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Securing the supply chain for wind and solar energy (RE-SUPPLY)

Final report

A report by E4tech and Avalon Consulting

For the International Energy Agency's Implementing Agreement on Renewable Energy Technology Deployment (IEA-RETD)

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1.1 Introduction

Renewable energy offers numerous potential benefits and increasing efforts are devoted to supporting its deployment. However, constraints along the supply chain may prevent deployment at the rate required to meet global energy and climate objectives. This study sets out to identify current and potential bottlenecks in the supply chains for wind and solar photovoltaics (PV), to inform decision makers about the steps needed to avoid these, enabling global deployment targets to be met.

Overall the study finds that the supply chains of both wind and PV are currently likely to be constrained by a range of bottlenecks that may critically impact the deployment of these technologies. Many of these bottlenecks are related to supply-demand imbalances (supply not being able to ramp-up at the same rate as fast-increasing demand), while some are due to absolute constraints on materials, and some to regulation. While many of these bottlenecks are expected to be felt after 2015, some are already affecting the wind and PV sectors today.

In spite of this negative assessment, there are grounds for optimism. The impact and likelihood of almost all of the bottlenecks identified can be reduced significantly, if not eliminated, by mitigating activities at policy and industry level. Most supply-demand imbalances can be mitigated by robust long term frameworks that secure demand, and many constraints on raw materials can be resolved by switching to alternative more abundant materials.

In many cases the problems are well understood and mitigation is being pursued, although these preventive actions would benefit from more coordination. In other cases the problems have yet to be addressed and this report sets out where resources need to be applied, in some cases very soon.

1.2 Context and scope

Most analysis of renewable energy deployment to date has focused on understanding how much renewable energy would be deployed given market push and/or pull, taking for granted that supply of technologies would follow. Given the high penetration rate of renewables contemplated in various scenarios and regions, and the significant share that intermittent renewables may represent in the energy mix in the medium term, a better understanding of supply side potential and constraints is necessary. This study identifies and analyses bottlenecks along renewable energy supply chains and recommends possible mitigating activities for decision makers.

The focus of this study is on the wind and photovoltaics supply chains, considering the technologies that have potential to make a significant contribution to the energy mix by 2025: large scale offshore and onshore wind; crystalline silicon PV (c-Si), and four leading types of thin film PV technologies. The main time horizon for the study is 2025, but some regard is given to the period out to 2050.

A bottleneck is considered to be any constraint along the entire physical supply chain of wind or PV technologies, from the source of raw materials all the way to equipment end-of-life that could significantly reduce the scale of development, deployment or operation of the technology in the absence of mitigating measures.

Demand barriers, such as lack of policy support for renewable energy deployment or social acceptance of wind energy, are not addressed in this report, although the importance of demand signals is considered when discussing mitigation of bottlenecks. In addition, barriers that are related to the wider value system (e.g. project planning or securing finance) rather than the physical supply chain are considered outside the scope of this study.

1.3 Approach & methodology

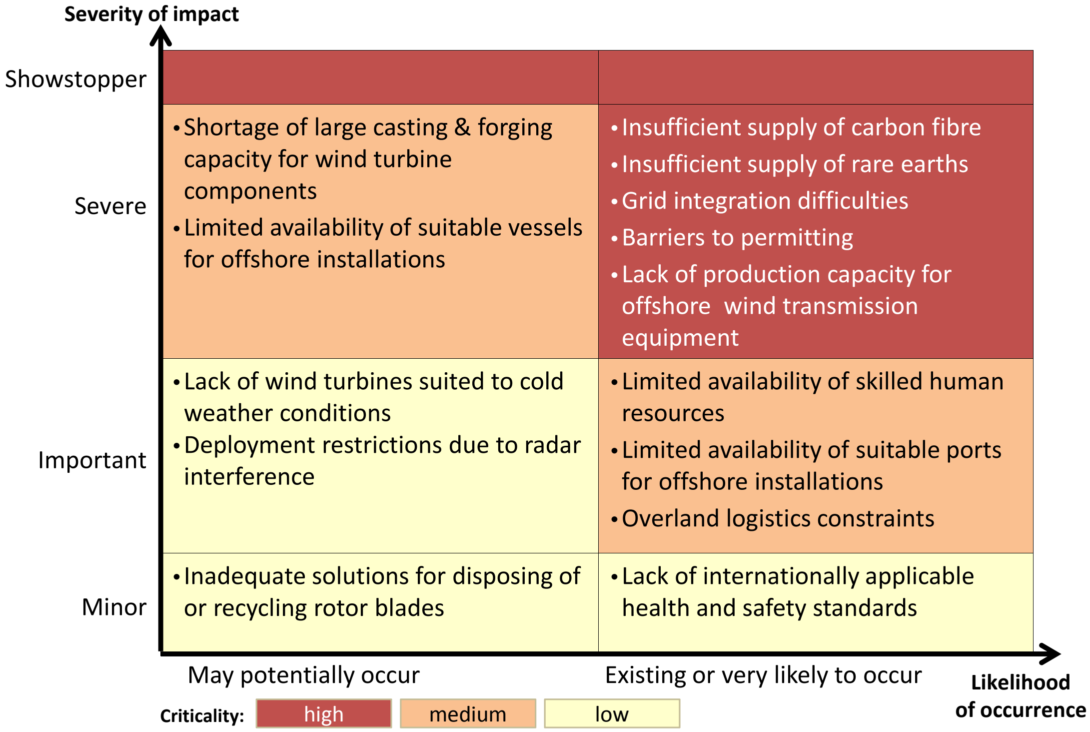
Bottlenecks were initially identified through literature review of more than 250 documents, followed by discussions with around 40 industry experts globally to inform and validate the consultants' assessment.

Each bottleneck was identified and then assessed assuming renewable energy deployment according to the aggressive BLUE Map Hi REN scenario of the IEA Energy Technology Perspectives (2010). A standard risk analysis technique was applied, assessing the likelihood and severity of impact of each bottleneck. Likelihood is considered as the probability of occurrence based upon the current status of efforts to avoid the problem. Impact ranges from minor to severe, depending upon the magnitude and location(s) of the problem. Combining these two components provides an overall assessment of the criticality of each bottleneck, grouped into low, medium and high categories.

For each bottleneck the mitigating actions that are already underway or which would logically be required at policy or industry level, were considered. Based on a discussion of each of these, the key recommendations for decision makers were drawn out.

1.4 Securing the supply chain of wind power

The wind sector is unlikely to be threatened by any showstopper-type bottlenecks. However, 14 potential supply constraints have been identified which may, to a lesser extent, affect the deployment of wind technologies. Of these, five bottlenecks can be considered highly critical, in the sense that they are very likely to occur and will have a major impact on the wind sector at global level in the absence of successful mitigation measures. A summary of all wind energy bottlenecks is presented in the criticality matrix below.



Severity of impact	May potentially occur	Existing or very likely to occur
Showstopper		
Severe	• Shortage of large casting & forging capacity for wind turbine components • Limited availability of suitable vessels for offshore installations	• Insufficient supply of carbon fibre • Insufficient supply of rare earths • Grid integration difficulties • Barriers to permitting • Lack of production capacity for offshore wind transmission equipment
Important	• Lack of wind turbines suited to cold weather conditions • Deployment restrictions due to radar interference	• Limited availability of skilled human resources • Limited availability of suitable ports for offshore installations • Overland logistics constraints
Minor	• Inadequate solutions for disposing of or recycling rotor blades	• Lack of internationally applicable health and safety standards

Figure ES1: Criticality assessment of bottlenecks in wind.

The shortage of essential materials (rare earth metals used in the permanent magnets of turbine generators and carbon fibre used in rotor blades) is very likely to constrain wind energy deployment at global level in the medium term (beyond 2015) if no pro-active mitigation steps are taken. However, these shortages are not absolute resource constraints but demand-supply mismatches which can in principle be remedied with timely planning and capacity augmentation. Although simple in theory, this requires a whole chain of cause and effect to be triggered. Capacity augmentation requires high capital investment, which can only happen if long term purchase contracts are secured, which in turn will only occur if strong demand signal are given. This ultimately relies upon robust long term policies reflecting the long term commitment of governments to increase wind energy deployment.

While material supply issues are only expected to be felt after 2015, wind projects are already being affected by three bottlenecks which will have a severe impact on global deployment levels if not addressed very soon. Two of these, permitting and grid integration of new projects, are delaying the rate at which projects are approved and connected, meaning that deployment levels are already being affected. The solution lies largely with policymakers who should create regulatory systems that match their ambitions for wind energy deployment. The third, a lack of production capacity for offshore transmission infrastructure, will be an increasing bottleneck over the next five years which requires industrial investment now to prevent it having a severe impact. Clarity is therefore needed about the volumes of such equipment that will be required in the coming years, which in turn relies upon policy signals to a large extent.

Two further bottlenecks could have severe impact at global level, though they are less certain to occur than the above in view of the mitigation activities that are already underway. The first is the shortage of vessels suitable for deeper water installations of offshore wind farms. This is diminishing thanks to a recent build-up of capacity and delays in project schedules. The second is a potential capacity shortage for very large cast and forged components in the medium term, as turbine sizes grow. Close communication and collaboration is needed along the supply chain to ensure timely capacity addition, together with R&D into alternative materials and alternative designs to allow large components to be split into sections in the longer term.

Besides the highly critical bottlenecks discussed above, five further supply constraints may hamper wind turbine deployment, though their severity is lower than those mentioned above mostly because their effect is more localised. Three of these are being felt already. The first is a shortage of skilled personnel in manufacturing, installation, and also operation and maintenance. This is felt most strongly in 'difficult' locations (e.g. offshore, remote areas) where the sector has grown quickly from a low base. Rapid training and skills transfer within the industry are urgently needed. Skills planning by industry and supportive education policy are longer term requirements. The second bottleneck is port infrastructure to support offshore wind installation which is lacking in several countries (e.g. UK, Eastern US). This requires a 'predict and provide' approach by policymakers and industry working closely, to ensure that this does not become a greater bottleneck. Thirdly, overland transportation of increasingly large turbine components is challenging in countries where installation takes place far from ports or manufacturing sites, such as the US. Policymakers can assist by removing low level regulatory barriers, and industry should collaborate along the supply chain to predict capacity needs for essential equipment.

Two bottlenecks relating to turbine design may become important on a localised basis if ongoing efforts do not succeed. The first is the lack of wind turbines suited to very cold conditions which precludes access to the large wind resource at high latitudes (e.g. Scandinavia, Labrador). Turbine designs are being explored to overcome the challenges, though further research, development and testing are needed. The second is the lack of a proven solution to radar interference from wind turbines, meaning that projects cannot be placed within line of sight of radar facilities. Technical approaches are being developed and tested to avoid this impact.

Finally it is important to mention that the deployment offshore wind appears much more vulnerable to supply constraints than onshore wind, with several bottlenecks affecting mostly, if not exclusively, offshore development (shortage of carbon fibre, lack of skilled personnel, shortage of barges and port infrastructure). Countries intending significant offshore wind deployment should look to the messages of this report and the ongoing experience of countries in the vanguard, in order to avoid future bottlenecks.

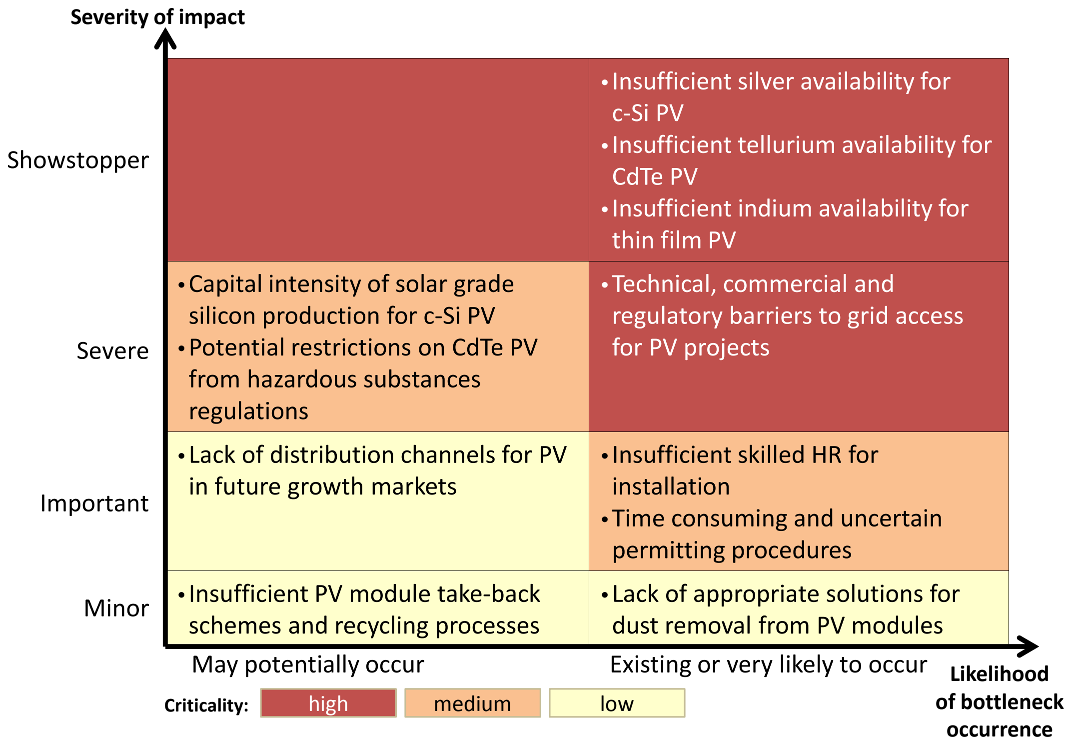
1.5 Securing the supply chain of solar photovoltaics

Shortages of critical materials - indium and tellurium for thin film technologies, and silver for crystalline silicon (c-Si) cells - are very likely to be showstoppers for the deployment PV in the medium term, with the first effects probably felt from 2015 if no pro-active mitigation steps are taken. This is aggravated by increasing demand for these metals from other industries (e.g. consumer electronics), which generally have an ability to pay higher input prices, unlike the PV sector which faces strong cost pressures. Given that the PV sector benefits from a mix of competing technologies, only a simultaneous shortage of silver, indium and tellurium would act as a showstopper to the entire PV sector at global level. At present, silver is proportionally the most critical of these three materials as it is used in c-Si cells which currently account for 85% of the PV market.

