15 A strategy to increase the resource efficiency of renewable energy technologies

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Introduction

The Paris Agreement, which was negotiated during the 21st Conference of the Parties (COP 21) in 2015, obliges all involved nations to accelerate and strengthen their activities in combating climate change. The main goal of the Paris Agreement is to maintain the global temperature rise below 2 °C while pursuing efforts to limit the rise to 1.5 °C. Within this context, the involved nations are required to outline their climate goals and actions which will collectively contribute to achieving the agreed climate goals. As an example, the climate goals in Germany aim at reducing the greenhouse gas (GHG) emissions by at least 80% compared to the reference emission values from 1990. By the end of 2017, the total GHG emissions in Germany have reduced by 27%. The realisation of these climate goals clearly requires a shift in the electricity production sector from the GHG-intensive conventional power plants towards GHG-free generators. The renewable energy technologies photovoltaics (PV) and wind turbines are among the most competitive electricity generating technologies, can be installed quickly in both centralised and decentralised manner and offer further declining installation costs. The expected increase in the installation of renewable energy technologies opens up the following question: Are there enough raw materials to cater to the increasing demand for renewable energy technologies in the future? In this chapter, the possibility of a raw material supply risk due to the increased deployment of PV and wind turbines will be presented using the example of a global energy transition scenario. In addition to that, ways to increase the resource efficiency of renewable energy technologies will also be discussed.

Energy transformation process and potential demand for raw materials

Energy scenarios are not predictions of how the future energy system will be, but they assist the energy transformation process by providing guidance and presenting possible risks that can occur while pursuing climate goals. The International Energy Agency (IEA) publishes the World Energy Outlook

(WEO) every year which provides an update on the global energy market and the projections of the energy system based on current trends and data. In the latest version of the WEO, three energy scenarios were presented, among which the Sustainable Development Scenario (SDS) is considered to be the most sustainable scenario (IEA 2018). The SDS scenario considers the broader energy picture taking into account the United Nations Sustainable Development Goals (SDGs) on energy, universal energy access, air pollution, clean water and sanitation. According to this scenario, the global energy-related CO₂ emissions will peak at around 2020 and will continuously decline thereafter. The IEA claims that the scenario is fully in line with the trajectory required to achieve a global temperature rise of between 1.7 to 1.8 °C by 2100.

According to this scenario, the global cumulative installed capacity of PV and wind turbines will reach 4240 GW and 2819 GW respectively by 2040. By the end of 2018, a total of 532 GW (PV) and 590 GW (wind) capacities are available globally (IRENA 2019). The expected massive expansion of PV and wind turbines is however conditioned to the supply of large raw material amounts. As an example, the requirements of selected metals are shown in Table 15.1. The demand includes new capacities that have to be installed to substitute older power plants that have reached their lifespan to achieve the proposed cumulative installed capacity in 2040. Furthermore, an annual reduction of 1% is considered for the specific material demand to take material efficiency measures into accounts, such as improvement in the manufacturing process and power conversion efficiencies.

There are several important points that can be understood from the results. Firstly, increasing demand for renewable energy technologies will eventually exhaust the reserve of relevant metals. If the SDS scenario is realised, approximately 13% of available silver reserves would have been mined and manufactured into PV modules by 2040. Although the use of rare earth elements (REEs) in wind turbines does not seem as critical as silver in PV, it should be mentioned that the installations of these technologies will not be ceased in 2040. Instead, the installations will continue beyond that at an even greater rate to reach the long-term climate goals. Secondly, the expansion of renewable energy technologies will most likely be constraint by the production capacity of raw materials, since the growth in annual demand by far outweighs the current production rate. In terms of dysprosium, the production has to be increased by more than 250% of today's level.

Thirdly, renewable energy technologies can expect tough competition from other sectors in securing raw materials for the future. Regarding silver, for instance, only 8% of the current global silver demand goes into manufacturing crystalline Silicon (c-Si) based PV modules, which dominate the global PV market with a share of over 95% per cent. Therefore, a twofold increase of the silver demand required for PV module can create tough competition among other silver-intensive sectors. With the exception of the financial crisis in 2011, the global GDP growth has been positive other the past 50 years.

