capacity and high power capacity used daily. Where storage technologies in the form of net generators are used frequently and have low round-trip losses, they may in some cases increase system EROI.

## 5. Conclusion and General Comments on EROI

Contrary to traditional beliefs based on several previous studies, EROIs of wind and solar PV technologies at suitable locations are high and increasing. These VRE technologies can provide the vast majority of annual electricity generation in the type of region considered in this paper: high solar and/or wind resources together with low once-through hydro-electric potential. (For regions with limited wind and solar resources and/or high demand for winter heating, sector coupling, e.g. power-to-gas and power to chemicals, and import-export of electricity by transmission line can reduce the need for energy storage, but this is not the subject of the present paper.)

Analysis of two Australian simulation models finds that storage requirements for 100% RE in regions of high solar and/or wind are likely to be small, even with very high penetrations of VRE, and therefore the impact of storage on system EROI is also likely to be small. It would be simplistic to attempt to provide general quantitative results, because each regional power system has different RE and storage resources, different distributions of population and industries, different physical infrastructures and different electricity market structures and rules. Therefore, each system will have different optimal mixes and operating strategies for its RE and storage technologies. Nevertheless, qualitatively, it can be said that the end points with 100% RE appear to be technologically, environmentally and economically viable, not only for electricity, but also in the longer term for the whole energy sector.

Despite the high and increasing EROIs of VRE technologies, the modest storage requirements in the regions of interest and the high ESOIs of some storage technologies, the dynamic situation during a rapid transition is more challenging. To satisfy the requirements of climate science, the transition to RE may have to proceed so rapidly that whole system EROI falls temporarily to low levels and so takes resources from other sectors of the economy. This energy-emissions dilemma may be unavoidable, whatever low carbon technologies are used.

Recent research (Raugei and Leccisi, 2016; Brockway et al., 2019) finds that $EROI_{el}$'s of FF electricity are comparable with $EROI_{el}$'s of VRE based on recent data. This follows to a large degree from the low efficiencies of generating electricity by fuel combustion, which entail that transitioning to an energy system based on 100% RE and efficient energy use would greatly reduce the demand for primary energy from fuel combustion – see Fig. 1 and Jacobson et al. (2018). As summarised by Brockway et al. (2019, p.616),

> in EROI terms, renewable-based electricity might not be as disadvantaged compared with fossil fuels as is often suggested in the literature (Hall et al., 2014)…the renewables transition may actually halt – or even reverse – the decline in global EROI at the final energy stage.

EROI is just one aspect of the socio-economic impacts of the transition from FF to RE. Most of the other impacts of the transition, listed in the introduction, are beneficial to both the economy and the environment. Temporary exceptions during a rapid transition are the dynamic impact on system EROI (Section 3.3) and the impact on employment of stranded assets in the fossil fuel industries and their inputs. Government policies will be needed to protect vulnerable economic sectors and to foster new industries and businesses, and the retraining of workers, in affected regions.

Finally, the question should be asked: does EROI matter if the energy invested is entirely renewable? One response to the question is based on the well-known fact that just a tiny proportion of Earth's surface is sufficient to provide many times current energy demand by industrial society from RE. In the words of White and Kramer (2019),

> Unlike in any previous epoch, energy in the future will not be scarce. This is fundamentally a technological achievement: sun and wind have always been plentiful resources, but solar photovoltaic panels and wind turbines have recently become practical, affordable devices to convert the resource into useful energy, notably electricity.

Already we are seeing the beginning of a move to use renewable electricity to mine and process the raw materials and to manufacture renewable energy technologies (see Section 1). According to Jacobson et al. (2018); Ram et al. (2019) and Bogdanov et al. (2019), most or all of the world's energy could be supplied from regions with high solar and/or high wind considered in this paper, together with regions of high once-through hydro resources. For storage to balance variability of VRE generation, the potential for off-river pumped hydro storage is huge. Therefore, the energy invested in the transition to 100% RE, together with the energy needed for other sectors of the economy, could be provided by RE. The only limits are the available land area, the finite resources of materials and the understanding that very large increases in energy use, even 100% renewable energy, would cause adverse environmental impacts apart from climate change. In the long run, on a finite planet, a steady state biophysical economy is necessary (Daly, 1977; Dietz and O'Neill, 2013).

## Declaration of Competing Interest

None.

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