The PV industry is well aware of these supply constraints, and has already taken steps towards substituting these metals with more abundant alternatives. However, the ease of substitution depends to a large extent on their actual role in the cells. Indium and tellurium used in the semiconducting layers of different types of thin film PV cannot easily be replaced as this would imply changing the very heart of the active photo-electric process upon which these technologies are based. The cost of these types of PV will increase, therefore, unless the supply of these materials can be increased. Critical materials used as conductors, namely indium and silver, can in principle be substituted by more abundant conductive materials. While indium used in transparent conductive oxide of different thin film PV cells has already largely been replaced by e.g. zinc, the replacement of silver used in the conductive grid of crystalline silicon cells is proving more difficult to achieve and requires more R&D efforts.

Although the shortages of silver, indium and tellurium are only expected to take effect in the medium term, mitigating activities at industry and policy level need to begin today. Relevant actions include increasing secondary supply of materials through improved take-back schemes and development of economically viable recycling technologies, while R&D efforts towards reducing the consumption of these critical metals, or substituting their use wherever possible, should be the primary focus of the PV industry.

As well as the shortages of critical materials, several bottlenecks of lesser criticality have been identified, as shown in the criticality matrix below.



Severity of impact

	May potentially occur	Existing or very likely to occur
Showstopper		Insufficient silver availability for c-Si PV Insufficient tellurium availability for CdTe PV Insufficient indium availability for thin film PV
Severe	Capital intensity of solar grade silicon production for c-Si PV Potential restrictions on CdTe PV from hazardous substances regulations	Technical, commercial and regulatory barriers to grid access for PV projects
Important	Lack of distribution channels for PV in future growth markets	Insufficient skilled HR for installation Time consuming and uncertain permitting procedures
Minor	Insufficient PV module take-back schemes and recycling processes	Lack of appropriate solutions for dust removal from PV modules

Likelihood of bottleneck occurrence

Criticality: high | medium | low

Figure ES2: Criticality assessment of bottlenecks in PV

Grid connection barriers are already holding back PV deployment and are going to have a severe global level impact if solutions cannot be found to alleviate grid capacity limitations, technical grid connection issues and administrative and regulatory barriers. Regulations to ease PV connection and enforce the upgrading of grids at fair return on investment are needed, in conjunction with widespread smart grid infrastructure.

Two further bottlenecks would have a severe impact were they to occur, though this is not certain. Firstly, a ban on cadmium that would include PV applications has been contemplated in the EU, and could occur elsewhere. Were this to be put in place it would require a significant switch from cadmium-based thin film PV, which accounts for 8% of installed PV systems in the EU. This could be achieved, given sufficient lead time, but would be disruptive. Secondly, a recurrence of the 2007 grade silicon shortage, which caused a major crisis in the PV sector, would be very damaging. With clear market demand signals more (highly capital intensive) silicon production will be brought on stream as demand increases. This bottleneck should not recur under these conditions.

Besides the above bottlenecks that affect the PV sector at global level, a further three bottlenecks are already being felt on a more localised (and hence less severe) basis. First, time consuming and uncertain permitting procedures are delaying the deployment of PV projects in some countries and there is scope for transferring lessons learned in permitting across PV markets. Second, insufficient skilled personnel are available for PV installation, especially as PV moves to markets where sunshine levels are high but skill levels are often lower. This requires careful skills planning and knowledge transfer by companies, supported by national education policies and PV industry associations. At industry level, there is a need to integrate skills considerations in product design, in particular through provision of simpler (ideally 'plug and play') PV systems. Third, the absence of product distribution infrastructures may hamper deployment particularly in developing countries. Long term planning and collaboration between policymakers and industry would allow this to be avoided. Vertical integration downstream from distribution down to planning and installation is one way for module manufacturers to also gain better control over the channels to market.

1.6 The need for action

This report identifies 25 bottlenecks across the wind and PV sectors with differing levels of criticality. With the exception of the lack of take-back and recycling schemes and the unlikely issue of a second shortage of grade silicon, all bottlenecks would 'bite' within a 2 to 6 year timeframe, regardless of their nature. The time to act is now, therefore, since many of the mitigating actions involve long lead times. This report recommends 137 actions that principally require industry or policy makers to take steps in the near term. Immediate steps range from carefully monitoring potential problems, to strengthening existing efforts, or initiating new activities.

Many bottlenecks, in particular those related to supply-demand imbalances and raw material constraints, can be diminished by clarity from policy makers about the intended growth of renewable energy and the frameworks to support this, combined with clear communication of these along the supply chain by industry and policy makers. Industry will invest and innovate under these conditions, as is shown by the example of numerous other industrial sectors as they mature. In this regard renewable energy should not be regarded as a 'special case'. However, many bottlenecks could have serious consequences for energy and climate goals, so they should be treated as 'urgent'.

2 Project background and objectives

2.1 The IEA-RETD mission and vision

The IEA-RETD is one of several independent bodies set up under the legal framework of the Technology Cooperation Programme of the IEA[1]. Implementing Agreements bring together experts from research, government and industry to address common challenges in specific technology areas and to share the benefits of their combined efforts. The IEA-RETD was formed after the International Conference for Renewable Energies in Bonn, Germany, June 2004. It was created as a complement to the other Renewable Energy (RE) Implementing Agreements, which are mainly focused on specific technology research, development and demonstration. In contrast, the IEA-RETD is cross-cutting and policy-focused and aims to bridge the gaps between technology development, market development and policy formulation.

The IEA-RETD's vision is to achieve significantly higher utilization of RE by promoting international cooperation and encouraging more effective, efficient and rapid deployment. The IEA-RETD's mission is to act as a catalyst for increased RE technology deployment by:

- Proposing solutions and options to maximize (a) the share of RE technologies in the global, regional and national energy systems, and (b) the contribution of RE to climate change mitigation, security of energy supply and economic growth; and
- Providing recommendations on how to overcome barriers for significantly increased RE deployment.

Building on the unique framework of the IEA, the IEA-RETD aims to disseminate information and enhance knowledge about RE technology deployment, thus supporting improved public and private sector decision making. IEA-RETD projects are intended to make transparent and demonstrate the impact of RE action and inaction and provide the necessary facts and comparisons to aid in the formulation of sound public policy.

2.2 Context and rationale of the project

Renewable energy can bring a number of benefits compared to the incumbent fossil energy options, such as reduced environmental impact, energy independence and local employment. However, the large-scale deployment of renewable energy technologies may be hampered by a number of barriers and constraints. These can be very varied in nature, such as material scarcity, shortage of human resources, environmental and health damages or logistical issues, and can result in bottlenecks anywhere along the supply chains of these renewable energy sectors.

A global understanding of the supply chain issues that may constrain RE technology deployment, and how the severity of these may evolve with time and differ with location, is paramount in order for policy makers and the renewable energy industry to be able to take mitigation measures that help

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[1] The IEA is an autonomous body which was established in November 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an international energy program. The IEA carries out a comprehensive program of energy cooperation on energy issues across 26 of the OECD's 30 member countries. More information about the IEA is available at the http://www.iea.org/.

reduce barriers and remove constraints in a proactive way, while ensuring that the most critical issues are tackled in priority order.

While great efforts at understanding and tackling these issues have been made in specific geographies or for particular technologies, many of these studies are dispersed and not always easy to access or find. In addition, no integrated assessment or broader scenario analysis at global level have been conducted, which is the gap that the IEA-RETD wishes to bridge through this project, focusing on photovoltaic and wind technologies as a first step.

2.3 Project objectives and target audience

The overarching objective of this study is to provide policymakers and renewable energy stakeholders with a clear view of the critical, current and future, supply chain constraints in the wind energy and photovoltaic (PV) sectors, and to provide them with concise recommendations as to which industry or policy measures can best remove or alleviate these barriers.

2.4 Project scope

2.4.1 Time horizon

The time periods considered in this study are from the present until 2025 and from 2025 to 2050. Inevitably, it is easier to provide a picture of the earlier period and this has informed the choice of countries above. The 2025 horizon is the main focus of the study.

For the later period, from 2025 to 2050, the study considers broader effects where it is appropriate to consider how supply chains may evolve.

2.4.2 Supply chain and bottleneck definition

Within this study a bottleneck is considered to be any constraint along the entire physical supply chain of wind or photovoltaic technologies, from the source of raw materials all the way to end-of-life of equipment that significantly reduces the scale of development, deployment or operation of the technology. Throughout this report, the terminology bottlenecks, barriers and constraints to deployment is used interchangeably to suit the context.

Quantitatively, an identified barrier to deployment is considered to be a bottleneck if it has the potential to threaten the 2050 RE technology deployment levels projected in the BLUE Map Hi REN scenario in the Energy Technology Perspectives (ETP) of the International Energy Agency (IEA, 2010c) or the derived target for 2025[2]. This scenario targets 75% of global electricity production in 2050 to come from renewable energy sources with solar and wind as the largest contributors (Figure 1). It is the most ambitious scenario variant in terms of RE technology deployment and has been chosen in keeping with the project's rationale to test whether bottlenecks may threaten large scale deployment of RE technologies.

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[2] 2025 values have been scaled from the BLUE MAP scenario since data on the intermediate years towards 2050 are not published for the Hi REN variant.

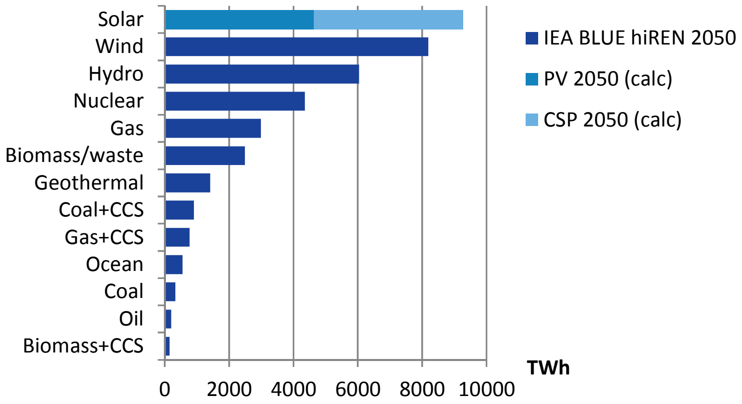
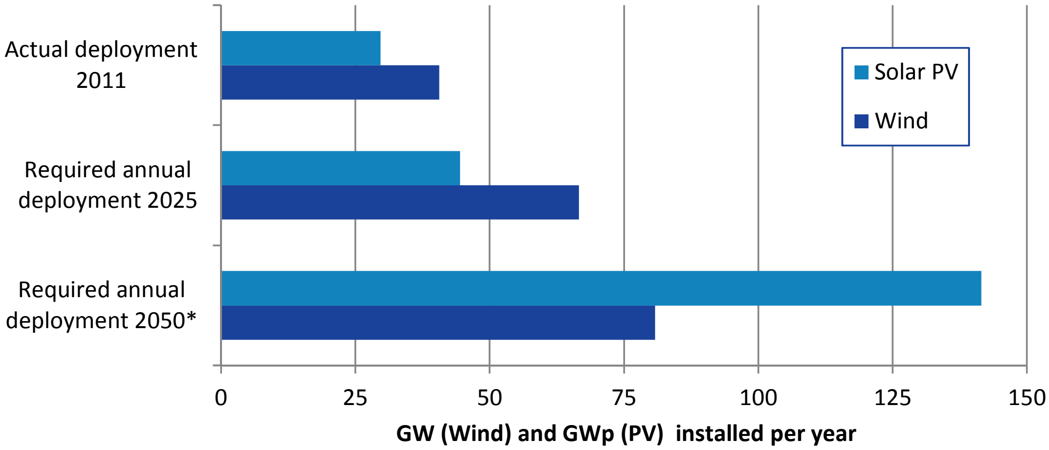


Figure 1: Electricity generation in 2050 as projected in IEA BLUE Map Hi REN scenario

Source: E4tech/Avalon Consulting based on IEA (2010c). Note: Split of solar technologies as in IEA BLUE Map 2050

Based on the Hi REN projections for electricity generation from wind (8,193 TWh) and solar (9,274 TWh) in 2050, the required annual deployment of wind and PV generation capacity[3] (Figure 2) has been derived for benchmarking of potential bottlenecks in the mid-term to 2025 and in the long-term to 2050[4]. Any supply constraint that may prevent these deployment targets being achieved for wind and solar will thus be considered a supply chain bottleneck in this study.