Table 15.1 Maximum annual and cumulative material demand of selected metals in PV and wind turbines for the Sustainable Development Scenario in WEO 2018

Metal	Specific metal demand [kg/MW]	Maximum annual material demand [kt]	Global production in 2018 [kt]	Percentage of demand to production [%]	Cumulative material demand 2020–2040 [kt]	Reserve 2018 [kt]	Percentage of demand to reserve [%]
PV	23	4.6	27	17	72.6	560	13
Wind turbine	90	13.6	19	71	170.4	23000	0.7
	7	1.1	0.42	251	13.3	320	4

Sources: The specific metal demand for Nd and Dy are obtained from Shannugam et al. (2019) whereas the specific demand for Ag is obtained from Fraunhofer internal data. USGS (2018) and Viebahn et al. (2015) provided the reserve and annual production of Ag and REEs respectively.

Assuming that this trend continues in the future, growth in all manufacturing sectors can be expected, which consequently creates competition for raw materials between different sectors. In most cases the outcome is predictable; those who are willing to pay the most can secure the raw materials they need.

Apart from the aforementioned arguments, there are several other risks that can occur due to the increasing deployment of renewable energy technologies. One of the most likely ones will be the hike in raw material prices as the availability becomes scarce. Being already the most expensive metal in c-Si PV modules, a strong increase in silver price will definitely hinder the cost reduction of PV modules, which in turn will impede a large-scale deployment. Furthermore, the increase in price might provide producing countries with useful leverage against other countries to increase their profit. This is possible since most of the metals required by renewable energy technologies are found in large concentrations in only a handful of countries. An example of this was the export restriction on REEs imposed by China in 2012, which eventually led Vestas, a major turbine manufacturer, to use squirrel cage induction generators for their turbines instead of their established high-speed generators with permanent magnets.

Material efficiency measures in solar cells and novel concepts

Based on the arguments presented in the previous chapter, it is clear that further improving resource efficiency in renewable technologies is vital in order to ensure their sustainability and cost-effective wide-scale implementation. Resource efficiency in photovoltaics can be achieved via direct or indirect measures. A direct material efficiency measure can be the improvement in the production process of PV products, like solar cells and modules. An example of this is the reduction of kerf losses which occur from the slicing of silicon ingots into thin wafers. By 2018, almost the entire c-Si PV industry switched from the slurry-based wafer sawing to the diamond wire sawing, which reduces the amount of silicon consumed per wafer by approximately 15% (ITRPV 2017). The further material reduction can be expected by using kerfless wafering technologies, thinner diamond wires as well as increasing the rate of recycling for the silicon residue during the sawing process. In addition to that, efforts are undertaken in order to reduce the use of silver in cell metallisation since it is currently – and will most probably remain – the most expensive metal in a crystalline solar cell. Besides reducing the amount of silver via improved screen printing and cell interconnection, feasible ways of substituting it with a mixture of copper and nickel are already available, which allows for comparable efficiency.

Material efficiency can also be indirectly achieved by improving cell efficiency, which reduces the specific demand for all relevant materials, as well as reduction of cell thickness, which improves the material efficiency of silicon. The most common cell thickness of a silicon-based solar cell is 180 μm .

Nonetheless, efforts are being carried out to reduce this, so that thickness as low as 120 μm can already be expected by 2030 for mono c-Si solar cells. In terms of efficiency, the maximum achievable efficiency for c-Si solar cells is limited at 29.4% (Polman et al. 2016). The current maximum recorded c-Si solar cell efficiency is 26.7%, which shows that there is still slight room for improvement (Green et al. 2019). Furthermore, the module efficiency, which lies currently around 17–20%, can also be improved further. For example, losses in cell interconnections can be reduced by utilising shingles solar cells whereas shading losses can be reduced by using frameless modules.

Improved concepts such as the Silicon heterojunction (SHJ) solar cell can help in further reducing specific material content of solar cells due to their high efficiency. SHJ has very high conversion efficiency due to distinctive surface passivation. Compared to other silicon-based solar cells such as Passivated Emitter and Rear Cell (PERC) or Back Surface Field (BSF), the main advantages of SHJ include the simple and low-temperature manufacturing processes, which decrease the thermal budget and thus the cost of the cell (Louwen et al. 2016). However, the production facility is not yet available on a large scale as main players in the industry often opt to optimise their current portfolio and respective products rather than adopting a new cell concept and corresponding production line. However, this is most likely to change in the future once the cost advantages increase, driven by significant learning effects.