*The 2050 deployment value represents the average annual deployment necessary between 2026 and 2050 to meet the 2050 target (linear approach).

Figure 2: Annual deployment in 2025 and 2050 required to meet BLUE Map Hi REN electricity generation projections for 2050

Source: E4tech/Avalon Consulting based on IEA (2010c), GWEC (2012), EWEA (2012) and EPIA (2012b)

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[3] Assumptions to the calculations: 67% (resp. 33%) of the wind generation in the Hi REN scenario has been attributed to onshore (resp. offshore) wind with a capacity factor of 25% (resp. 33%). 50% of solar power generation in the Hi REN scenario has been attributed to solar PV (4637 TWh in 2050) with a capacity factor of 13% (1162kWh/kWp/yr).

[4] The deployment figure in 2025 (resp. 2050) is calculated as the average annual deployment over the 2020 to 2025 (resp. 2026-2050) period and serves as an indication for the mid-term (resp. long term) annual deployment requirement.

This study focuses exclusively on supply side constraints along the supply chain. In this regard, demand side barriers such as lack of policy support for renewable energy deployment are not addressed. In other words, the demand to meet the IEA BLUE Map Hi REN scenario is taken for granted, though it is axiomatic that without this supply chains would not develop. The importance of demand signals is taken into account when discussing mitigation of bottlenecks, where appropriate.

In addition, barriers that are related to the wider value system rather than the physical supply chain are considered outside the scope of this study. Value system activities include steps such as project planning or securing finance. However, given the strong potential impact of these topics on the supply chain, key value system barriers are nonetheless discussed on an ad-hoc basis when they are found to be critical.

Finally, issues that relate to the overall capacity of the grid to absorb a growing intermittent electricity share, such as a lack of storage capacity or insufficient cross-border grid interconnectivity, are also not included in the direct scope of this study. However, where actual access to the grid presents a bottleneck, including the issues of insufficient grid capacity at the connection point and reluctance of grid operators to offer connection to intermittent electricity sources, this is covered in the study.

2.4.3 Technologies considered

This study focuses on those technologies that can be considered commercial in 2012 and that offer large scale deployment potential. In this regard, any future technology breakthrough or technical improvements that might potentially lower or remove some of the current or future barriers to deployment are considered as mitigation measures to identified bottlenecks.

2.4.3.1 Wind technologies

The following categories of wind technology are included in this study:

- Offshore wind
- Onshore wind

This report focuses on larger (over 1 MW) on and offshore wind turbines, primarily because it is expected that the industry will rely more on larger turbines in the coming years. This is likely given the targets in the IEA BLUE Map Hi REN scenario, the inherent economics of larger scale machines, and the fact that many of the easy, smaller scale installation areas have been exhausted.

The report also focuses primarily on the turbine designs mostly in use now, which are horizontal axis three blade turbines. Vertical axis turbines, double blade turbines and other emerging technologies have not been considered because both the technology and the supply chain are evolving in these cases and they are not currently forecast to play a major part by 2025.

2.4.3.2 Photovoltaic technologies

The following fully commercial PV technologies are included in this study:

- Crystalline silicon: mono- and poly-crystalline (c-Si)

- Thin films: Cadmium Telluride (CdTe), Amorphous Silicon (a-Si), Copper-Indium-(Gallium)-Selenide (CIGS/CIS)

The early commercial micromorph (μ-Si) and silicon hetero-junction cells are not considered explicitly in the analysis, but are implicitly considered when discussing the crystalline silicon and amorphous silicon technologies, with which they are expected to share most bottlenecks.

To a lesser extent, next generation PV technologies are also discussed whenever they represent a mitigation measure to overcome bottlenecks in currently commercial technologies (e.g. Copper-Zinc-Tin-Sulphide-Selenide (CZTSSe) to avoid using indium in CIGS/CIS). Technologies designed for niche applications (e.g. indoor and/or consumer products), rather than for large scale installations are not considered (e.g. dye sensitized solar cells and organic PV).

Concentrated photovoltaics (CPV) using high performance multi-junction cells are excluded from the study as these are not expected to gain significant market share in the short to medium term (SVC, 2011).

Advanced PV technologies such as up/down converters, hot carrier cells, luminescent concentrators and intermediate band cells are also excluded from the analysis on the basis that they are at an early laboratory development stage and do not have defined supply chains.

2.4.4 Geographical scope

The constraints along the supply chains can differ significantly with different geographies. The deployment targets of the BLUE Map Hi REN scenario are global, and so is the scope of this project, although the focus is on OECD countries when discussing the implications. In order to satisfy this requirement for global reach, while optimising the resources, the geographical scope is narrowed while moving down the supply chain:

- A worldwide scope is considered for the supply of raw materials and generic components
- Leading manufacturing countries are considered for the supply of the different technologies considered.
- OECD countries are considered for the implementation of wind and solar technologies, with a special focus on IEA-RETD member countries. Should specific supply chain barriers to implementation be identified in those non-OECD countries with high wind and solar potential, these will then also be discussed on an ad-hoc basis (e.g. PV in India and North Africa, wind in China, etc.)

2.4.5 Depth of analysis

The depth of analysis performed varies between bottlenecks. Generally speaking, the higher the criticality ranking, the deeper the analysis. The most critical bottlenecks have thus been assessed quantitatively and through interviews of industry experts, while less severe issues have only received attention at qualitative level.

However, the depth of analysis carried out for each bottleneck is not always in direct proportion to their level of criticality. This is for three main reasons:

- A bottleneck may have appeared as critical in the preliminary assessment, and was subsequently classed as needing deeper analysis in the second project phase. That analysis in turn may have subsequently led to the conclusion that this bottleneck was not as critical as originally thought.
- There was a deliberate wish from the IEA-RETD to focus the analysis on some of the supply constraints that were less well documented in existing literature. Hence particular emphasis was put on some issues that may be less critical in order to gain a better understanding of them.

2.5 Structure of the report

Section 3 describes the approach and methodology taken to identify and assess supply chain bottlenecks; Sections 4 and 5 analyse the bottlenecks that threaten the wind and PV sectors respectively and discuss possible mitigation measures to remove or alleviate these deployment barriers. The mitigation measures are followed by specific recommendations addressed at decision makers in the policy, industry and NGO communities. Finally, section 6 synthesises the conclusions and recommendations at individual technology and cross-cutting levels.

3 Approach and methodology

The approach taken to meet the objectives of the study combines a bottom-up and a top-down methodology in order to capture both the constraints to deployment that are specific to a given technology (e.g. lack of barges to transport large offshore wind components) and those that are industry-wide (e.g. lack of human resources for installing rooftop PV of all types).

This step-by-step approach taken is described in the subsections below.

3.1 Identification of bottlenecks

In order to identify supply chain bottlenecks in the wind and PV sectors, the following steps were taken:

- The supply chains of wind and PV technologies were first characterised using chevron diagrams. The identified bottlenecks were then mapped onto the supply chain steps (see Figure 7 for wind and Figure 22 for PV).
- Relevant sources of information were identified, based on the knowledge of the authors, the Project Steering Group and additional experts. A total of 267 separate sources were identified, ranging from academic papers to news items on industry specific websites and magazines, with roughly equal numbers covering wind and PV. It was found that:
    - Roughly half of these sources provided relevant insights for specific supply chain bottlenecks either in PV or wind, while other documents cross-referenced the original sources.
    - Most relevant sources provided qualitative descriptions of the bottlenecks and were often location specific. In addition, a handful of sources did provide quantitative information on the severity of bottlenecks.
    - Approximately half of these sources did not mention specific bottlenecks, and thus do not feature as direct references in this report.
- The relevant material identified was reviewed and all the relevant information related to bottlenecks for wind and PV technologies systematically was extracted and associated with the corresponding step on the supply chain of the corresponding technology.
- The time horizon to which these individual constraints might apply was assigned to each constraint, allowing for a mapping of when each type of constrain is expected to occur.
- Feedback from the Project Steering Group and Experts was sought and supplementary data reviewed when additional information was required to bridge knowledge gaps or due to uncertainties revealed from the collected material.
- Wherever obvious knowledge gaps and uncertainties still remained, these were addressed by interviewing a limited number of key experts mainly from industry.

3.2 Assessment of criticality

The criteria for ranking the criticality of an identified barrier should reflect its potential to affect the large-scale deployment of the wind and PV technologies against IEA scenario levels. It should be noted that the assessment is based on current commercial technologies with market shares of these technologies changing according to the scenarios specified below (see 3.4.1 and 3.4.2). Based upon the science of risk analysis, the criticality of the identified bottlenecks is assessed by the combination of the *likelihood* that these bottlenecks will actually occur and the *severity* of their damage to RE deployment should they occur.

Each identified issue has thus been assigned a *likelihood* of occurrence and a level of *severity* for the sector as a whole using the semi-quantitative scales defined in Figure 3. Colour coding is used to differentiate between different levels of likelihood, which then serves to map identified bottlenecks onto the supply chain diagrams.

The *severity* rating is based on the product of two further factors, the first being the extent to which the relevant bottleneck can affect the overall deployment of PV or wind, the second being the geographic extent of the bottleneck (whether regional or global). A scale of severity from 'showstopper' to 'minor' was then assigned. The direct impact of a bottleneck can be varied in nature, ranging from e.g. price rising to unaffordable levels, to the impossibility of manufacturing equipment or transmitting electricity.

Likelihood of bottleneck occurrence

● Bottleneck existing or very likely to occur
⊗ Bottleneck may potentially occur
⊕ Bottleneck is unlikely to occur

Severity of bottleneck
4 = Show stopper - Show stopper at global level
3 = Severe - Major impact on deployment at global level or show stopper at regional level
2 = **Important** - Minor impact on the deployment at global level or significant impact at regional level
1 = **Minor** - Minor impact on deployment at regional level (only in certain regions or under specific circumstances)

Figure 3: Semi-quantitative metrics used to rate the criticality of the identified bottlenecks

3.3 Criticality matrix

The bottlenecks are presented in several different ways for both the wind and PV sectors:

- A positioning of the bottlenecks along the supply chains

- A criticality matrix of the bottlenecks mapping their likelihood of occurrence against their severity, as illustrated in Figure 4.

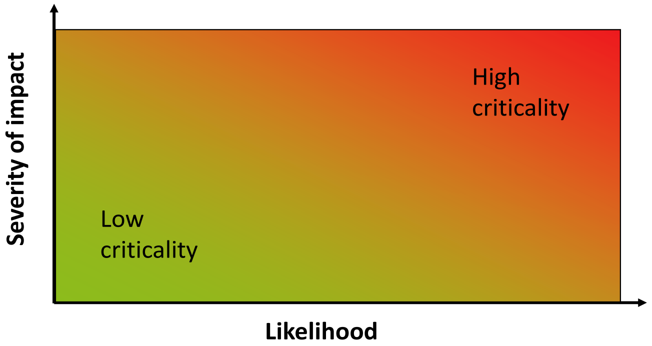


Figure 4: Illustration of the criticality matrix on which bottlenecks can be positioned

- A classification of the bottlenecks by category, along the supply chain. Category types were chosen that were meaningfully distinctive and inform the identification of mitigation measures. Whilst others could have been identified, these were found to be both distinctive and exhaustive:
  - Material supply (raw materials);
  - Industry related activities (manufacturing and operations);
  - Human resources (people and skills);
  - Regulatory aspects (standards, licensing and permitting).

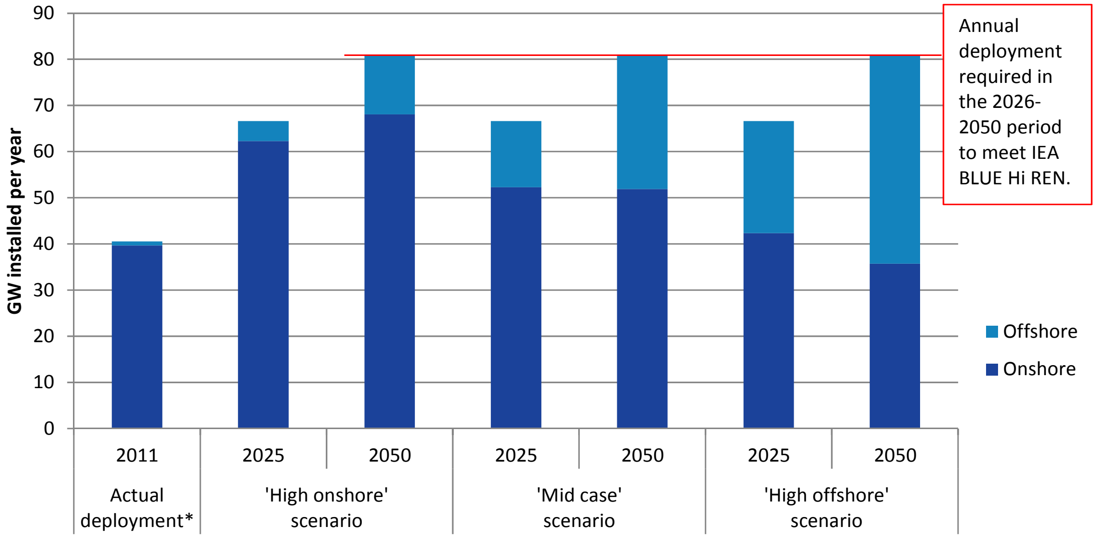
3.4 Bottleneck severity against wind and PV deployment scenarios

The various possible consequences of supply bottlenecks all boil down to constraining wind or PV deployment to a level below the BLUE Map Hi REN scenario. To assess the severity of the identified bottlenecks quantitatively, different technology mix scenarios are considered for both wind and PV, assuming that the Hi REN deployment figures would be met.

These scenario variants for wind and PV, which are presented in the next two sections, will be referred to throughout the report when discussing the detailed assessment of bottlenecks. It should be pointed out that these scenarios are solely used to test how robust bottlenecks are to extreme circumstances and thus gain deeper understanding of the supply constraints. They are not intended as forecasts of market shares among technologies.

3.4.1 Wind technology deployment scenarios used for bottleneck testing

The challenges of logistics and infrastructure differ significantly with regard to on- and offshore wind. These technologies also differ in turbine size and increasingly in generator design. Therefore bottlenecks are tested against three wind scenarios, a ’mid case’, a variant with ‘high onshore’ and one with ‘high offshore’ deployment (Figure 5).



*actual installation of 40.6 GW globally from GWEC (2012), offshore only comprises 866 MW installed in EU27 countries (EWEA, 2012)

Figure 5: Scenarios considered for the wind technology deployment required to meet the BLUE Map Hi REN 2050

Source: E4tech/Avalon Consulting, based on IEA (2010c), GWEC (2012) and EWEA (2012)

3.4.2 PV technology deployment scenarios used for bottleneck testing

Deployment of PV systems has been so far largely dominated by c-Si modules, which covered 85% of the overall PV market in 2011. However, thin film technologies may gain significant market shares in the future thanks to their strong potential to reduce their production cost per W_p. Thus, bottlenecks in the PV supply chains have been tested against the following three scenarios (Figure 6):

- a business as usual or ‘2011 mix’ scenario (today’s market shares unchanged to 2050),
- a ‘technology mix’ scenario in which CIGS/CIS and CdTe each grow to a 20% share of the market, a-Si remains at 3% market share while c-Si contributes the remaining 57%.
- a ‘thin film’ scenario, in which the PV market is dominated by CIGS/CIS, CdTe (each 30%) and a-Si (10%), whereas c-Si has only 30% of market share.

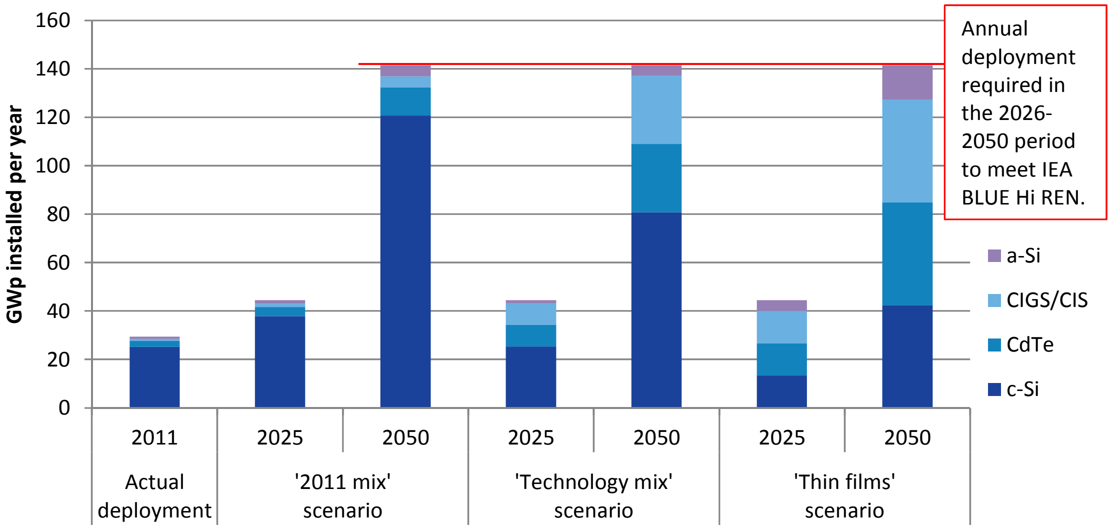


Figure 6: Scenarios considered for the PV technology deployment required to meet the BLUE Map Hi REN 2050

Source: E4tech/Avalon Consulting, based on IEA (2010c) and EPIA (2012b)

Note to Figure 6: As will be seen, no supply chain constraints have been identified for a-Si technologies, while no bottlenecks have been identified that are specific only to micromorph or silicon heterojunction technologies. Therefore, the deployment scenarios considered for testing identified bottlenecks do not need to contain high shares of amorphous silicon-based technologies.

3.5 Expert and industry interviews

After identifying and assessing bottlenecks mostly based on literature review (Phase I of the project), a wider range of experts and relevant industry players were approached and interviewed systematically (Phase II of the project). Through these interviews the initial understanding of the bottlenecks was confirmed and sharpened, and information previously unavailable in literature was gathered. 23 such interviews were conducted for wind and 16 for solar. In some cases interviewees agreed to be cited directly in this report, and in other cases their input remains unattributed at their request. A list of interviewees is provided in 7.1.

3.6 Identification of mitigation strategies and recommended actions

For each of the bottlenecks identified, possible mitigation actions are discussed that are realistically implementable and, in some cases, may already be underway. This part of the study builds upon literature review and expert judgement, as well as on past experience of how the industry or policy makers have reacted to similar issues in other sectors. The aim is to provide the reader with an overview of possible mitigation strategies.

For each bottleneck, specific recommendations addressed at decision makers have been summarised. Decision makers are grouped into the broad categories of industry (companies and commercial actors in the supply chain), policy makers (national and international bodies whose aim is to address market failures), and NGOs (entities that monitor and aim to secure improvements in ecological and societal wellbeing). In each case the first consideration was whether the industry will address, or is already addressing, the bottleneck through normal industrial activities. Where it was felt unlikely that this will be adequate then a market failure can be said to exist and so interventions by policymakers are recommended. In some cases interventions are proposed to reinforce industrial activities.

3.7 Caveats

Several important caveats should be kept in mind in reading this report:

- A bottleneck is considered to occur where there is a current or expected constraint on deployment, based upon the currently known situation. In many cases this constraint is well understood by decision makers and so mitigating activities are underway. However, unless these activities have already yielded a concrete solution to the problem, the problem is still considered to be a bottleneck. The likelihood assessment of the bottleneck does take into account any ongoing mitigation.
- Imbalances between supply and demand are hard to predict in the longer term, especially for 'commodities' that have very elastic supply such as personnel. This report applies the most suitable assessment possible to quantify bottlenecks, where quantification is meaningful.
- The assessment considers whether the demand implied by the IEA's BLUE Map Hi REN scenario will create bottlenecks. This scenario was that with the highest renewable energy technology deployment published by IEA at the time of preparing this report. This is meant to test the robustness and ability of the supply chain to respond to a potentially very high demand. In practice, there is a risk of discrepancy between reality and this scenario, in particular given the recent global economic slowdown that may affect deployment in some regions . In other words, this means that bottlenecks under the BLUE Map Hi REN scenario may prove not to be constraints under less aggressive deployment of wind and PV. Care is taken so that conclusions are drawn in light of these starting assumptions in order to avoid the risk of oversimplifying key messages.

4 Securing the supply chain of wind power

4.1 Mapping of bottlenecks along the supply chain of wind power

The main elements of the wind supply chain are listed under their corresponding supply chain stages in Figure 7. Colour coding of the text has been used to differentiate between offshore (blue) and onshore (brown) wind as required, which allowed for both offshore and onshore wind supply chains to be presented in a single figure. One of the aims of this list is to give an informative overview of the different key components or activities in each of the supply chain stages.

The additional level of colour coding using “traffic light” circles in front of each element indicates the likelihood of occurrence of a bottleneck in this element. These assessments have been made following the methodology described in section 3.2.

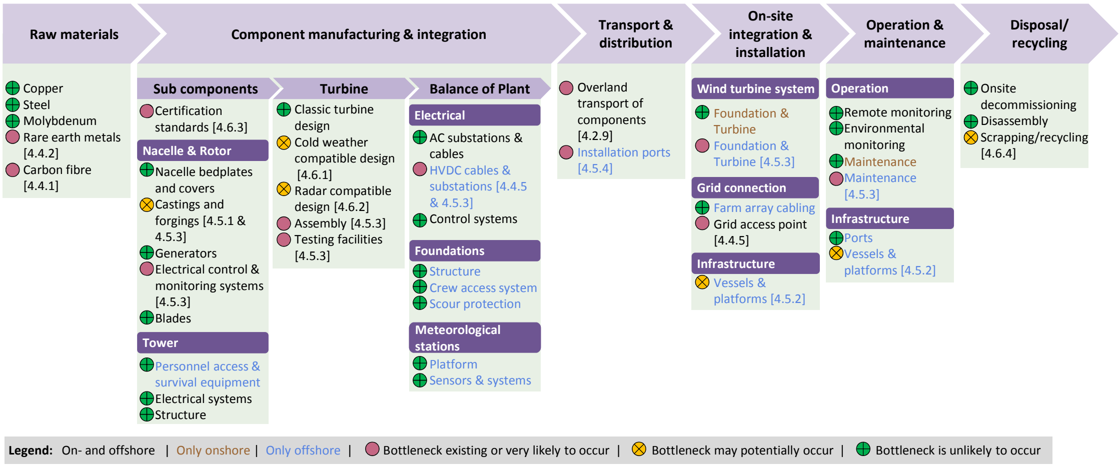


Figure 7: Likelihood of occurrence and location along the supply chain of identified bottlenecks in wind power [5]

As can be seen in Figure 7, out of the 43 elements listed, six have been categorised as having existing or very likely to occur bottlenecks and thus are marked with red circles. Out of these, two bottlenecks are related to the supply of raw materials, two concern component manufacturing, one is related to transport for offshore wind farm installation, and another highly likely bottleneck can be found in on-site integration and installation. While most elements indicated as (potential) bottlenecks on the map are discussed in dedicated sections in chapters 4.4-4.6, some of the elements have been grouped together to form a single bottleneck. This is the case with castings and forgings, electrical control & monitoring systems, turbine assembly, testing facilities, foundation & turbine installation and offshore maintenance, which are discussed in section 4.5.3 as these elements are affected by “limited availability of skilled human resources”. Chapter 4.3 gives an overview and assessment of the criticality of each of these 13 bottlenecks, and presents the temporal dimension of the occurrence of the bottlenecks.