A further increase in efficiency above 30% can be achieved by the transition from one to two or more p-n-junctions, named tandem or multijunction solar cells. In terms of tandem solar cells, one of the most widely discussed concepts is the perovskite cell in combination with Si-cells. This solar cell has gained much attention in the past few years due to the enormous increase in efficiency in a very short period of time, as well as the utilisation of inexpensive materials. Nonetheless, the main challenges faced by perovskite cells is the instability issue and the use of lead which is toxic and faces the uncertainty of being banned in the EU Directive for Hazardous Substances (RoHS). Research efforts are already being undertaken to substitute lead with other metals such as bismuth. Nonetheless, the power conversion efficiency is still low compared to the requirement for large scale commercial application. Another promising multijunction concept is the monolithic application of III-V solar cells onto a Si bottom cell. A triple junction configuration has demonstrated to reach efficiencies beyond 37% for terrestrial applications, which clearly offers an enormous material-saving potential (NREL 2019).

Reducing the demand for rare earth elements in wind turbines

The most critical metals in wind turbines are clearly rare earth elements (REEs), namely, dysprosium and neodymium. Improvements in the production technique can reduce material losses and decrease the utilisation of

REEs. For example, Viebahn et al. (2015) reported that the specific material demand of neodymium in a middle-speed generator in wind turbines can be reduced from the current 50 kg/MW to around 32 kg/MW by 2050. Pavel et al. (2017), on the other hand, project an even more intensive reduction by stating that 35 kg/MW of neodymium can already be achieved by 2030. Apart from improving the production techniques, material efficiency in REEs can also be achieved via substitution measures. Principally, two different substitution measures can be applied. Firstly, neodymium and dysprosium can be substituted by other less expensive metals such as cerium and cobalt doped alloys (Pathak et al. 2015). The problem with this solution is that cobalt can face a severe bottleneck in the future with expected strong demand for batteries in electric vehicles. Therefore, although the substitution of REEs can reduce the cost of wind turbines in the near future, it might not be sustainable in the long run when the price of cobalt spikes due to substantial demand and stiff competition, especially from the automotive industry.

This leaves us with the second substitution measure, namely the utilisation of complementary wind turbine concepts without permanent magnets (PM). There are numerous other PM-free concepts available on the market, namely electrically excited generators such as the synchronous direct-drive generator by Enercon or the doubly-fed induction generator by Siemens-Gamesa. Despite the availability of such concepts, generators with PM remain the preferred concept for offshore turbines in part due to their high reliability. Since maintenance work can be highly costly especially when the turbines are built further from the shores, developers tend to opt for the turbines that require less maintenance and repair works. Therefore, efforts in improving the reliability of wind turbines are necessary to close the gap between electrically-excited turbines and turbines with PMs and thus suppressing the need for REEs. Nonetheless, this substitution measure should be treated with care as the increased use of electrically excited turbines might lead to supply bottlenecks of copper (Shammugam et al. 2019). Therefore, a balance between both generator concepts is necessary to overcome the overall metal supply risk. Further state-of-the-art concepts such as the high-temperature superconducting and the pseudo-direct-drive generators can also facilitate in reducing metal requirements due to their lesser weight and improved efficiency.

Secondary production of metals via recycling

A substantially different way of reducing material demand is recycling. In the example of the cumulative demand for silver, assuming a 100% recycling rate reduces the total demand by 20%. Besides that, the peak silver demand could also be reduced by half. In terms of the demand for neodymium and dysprosium, the total cumulative demand can be reduced by 25% assuming a 100% recycling rate. One could argue that the effect of recycling in reducing material demand might seem small. However, it is essential to mention that most of the metal demand will still be in use in 2040 and will be available for

recycling beyond that. Therefore, the virgin demand for manufacturing the technologies in the future can be much lower assuming that most of the material can be won by recycling. In the long term, recycling is probably the most sustainable way of producing metals in order not to exhaust the available raw material resources.

A major challenge faced by the recycling sector is the current lack of market. In Germany for example, although there are around 40 GW of installed PV capacity, most of them were installed from 2010 onwards and will be available for recycling at the earliest by 2035, assuming a lifespan of 25 years. Therefore, it is understandable that there are few available business models and facilities to recycle them. Within this context, First Solar stands out as one of the very few module manufacturers that collects and recycles their own modules. With a reported recycling rate of 90% including semiconductor materials, First Solar not only ensures that the material can be recovered and reused but also has to make sure that no toxic wastes such as cadmium are disposed inappropriately. Similar challenge is also faced by wind turbines since the market is still small for business models and infrastructure developments. In addition to that, a literature review (Jensen and Skelton 2018; Cousins et al. 2019) shows that most of the research today focuses on the recycling of carbon fibres in the turbine blades and very less on the recycling of the generators which contain REEs.