4.2 Classification of bottlenecks

In order to facilitate a systematic approach for policy and framework discussion, the bottlenecks have been classified into the four categories "material supply", "industry related activities", "human

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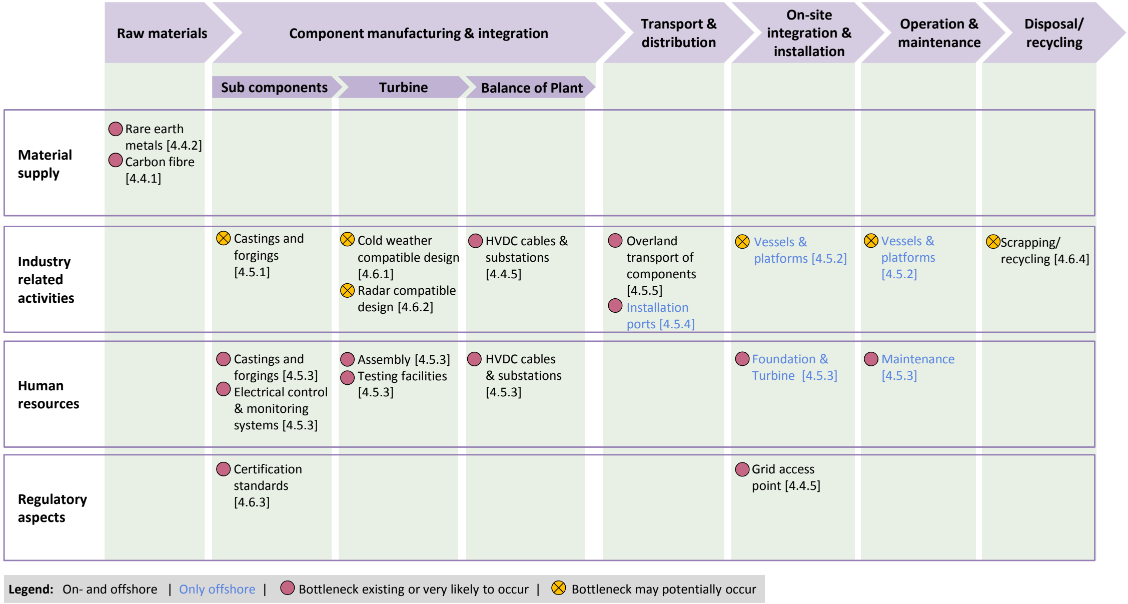
[5] References to the sections where bottlenecks are described in the report are provided in square brackets.

resources", and "regulatory aspects" as discussed in **Error! Reference source not found.**. The result is presented in Figure 8. Some steps along the supply chain face several types of bottleneck and are mapped twice, (for example the manufacturing of castings and forging suffers both from industrial and human resources issues).

While the greatest number of bottlenecks is related to industry or human resource issues, the most likely ones are of a regulatory nature or are related to shortage of materials.



	Raw materials	Component manufacturing & integration: Sub components	Component manufacturing & integration: Turbine	Component manufacturing & integration: Balance of Plant	Transport & distribution	On-site integration & installation	Operation & maintenance	Disposal/ recycling
Material supply	● Rare earth metals [4.4.2] ● Carbon fibre [4.4.1]							
Industry related activities		⊗ Castings and forgings [4.5.1]	⊗ Cold weather compatible design [4.6.1] ⊗ Radar compatible design [4.6.2]	● HVDC cables & substations [4.4.5]	● Overland transport of components [4.5.5] ● Installation ports [4.5.4]	⊗ Vessels & platforms [4.5.2]	⊗ Vessels & platforms [4.5.2]	⊗ Scrapping/ recycling [4.6.4]
Human resources		● Castings and forgings [4.5.3] ● Electrical control & monitoring systems [4.5.3]	● Assembly [4.5.3] ● Testing facilities [4.5.3]	● HVDC cables & substations [4.5.3]		● Foundation & Turbine [4.5.3]	● Maintenance [4.5.3]	
Regulatory aspects		● Certification standards [4.6.3]				● Grid access point [4.4.5]		

Legend: On- and offshore | Only offshore | ● Bottleneck existing or very likely to occur | ⊗ Bottleneck may potentially occur

Figure 8: Classification of bottlenecks in the supply chain of wind power[6]

4.3 Criticality assessment of key bottlenecks in wind power

Following the approach described in 3.2, the severity of the identified bottlenecks has been estimated based on an assessment of the extent to which the relevant bottleneck can affect the overall deployment of wind, both in terms of severity and geographic expanse of the impact (whether regional or global).

4.3.1 Criticality matrix

The criticality matrix has then been drawn by plotting the severity rating against the likelihood of occurrence of the bottlenecks (Figure 9). Depending on both the likelihood and the severity rankings of each bottleneck, it was categorised as “high”, “medium” or “low” criticality. The criticality matrix thus helps identify which are the most vulnerable elements and activities along the entire wind supply chain, which in turn can help decision makers prioritize actions to mitigate these barriers.

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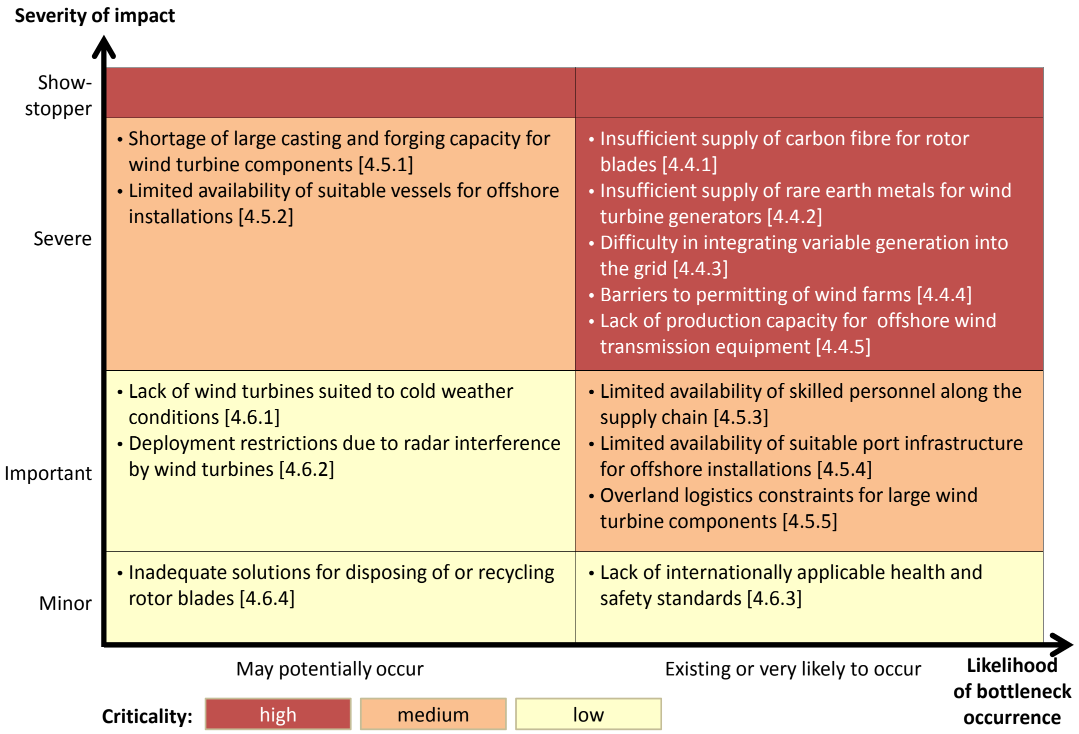
[6] References to the sections where bottlenecks are described in the report are provided in square brackets.



Severity of impact	May potentially occur	Existing or very likely to occur
Show-stopper		
Severe	• Shortage of large casting and forging capacity for wind turbine components [4.5.1] • Limited availability of suitable vessels for offshore installations [4.5.2]	• Insufficient supply of carbon fibre for rotor blades [4.4.1] • Insufficient supply of rare earth metals for wind turbine generators [4.4.2] • Difficulty in integrating variable generation into the grid [4.4.3] • Barriers to permitting of wind farms [4.4.4] • Lack of production capacity for offshore wind transmission equipment [4.4.5]
Important	• Lack of wind turbines suited to cold weather conditions [4.6.1] • Deployment restrictions due to radar interference by wind turbines [4.6.2]	• Limited availability of skilled personnel along the supply chain [4.5.3] • Limited availability of suitable port infrastructure for offshore installations [4.5.4] • Overland logistics constraints for large wind turbine components [4.5.5]
Minor	• Inadequate solutions for disposing of or recycling rotor blades [4.6.4]	• Lack of internationally applicable health and safety standards [4.6.3]

Figure 9: Criticality assessment of bottlenecks (wind)[7]

A first impression of the criticality matrix is that bottlenecks in the wind supply chains have the potential to be of significant consequence, although no showstoppers were identified. Should they occur, all the identified bottlenecks would have at least an important impact on the deployment of wind energy, with the exception of the rotor blade disposal/recycling and safety standards issues.

The structure of this chapter follows the criticality ranking by first discussing the "high", then "medium" and finally "low" criticality bottlenecks shown in Figure 9.

- **High criticality bottlenecks (4.4)**. The most critical bottlenecks are found in the upper right hand corner in Figure 9. These bottlenecks are related to material shortages, production capacities of materials and components, but also include bottlenecks rooted in permitting processes and the capacity of the overall power system to assimilate wind power.
- **Medium criticality bottlenecks (4.5).** Several barriers could prove critical either because of their high likelihood of occurrence or high impact severity. These bottlenecks are found in production capacity for large components, installation infrastructure for offshore wind farms (ports & vessels), overland logistics, but also related to personnel shortages.
- **Low criticality bottlenecks (4.6)**. The potential barriers identified in the quadrants on the lower left hand side of Figure 9 are unlikely to affect the large scale deployment of the wind sector, as either their severity or their likelihood of occurrence is low enough. These bottlenecks are related to turbine design issues for specific conditions or circumstances, international standards, as well as end of life disposal of wind turbines.

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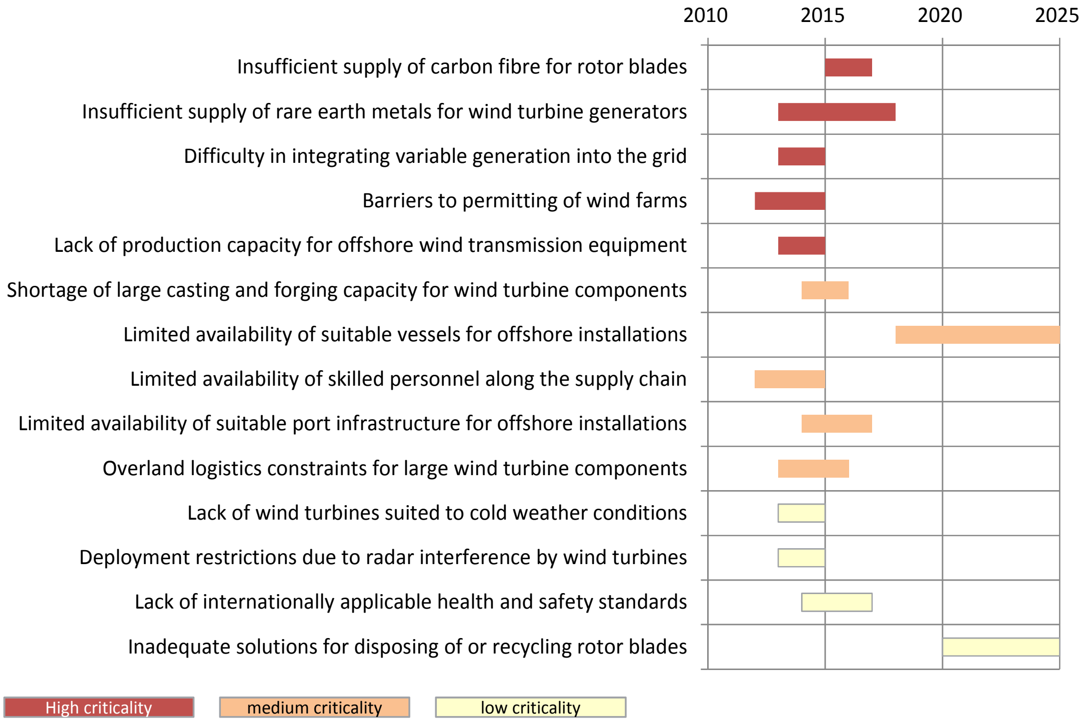
[7] References to the sections where bottlenecks are described in the report are provided in square brackets.

4.3.2 Time dimension of key bottlenecks in wind

Almost all bottleneck identified in the wind sector are related to supply-demand imbalances (lack of large casting and forging, shortage of vessels or port infrastructure, shortage for skilled resources, etc.), whereby ramp-up in capacity building is expected to lag behind demand growth due to longer lead time on the supply than on the demand side. It should be emphasised that this is also what explains the expected shortage of critical raw materials (rare earths, carbon fibre), which should not be misinterpreted for actual constraints on the resources.

With the exception of the lack of adequate solutions for disposing or recycling of rotor blades, all identified bottlenecks that are expected to hit the wind sector would bite from basically today (barrier to permitting, limited availability of vessels, shortage of skilled personnel) to within a 6 year timeframe, irrespective of their nature (see Figure 10).



Note: Bars indicate the period over which the bottlenecks are expected to appear, in the absence of mitigation. The end of the bars reflects the latest when the issues are expected to appear, and not the time when the bottlenecks could be overcome by mitigation (the latter is too uncertain to predict).

Figure 10: Predicted timescale over which wind bottlenecks might start being felt in the absence of successful mitigation

4.4 High criticality bottlenecks

4.4.1 Insufficient supply of carbon fibre for rotor blades

Wind turbine designs are moving towards higher capacities to capture more wind and to improve power generation per installation. This results in increasing turbine blade sizes. However, longer turbine blades tend to deflect more and run the risk of striking the tower. Today, most turbine blades are made of glass fibre reinforced epoxy resin, which does not offer the required stiffness to design longer blades. Carbon fibre composite is increasingly being used by some manufacturers as a reinforcement material to mitigate the deflection issue for blades of more than 40 m in length (Plastics Technology, 2008; carbon fibre manufacturer, 2012[8]). Carbon fibre also provides higher strength at significantly lower weight, which helps improve the turbine performance (WES, 2005). For instance, a 27% higher swept area at equal weight can be achieved using 44 metre carbon reinforced blades instead of 37 metre blades composed totally of glass fibre (Composites World, 2007). Lighter blades also require less robust turbine components thus reducing both the capital and transportation cost of these components (Composites World, 2012a).

The strong trend towards longer turbine blades will continuously increase the need for carbon fibre, which may generate a bottleneck should supply not keep up with growing demand. However, carbon fibre costs US$ 20-30/kg which is 10 to 20 times more than glass fibre (E-glass) (Composites World, 2012b). Carbon fibre is thus being used selectively for strength and stiffness. Currently, only a few top-tier firms in North America and Europe are known to use carbon fibre, primarily in the structural spar cap (central spine) of long blades (40 metre and up) (WES, 2005; carbon fibre manufacturer, 2012[9]). Other large manufacturers may rely on carbon fibre in the future should the need arise (wind turbine manufacturer, 2012[10]).

Assessment

The wind turbine industry has been the clear demand leader, accounting for 26% of global consumption, followed by the aerospace industry with 16% (see Figure 11)

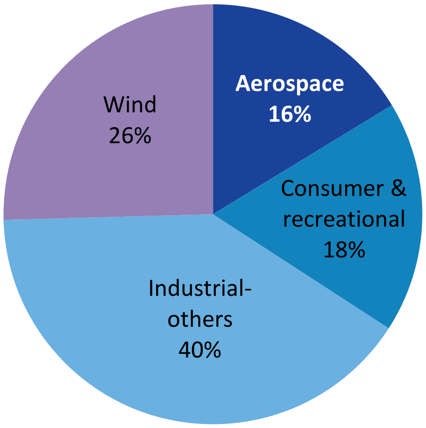


Figure 11: Carbon fibre demand from different sectors in 2010; total: 39,000 tonnes

Source: Composites World (2011)

Demand from the wind Industry. Wind industry uses large-tow (≥24,000 fibres), standard-modulus Polyacrylonitrile (PAN) based carbon fibre[11]. The main use is in the spar cap which is the backbone of the blade. The average use of carbon fibre in 2007 was 2.2% of blade weight (Composites World, 2008), which is expected to increase to 6% by 2019 due to increasing average blade length

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[8] Information gathered through interview with key individuals from the industry who wished to remain anonymous.

[9] Information gathered through interview with key individuals from the industry who wished to remain anonymous.

[10] Information gathered through interview with key individuals from the industry who wished to remain anonymous.

[11] Tow is defined as number of individual fibers in a bundle, i.e. 24K represents 24,000 individual fibers with a bundle. Standard-modulus represents tensile modulus of 33-34 msi. PAN stands for Polyacrylicnitrile, which is the chemical precursor for carbon fiber.

(Composites World, 2011). At the same time, the number of manufacturers using carbon fibre will also increase significantly, from a few major ones today to about three quarters for onshore wind and all offshore wind manufacturers by 2025 (project management company, 2012[12]). Combining these trends indicates that annual carbon fibre demand from the wind industry could grow from 10,000 tonnes in 2010 to about 46,000 tonnes by 2025 and 55,000 tonnes by 2050, corresponding to respectively 117% and 140% of the 2010 global carbon fibre supply (see Figure 12).

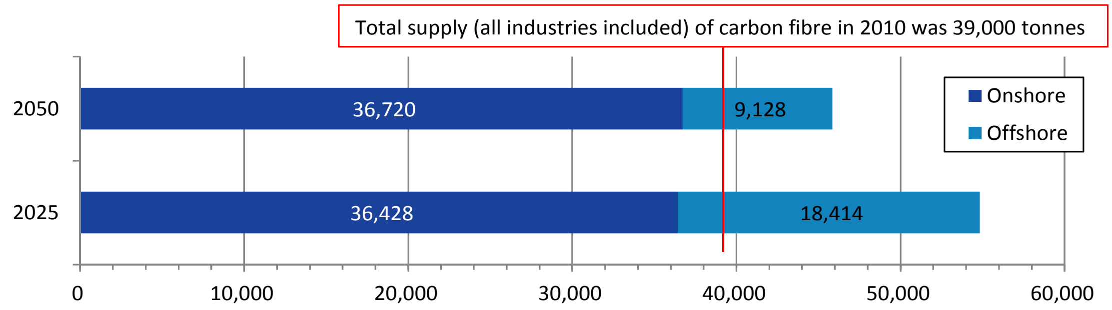

Figure 12: Demand of carbon fibre from wind industry (Wind turbine blades only)

Source: E4tech/Avalon Consulting based on Composites World (2011) and project management company (2012)[13]

Besides its use in spar caps of blades, carbon fibre is also increasingly used in blade roots and nacelle housings, while it has promising potential for a range of new applications such as towers and foundations, drive shaft, subsea and grid connection cables (Red, 2011). This may add significantly to the above forecast demand for carbon fibre from the wind industry.

Demand from other sectors. Several sectors are competing for the supply of carbon fibre.

- The aerospace industry was the pioneer user of carbon fibre. Demand is expected to rise from 6,400 tonnes in 2010 to above 18,000 tonnes in 2019, corresponding to a CAGR of 12% (Composites World, 2011).
- Consumer and recreation industry uses mainly include sporting goods, yachts and prosthetics manufacturing. The demand for carbon fibre from these industries is expected to rise from 7,000 tonnes in 2010 to 11,000 tonnes in 2019 with a CAGR of 5% (Composites World, 2011).
- Other industrial usage of carbon fibre is varied and found across industry sectors such as automotive, oil & gas, pressure vessels, tooling, etc. The global demand for carbon fibre from these sectors is expected to rise from 16,000 tonnes in 2010 to 41,000 tonnes in 2019 with a CAGR of 11% (Composites World, 2011).

Combining the above figures indicates that the overall demand from these various sectors competing with wind for the supply of carbon fibres is expected to grow from current 29,400 tonnes to 70,000 tonnes by 2020 (see Figure 13). The latter figure corresponds to 180% of the 2010 carbon fibre supply. Adding the increased demand from the wind industry indicates that carbon fibre supply would have to grow about two-fold by 2020 to meet global rising demand.

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[12] Information gathered through interview with key individuals from the industry who wished to remain anonymous.
[13] Information gathered through interview with key individuals from the industry who wished to remain anonymous.

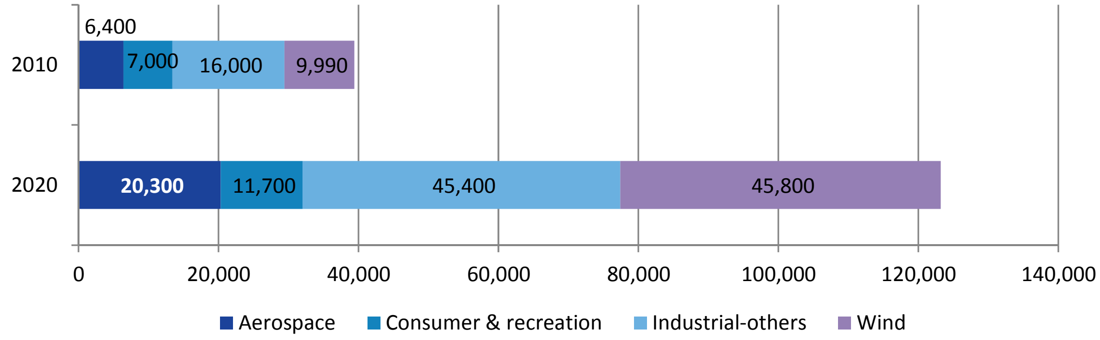

Figure 13: Total carbon fibre demand in 2010 and 2020[14]

Source: E4tech/Avalon Consulting based on Composites World (2011)

Availability of precursor raw material. About 90% of the industrial grade carbon fibre is manufactured from Polyacrylonitrile (PAN) (IACG, 2008). PAN, of which 2.2 kg is required to produce 1 kg of carbon fibre, currently represents about 55% of the carbon fibre cost**[15]** (SGL, 2012). The remaining 10% of carbon fibre are pitch based (coal tar or petroleum based product), however, it has lower mechanical properties and are therefore rarely used in critical structural applications, like wind turbine blades.

PAN is itself produced from Acrylonitrile (AN), which in turn is derived from propylene. Propylene is a crude oil derivative, and subject to oil price fluctuations. A major proportion of propylene is used as raw material for polypropylene, which is the fastest growing thermoplastic. Also AN is used in manufacturing acrylic fibre, which is an economical replacement for wool. This has led to the shortage of PAN globally, which led to constraints in the supply of carbon fibre.

A PAN plant of 1,000 tonnes annual production capacity is estimated to require an investment of US$ 30 million. The high capital requirement combined with the strong competition for key AN makes investors reluctant to invest in new capacity. As a consequence, no new facility or plant expansion for PAN supply is currently foreseen (Composites World, 2012c).

Supply-demand gap. The supply of carbon fibre is unlikely to meet the fast growing global demand in the short to medium term, hence constraining the large scale deployment of wind if no mitigation measures are taken. Based on the existing plans of the carbon fibre manufacturers, total supply should reach about 70,000 tonnes[16] in 2014, up from 40,000 in 2011, but already below the overall demand (Composites World, 2011). If additional production capacity is not rapidly planned, availability of carbon fibre could become a significant constraint from 2014 onwards, given that the lead time for new capacity is about two years. This would not only slow down the predicted trend towards increasing blade sizes and higher rated output of wind turbines, but is also likely to actually discourage wind turbine manufacturers from investing in additional production.

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[14] Demand for non-wind sectors till 2020 is estimated by extrapolating CAGR from 2010 to 2019 (Composites World, 2011)

[15] For manufacturing of 50,000 carbon fibres about 55% of the cost of production is for PAN

[16] 70,000 tonnes is estimated as 65% of the nameplate capacity. A carbon fiber manufacturing facility can typically produce 60-70% of the name plate capacity (composites World, 2011)

Although the wind industry is not expected to be affected by carbon fibre shortages in the next 2-3 years as it can largely rely on existing mostly carbon-fibre free technologies, the effect of the bottleneck may bite in from 2015 onwards, in particular with the growing deployment of offshore wind, which relies on extra long blades and would like to reduce extreme weights (Hadorn, 2012).

It should be emphasised that the expected shortage of carbon fibre is not related to an actual resource constraint, but to an imbalance between supply and demand. This situation is very similar to the "silicon bottleneck" that hit the PV sector in the mid-2000s, and that was then resolved from 2009 once additional production capacity came online. It can be expected that a similar market dynamic should close the supply-demand gap for carbon fibre like it did for grade silicon. How quickly this gap could be bridged depends in particular on the long term prospects and robustness of the demand.

Mitigation

Given that there is no inherent shortage of carbon fibre for primary resource reasons, the challenge is therefore to increase supply or reduce demand. A number of actions could be taken.

Industrial partnerships*.* Almost all the supplies of carbon fibre to the large turbine manufacturers are based on long term arm's-length contracts. Closer collaboration and coordination of between wind turbine manufacturers and carbon fibre manufacturers could encourage the latter to invest in additional production capacity. Such partnership exist for instance in the automotive industry, where leading vehicle companies have joint ventures with carbon fibre manufacturers who work closely with them on future product and supply chain developments.

Vertical integration by carbon fibre suppliers. Carbon fibre manufacturers could consider securing the supply of precursor for which supply is constrained. One option to be explored is backward integration into PAN production, potentially by co-investment in projects to share the very high capital investment. Such vertical integration is already observed today: for example carbon fibre manufacture SGL has recently acquired an 86% stake of Fisipe S.A., Portugal, a carbon fibre PAN manufacturer (SGL, 2012).

Alternative precursor material*.* The bottleneck in the supply chain of carbon fibre lies in the insufficient availability of PAN. R&D efforts should thus be focused onto finding substitute material to PAN (Composite World, 2008). Materials such as lignin, olefin and polyethylene seem to have promising potential.

Process development to improve actual production vs. nameplate capacity. A carbon fibre manufacturing facility can only produce 60-70% of the nameplate capacity (Composites World, 2011). A concerted technology effort to improve overall production yield would increase the overall supply of carbon fibre therefore.

Alternative material to carbon fibre. While the maximum technically advisable length for glass fibre spar wind turbine blades was considered to be around 55-60 m until around 2010, glass fibre blades up to 70 m are observed today (Hadorn, 2012) and blades up to 100 m length are in the development stage (Griffith and Ashwill, 2011). Currently the more expensive carbon fibre material is predominantly used in light weight blades for higher wind classes and will increasingly be used in ultra-long blades in the future (Hadorn, 2012). This shows that higher grade glass fibre, in particular S-glass[17], offers promising properties as compared to classical E-glass while being an economical alternative to carbon fibre in large size blades (Oliveira & Fernandes, 2012). An increased R&D effort towards substituting carbon fibre by alternative more available materials such as S-glass fibre should be made.