Towards a sustainable energy system with efficient resource utilisation

The Waste Electrical and Electronic Equipment (WEEE) Directive was first introduced in the EU in 2002 to properly manage waste from electric and electronic products. The main goal of the directive is to prevent and reduce the negative environmental effects resulting from the generation and management of WEEE by introducing sustainable production and consumption by reducing, reusing and recycling. Since 2012, this directive also included PV modules and requires manufacturers to take back and recycle their decommissioned products. However, the biggest drawback of this directive is that the exact metals to be recycled are not defined. As an example, the organisation PV-Cycle, which consists of a group of module manufacturers, aims at recycling more than 80% of the weight of PV modules. However, this goal can already be reached if the glass and aluminium frame are recycled, which contributes to more than 90% of the total module weight. Critical metals are often neglected due to their modest amount, which calls for a more specific regulation to define recycling targets for exact metals.

To fully utilise the potential of recycling, a closed-loop recycling process can be implemented. This process means that the materials won by recycling wind turbines and PV modules are used to manufacture new turbines and modules. Such a system is seen as the most effective risk mitigation measure to fend off competitions from other sectors and ensures that the RE industry can secure its long-term material needs. For example, more than half of the silver demand

globally is used as financial commodity and jewellery, which rarely gets recycled. Without a closed-loop recycling process, there is a high possibility that the recycled silver demand from PV modules might end being purchased as a financial asset, especially if the price keeps increasing. On a different note, there is also a possibility that decommissioned RE technologies contain more amount of metals than the amount required to manufacture material-efficient RE technologies at certain time points in the future. This is possible if the market growth remains fairly consistent or existing technology is replaced by a much more efficient technology in the future. For example, the existing wind turbines with PM can provide a surplus of REEs assuming that turbines with electrically excited generators will strongly dominate the market in the future. Ultimately, this provides the industry the opportunity to sell the surplus amount of material which contributes to increasing the financial attractiveness of RE technologies. Besides that, a local closed-loop recycling process also reduces the dependency of the producing countries on foreign markets and makes them more immune towards price fluctuations on the global market.

Furthermore, in order to allow efficient implementations of such a recycling process, the idea of recycling has to be integrated already during the manufacturing process. In doing so, a product will be designed in such a way that it can be easily dismantled and prepared for remanufacturing or recycling during the end-of-life stage. Regarding the issue of lack of a general market for recycling, there is ample time for the industry to prepare for the large-scale decommissioning of the technologies. Research activities should nonetheless already be conducted intensively for recycling so that the industry is fully prepared with appropriate infrastructure. Although the entrepreneurial risk might be very high to start a business where the market is currently very limited, such a strategy might be possible with governmental support. These recycling facilities and business models can already be tested using PV modules or wind turbine components that have been prematurely decommissioned due to failures. For example, Shammugam et al. (2019) estimated that almost 30% of the total material demand in a lifespan of wind turbines is a direct result of maintenance, repair and component exchanges due to failures. The significant amount of failed modules shows that a sufficient supply of components will be available to test the recycling facilities and business models before the large-scale decommissioning of RE technologies actually occurs in the near future.

As of efficiency measures and substitution strategies discussed in this chapter to increase the material efficiency of RE technologies, most of them are still being researched and are not available on a large commercial scale. Therefore increased research works are necessary in these fields in order to accelerate the implementation and market entry of these measures. More governmental support is required for start-ups that are willing to venture into innovative and novel technologies to initiate the activities that will eventually attract more players to be involved and eventually increase the learning rate of these technologies and infrastructure. These efficiency measures are all the more important that renewable technologies have an expected lifespan of at least

25 years, which means that the amount of metals in-use will only be available for reuse upon reaching the lifespan. Therefore it is essential to accelerate the implementation of the material efficiency measures to ensure the long-term sustainability of RE technologies.

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Abbreviations

BSF	back surface field
CO ₂	carbon dioxide
COP	Conference of the Parties
c-Si	crystalline silicon
GDP	gross domestic product
GHG	greenhouse gas
IEA	International Energy Agency
PERC	passivated emitter and rear cell
PM	permanent magnet
PV	photovoltaics
REE	rare earth elements
RoHS	directive for hazardous substances
SDS	sustainable development scenario
SHJ	silicon heterojunction
WEEE	waste electrical and electronic equipment
WEO	World Energy Outlook

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