Recommendations

Partnership of wind turbine manufacturers with carbon fibre manufacturers	
Industry	Capital investment by turbine manufacturer in developing carbon manufacturers' facility with supply guarantee Expertise sharing to co-develop the required type of material
Securing Polyacrylonitrile (PAN) supply	
Industry	Backward integration investment by the carbon fibre and/or blade manufacturers into new precursor production capacity
Developing alternative precursor for carbon fibre	
Policy	Support for targeted research and development activities into development of alternative precursors
Industry	Implementation and pilot projects with the alternative materials
Technology development on improving actual production vs. nameplate capacity of carbon fibre	
Policy	Rewarding manufacturing facility with higher plant efficiency
Policy	Sponsoring research on improving manufacturing process efficiency
Industry	Focused research on increasing carbon fibre yields
Developing alternative to carbon fibre	
Industry	Collaboration of turbine manufacturers with material suppliers to develop alternative materials, which meet the required specification for large wind turbines
Policy	Support research with a focus on alternative materials to carbon fibre

4.4.2 Insufficient supply of rare earth metals for wind turbine generators

The rare earth elements (REEs) neodymium and dysprosium are magnetic metals that are alloyed and used to produce permanent magnets (PMs). The major applications of PMs are computer drives and electric motor generators, such as those used in wind turbines to convert mechanical energy from the rotating blades into electricity.

In a traditional WTG design, a high speed generator running at about 1,000-1,500 rpm converts the mechanical energy of the rotor into electricity. With the rotor driven by the blades delivering slow rotational speed of 10-20 rpm, a gearbox is used to speed up the rotational speeds to the

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[17] S-glass fiber is a modified E-glass (fiber glass) with lower density of 2.49 g/cm3 (E-glass- 2.55 g/cm3), higher tensile strength of 4,750 MPa (E-glass- 2,000 MPa) and Young modulus of 89 GPa (E-glass- 80 MPa) Source: http://www.azom.com/article.aspx?ArticleID=764

requirements of the generator. Because of their large number of moving parts, WTG gearboxes are a major source of reliability issues and maintenance requirements, as well as friction losses.

Direct drive generators are able to convert the slow rotation speed of the blades directly into electricity. Generators that make use of permanent magnets (PMs) instead of the classical electromagnetic copper coils are a rapidly growing design trend. In addition to the benefits of the reduced weight of the nacelle by not having to use a gear box, PM generators also increase the energy conversion efficiency of the wind turbine.

This trend towards more PM generators in the wind industry, growing demand for neodymium and dysprosium from various other industries, combined with their naturally constrained supply, may however lead to a demand-supply gap.

Before assessing the extent of this potential demand-supply gap and what it may mean for wind energy deployment towards 2025 and 2050, it is important to note that myriad design options exist for WTGs. For example, is possible to design WTGs with ***direct drive*** generators using copper coils (Enercon, 2012) or ***geared*** turbines using PM generators, often referred to as hybrid drive generators[18] (Vestas, 2012). There are several other design options aimed at decreasing maintenance issues and increasing efficiency, some of which are mentioned in the mitigation section of this chapter. Essentially this means that while PMs offer many benefits to WTG design, they are not the only available approach.

Assessment

Demand: Currently, hard disk drives, motors and generators account for approximately 80% of the annual demand for permanent magnets (EC-JRC, 2011a).

The annual demand for neodymium and dysprosium oxide for permanent magnet production was above 10,000 tonnes in 2008, up from 5,500 in 2005, corresponding to a CAGR of 13.6% (EC-JRC, 2011a)

Estimates for total global demand in 2014 range from 1,900-2,800 tonnes for dysprosium oxide, and 34,900-45,400 tonnes for neodymium oxide (Oeko Institut, 2011), with over 90% of both materials expected to go into permanent magnet manufacture (EC-JRC, 2011a).

Neodymium and dysprosium demand from WTGs*.* The consumption of rare earths in generators varies greatly with turbine drive train technology. In a direct drive WTG, approximately 600kg of permanent magnet is needed per MW installed, which corresponds to a consumption of about 200 kg of neodymium metal and 14 kg of dysprosium metal per MW. These figures are about one order of magnitude lower for hybrid PM WTGs (US-DoE, 2010a; Control Engineering, 2011; EC-JRC, 2011a; Vestas, 2012).

Today, the global market share of direct drive wind turbines using permanent magnets is about 14% (Hoenderdaal, 2011). WTG manufacturers are expanding their activity in direct drive technology, and both direct drive and geared permanent magnet generators are expected to gain market share with

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[18] Hybrid systems are a middle route between the standard geared design with several levels of gearing, and direct drive solutions. The intention is to have a simpler and more reliable gearbox, without having to increase generator diameter significantly

forecasts of total WTGs being 20% geared drive PM and 19% direct drive PM by the end of 2012 (Shreve, 2011).

Mining and production of neodymium and dysprosium: Rare earths are abundant in the earth's crust, but are mostly present in low concentrations and often not found in exploitable form (USGS, 2002). Approximately 1,370 tonnes of dysprosium oxide and 21,300 tonnes of neodymium oxide were produced in 2010 (US-DoE, 2010a).

Rare earth elements are categorized as light rare earth elements (LREE), which include neodymium, and heavy rare earth elements (HREE), which include dysprosium. Rare earth mines are typically richer in LREE than in HREE (British Geological Survey, 2011). In fact, the majority of advanced new rare earth mining projects globally have very low concentrations of HREE, meaning that very little new dysprosium mining capacity is in the pipeline. As a corollary it can be said that the supply of dysprosium is more constrained than that of neodymium.

China dominates REE mining as well as most of the other upstream processing steps of PM production, which means that mined and concentrated REEs from around the world currently have to be sent for processing into metals to China (Figure 14).

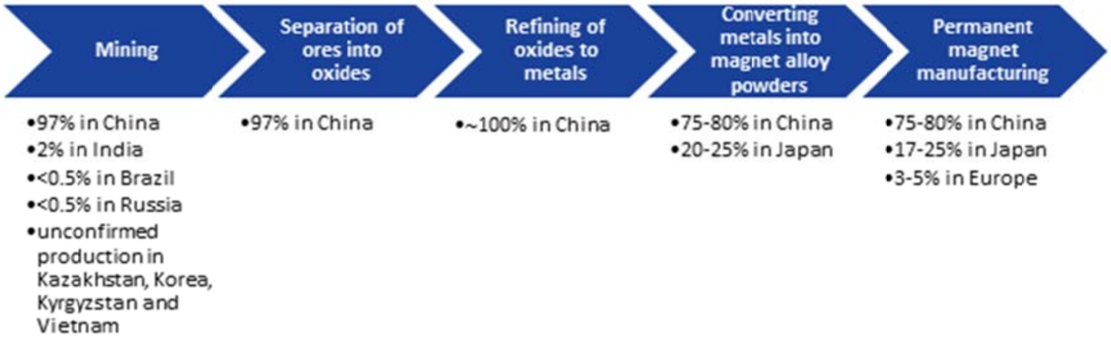

Figure 14: Process steps and national shares of PM production

Source: E4tech/Avalon, based on Oeko Institut (2011), US-DoE (2010a) and Northern Minerals (2011)

Not only does China control PM production steps rendering the rest of the world dependent on its exports, it has also imposed rare earth export quotas, which have been progressively tightened since 2005 (Figure 15).

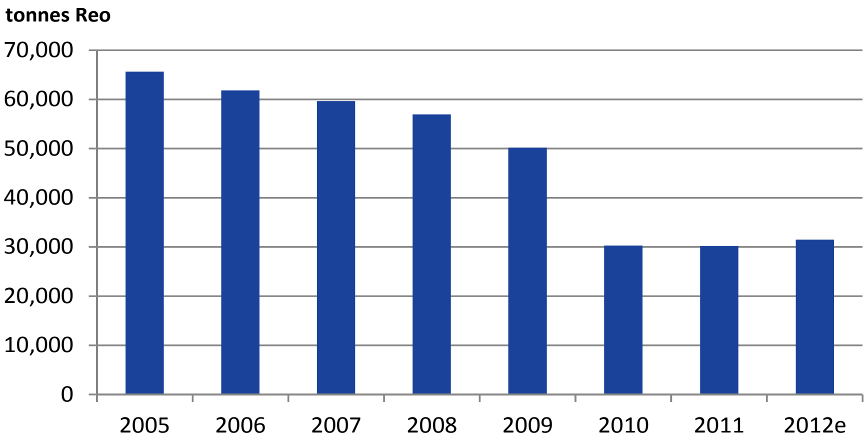

Figure 15: China annual export quota on rare earth oxides (REO)

Source: US-DoE (2010a)

More recently, China started to set separate quotas for light and heavy rare earths (Resourceinvestor.com, 2011). The majority of advanced rare earth projects globally have very low concentrations of HREE, so this may indicate that the Chinese government expects dysprosium (part of the HREEs) to become a more serious bottleneck compared to neodymium (metal research company, 2012[19]; mining company, 2012[20]).

Mining companies have recently started focusing on developing new exploitable reserves outside of China. About 430 rare earth mining projects have been inventoried outside China, of which around 36 are expected to have exploitable REE reserves (metal research company, 2012[21]). Similarly, a new processing plant should be commissioned in Malaysia in 2012 (Canadian Chamber of Commerce, 2012). However, forecasted new supply from a reopened US mine and a handful of new mines in Australia, Canada and Vietnam are expected to add annually around 9,000 tonnes of neodymium oxide, but only 167 tonnes of dysprosium oxide by 2015 (US-DoE, 2010a). This means that the production of neodymium is expected to increase by over 40%, while dysprosium production is expected to grow just over 10%, further confirming dysprosium as the more heavily constrained element of the two.

Developing new rare earth mines involves long lead times and complex commercial and technical challenges. These are rooted in the project specific process routes needed by the varied compositions and concentrations of REEs, the frequent presence of radioactive elements, and the environmental impact assessments required (EC-JRC, 2011a, Kingsnorth, 2011; Paju, 2012), as mining and processing rare earth ores can cause serious environmental damage to the groundwater, air and soil. (Oeko Institut, 2011).

Another crucial factor in the opening of new mines is the financing of the complex operations that vary by mine due to the differences in REE compositions and concentrations. In particular the processing steps give rise to high specific costs of around US$ 30,000 per ton of REE production

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[19] Information gathered through interview with key individuals from the industry who wished to remain anonymous.
[20] Information gathered through interview with key individuals from the industry who wished to remain anonymous.
[21] Information gathered through interview with key individuals from the industry who wished to remain anonymous.

capacity (Oeko Institut, 2011). The issue of financing has been highlighted by rare earth mining companies as the main constraint in increasing the supply of REEs.

Price development: Rare earths are not traded commodities, but are mostly procured through bilateral contracts, making it difficult to assess price developments. However, estimates and observations have seen the price of dysprosium (metal) soaring from US$ 100 per kg at the start of 2010 to US$ 1,500 per kg in 2011, while the price of neodymium (metal) increased from US$ 90 per kg to US$ 300 per kg over the same period (EC-JRC, 2011a).

Supply-demand scenarios: Based on the deployment scenarios discussed in 2.4.2, Figure 16 presents scenarios of different levels of market share of PM generators (low, medium and high) in the annually newly installed WTGs. The "low" scenario corresponds to 14% direct drive (DD) PM, and 20% geared drive (GD) PM generators (these are current figures estimated by Shreve (2011) and Hoenderdaal (2011)), "medium" involves 20% DD PM, and 25% GD PM generators, and "high" represents 25% DD PM, and 30% GD PM generators. The actual 2011 installation figure is provided for comparison (GWEC, 2012). The length of the bars presents the absolute amount (in tonnes REE) of neodymium (Nd) and dysprosium (Dy) that would be needed to satisfy the demand for PMs. The percentage figures at the end of the bars indicate the percentage of the 2011 global production of neodymium and dysprosium that these levels of PM WTG market participation would require.

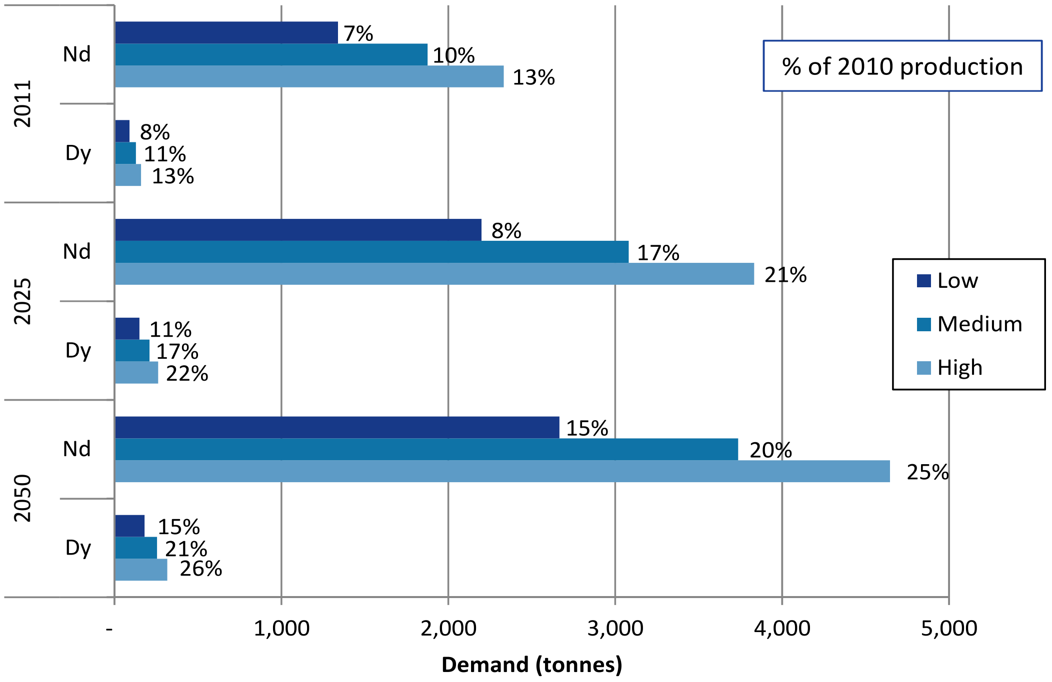

Figure 16: Permanent magnet generator scenarios leading to neodymium (Nd) and dysprosium (Dy) demand

Source: E4tech/Avalon Consulting based on US-DoE (2010a) Shreve (2011), Hoenderdaal (2011), Control Engineering (2011), EC-JRC (2011a), Vestas (2012)

These scenarios show that even if the market share of PM generators is kept at today's levels ("low"), the wind industry would require up to 15% of global neodymium and dysprosium production in the long run. If high growth in use of PMs occurs, as expected by many, then 25% of global production will be required for WTGs. Given the forecast rapid increase in electric powertrains for road transport (amongst other PM uses), it is very likely that price pressure will increase in the absence of mitigating measures.

If prices of neodymium and dysprosium increase, the cost impact on WTGs may be substantial. The price spikes reported for 2011 discussed above have already caused the cost of dysprosium required for 1.5 MW turbine to increase from US$ 2,100 at the start of the year to US$ 31,500 by the end. Correspondingly, the neodymium cost per turbine increased from US$ 27,000 to US$ 90,000. A 1.5 MW wind turbine costs in the region of US$ 1.6 million to produce, which means that the cost share of dysprosium and neodymium increased from 2% at the start of 2010 to 8% in 2011, causing an overall cost increase of US$ 92,000 per turbine.

Conclusions: Given the serious supply constraints and potentially strong competing demand from the automotive industry, neodymium and in particular dysprosium are severe limiting factors for permanent magnet direct drive WTGs in the future. Even a low PM share in the technology mix will demand a high proportion of neodymium and dysprosium production, which may lead to WTG cost issues at high prices of these metals. However, deployment of wind energy does not necessarily have to be limited by this constraint, as expansion of supply is possible, as are alternative WTG designs and PM approaches.

Mitigation

It has to be borne in mind that traditional both direct drive and geared WTGs use electrically synchronous generators that do not require rare earth materials. Hence, mitigation actions can target both the expansion of neodymium and especially dysprosium supply, as well as R&D in the areas of materials science and drive train design to deliver alternative turbines.

Supporting REE miners to accelerate new mining and refining capacity outside China*:* The supply chain of rare earth metals needs to be diversified to locations outside of China. Bringing new REE mines on stream takes 5 to 12 years, and several recent projects have started to exploit REE reserves. Capital availability for funding the projects and loan guarantees for high risk projects are the two key ingredients to enable this to be accelerated. For example, the Australian government has supported the REE mining industry by:

- Imposing low tax on value of extracted resources and higher taxes on mine profits, resulting in taxation mainly from profits rather than total production
- Tax rebates for mineral exploration, and
- Fast turnaround of land permit applications.

Initiatives to develop new mines and processing capacity should also come from industry directly. Companies requiring large amounts of neodymium and dysprosium should build direct relationships with mining companies and play an active role in financing the expansion, whether directly or indirectly. Clear demand forecasts and open discussion of technology options will increase certainty for investors.

I***mproving material efficiency of mining, processing and magnet production*****:** new technology for exploration and mining can deliver both cost improvements and recovery rates in the mines. Further downstream, new processes and technologies can deliver better efficiency in the processing steps of the neodymium and dysprosium production. Permanent magnets should be produced using the "press to shape" technique instead of cutting magnets of the desired shape from larger blocks (Oeko Institut, 2011). Investing into R&D has the potential to make mines and processing competitive with Chinese exports.

Promote recycling of PMs: Even if PM WTGs are only expected to be available for recycling in 10 to 15 years, hard disk drives that use PMs are already being discarded in volumes that could make recycling processes viable. Governments can promote recycling of metals by providing logistical support to increase volumes and thus achieve economic viability, as well as by promoting a life-cycle based approach for mineral management (US-DoE, 2010a). An example of industry-led R&D efforts is the consortium led by Siemens, which is investigating the recycling of PM motors and generators (Siemens, 2011).

Reducing the amount of neodymium and dysprosium required: materials science can deliver options for reducing the amount of REEs needed in permanent magnets. Approaches currently being investigated include:

- Nano composite magnet materials: they are made up of nanoparticles of the same materials of regular magnet alloys. Exchange coupling between different nanoparticles in the composite leads to stronger magnetic properties and less use of rare earth metals (technologyreview.com, 2011).
- Minimizing/replacing dysprosium: Dysprosium is alloyed in NdFeB magnets to retain magnetism at high temperatures. Improved cooling systems can help to reduce the amount of dysprosium needed. Terbium is another REE that can be used instead of dysprosium, even though it suffers from many of the supply constraints as dysprosium (Oeko Institut, 2011).
- Alternative materials alloys: Investigations include iron-nitride compound with a specific phase that potentially exhibits a very high saturation magnetisation. Alloying conditions have to be understood in order to stabilize the material so that it retains its magnetic properties (windpowerengineering.com, 2011). Other research efforts are directed towards samarium-cobalt (SmCo) magnets, even if shortages of samarium may be likely to hamper these efforts (Oeko Institut, 2011).

Alternative drive train designs**:** Alternative drive train designs can avoid the use of neodymium and dysprosium altogether. The key issues that have to be considered are the need for low maintenance requirements (especially offshore), high wind conversion efficiencies, low costs and high-quality power output for connection to the grid. Examples of such designs are:

- Enercon's commercial direct drive machines feature asynchronous generators and AC/DC power electronics to ensure desired power output properties.
- Mitsubishi's hydraulic drive, which replaces a mechanical drive train or direct drive plus PM with a hydraulic system (de Vries, 2012). This design is currently being tested in a 7MW WTG

for offshore installation and expected to be commercial in 2015 (wind turbine manufacturer, 2012[22]).

- A more distant prospect is the use of high temperature superconductor technology in WTGs. Superconducting materials offer very low electrical resistance at low temperature, allowing the creation of electromagnets without the use of heavy windings. However, the temperature required in so-called high temperature superconductors (HTS) remains at or near -196°C (the boiling point of nitrogen). Developments are continuing and the largest manufactured and tested device was a 36.5 MW 120 rpm HTS propulsion motor for the US Navy in 2007, (Cao, 2011). Towards 2020, it is anticipated that the early application of high temperature superconductor technology will be in use. The US-DoE is funding a wind industry project, which is expected to demonstrate new (Nano) magnet materials in 2013 (Technologyreview.com, 2011).

Recommendations

Accelerating new mining and refining capacity outside China	
Policy	Capital availability for funding the projects, loan guarantees for high risk projects, tax incentives for exploration and mining activities.
Industry	Supply chain collaboration and industry consortia to give investor confidence about future REE demand
Improving material efficiency of mining, processing and magnet production	
Industry	Focus on improving the recovery rates of neodymium and dysprosium mines, as well as processing steps further downstream
Policy	Provide R&D support to the rare earth mining sector to enhance recovery rates and to the PM manufacturing industry to improve materials efficiency of processes
Promoting recycling of permanent magnets	
Policy	Provide policy frameworks to encourage and support PM recycling and recycling friendly designs
Exploring alternative drive train designs	
Policy	Support R&D programmes of PM free drive trains
Encouraging R&D in materials science	
Policy	Support R&D programmes in materials science

4.4.3 Difficulty in integrating variable generation into the grid

Integrating wind power into the electricity grid faces three main constraints: wind power output is variable and not easy to predict, it may face grid capacity issues, and it may be of uneven quality.

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[22] Information gathered through interview with key individuals from the industry who wished to remain anonymous.

Each of these can create difficulties for maintaining a stable power system, and may cause some of the electricity generated by wind farms to be ‘constrained off’.

Grid operators have to maintain constant balance between the total demand and supply from all generators in the power system at all times. This makes the variability of power output from wind farms problematic if the availability of energy at specific points in the future cannot be reliably forecasted.

Wind power generation is variable since the wind does not blow continuously at the same speed: an individual wind turbine generates electricity for 70-85% of the time but at a load factor that ranges from 0% to 100% of the production capacity depending on the wind speed. However, the larger the interconnected area, the more likely it is that the wind will blow somewhere in the system, and so less variability can be expected (BWEA, 2005). Another related issue is that at certain points in time there may be more wind power than demand in the system, for example during a windy night, forcing the grid operators to constrain electricity output from wind farms.

Grid congestion issues are not caused by wind farms as such, but are rather a consequence of the fact that wind farms are normally constructed in the windiest places available, which generally do not correspond to the load centres. Given limited capacity of transmission lines, congestion may result in the inability of the system to transmit electricity to where it is demanded. This is a second cause of wind generation curtailment in some markets.

Wind farms, especially those equipped with older wind turbine models, may cause variations in voltage and frequency as well as a low power factor (a measure of losses caused by the reactive power demands of inductive generators). If wind turbines absorb too much reactive power from the grid, the power system may face instabilities. These problems can be solved at the level of the wind turbine by using power electronics and variable-pitch systems to ensure that a constant power quality can be met at varying wind speeds, or at the level of the interconnection to the grid by using DC and voltage source converters (Georgilakis, 2008).

Assessment

National electricity grids in many countries face increasing instability, especially as the penetration of wind in the total electricity generation portfolio rises (Renewable Energy World, 2011a). Solving the grid balancing and stability requirements of wind energy demands the extension of grid capacity and the effective connection of generation assets and load centres, requiring an estimated investment of US$ 40-50 billion in the European Union alone (ECORYS, 2010).

Since the development and uptake of mitigation measures such as smart grids, interconnectors and large scale energy storage are difficult to predict, modelling the impact of wind integration into the grid would require more attention than can be done as part of this report. It is important to note, however, that negative prices of electricity already occur in markets such as Germany when demand is low, and wind output is high (Bloomberg, 2011). Avoiding negative prices by curtailing wind output has affected 17% of Texas’ wind energy production. However, after a new transmission line was built in Texas, curtailment decreased from 17% in 2009 to 8% in 2010 (EC-JRC, 2011b).

Mitigation

Several approaches are needed in conjunction to balance the grid and allow for a better integration of wind power into the grid (Varrone, 2011):

Improve accuracy of power output forecasting: Better forecasting of wind farm power output allows grid operators to schedule generators accordingly (Dragoon et al., 2008; Varrone, 2010). Furthermore, maintenance downtimes of the wind farm can be planned according to these forecasts to maximise output (Lerner et al., 2009). Wind power output forecast models based on standard weather forecasts are somewhat simplistic and may lack accuracy. However, state-of-the-art forecasting models that not only use real-time wind and energy data from the wind turbines, but also include machine learning algorithms, are able to provide hour-by-hour power output forecasts from individual wind farms with a mean absolute error of 10-15% (Georgilakis, 2008).

Facilitate co-ordination of transmission and interconnection: Transmission corridors are required to connect wind farms to load centres without overloading sections of the grid. Coordination on standards, regulation and agreements on the financing within and between countries and wider regions will increasingly be needed to enable the connection that strong penetration of wind energy requires. This is especially the case for production regions located on the edge of grid networks such as the North Sea offshore wind farms, which require connection to the grids of all adjoining countries (Renewable Energy World, 2011a).

***Encourage dynamic load management*:** an important approach to avoid wind curtailment is to act both on the supply and the demand side. Smart grid technologies should assist dynamic interaction between generators and consumers, helping to counteract the variable power output of wind farms. The smart grid can involve individual domestic consumers, but can also address the integration of larger users or generators of electricity. In Denmark, for example, existing distributed CHP plants have been enabled to participate in the electricity market not only selling electricity, but to also buying excess wind-generated electricity. The latter takes place when low demand and high wind power output coincide, causing prices to drop. The CHP plants shut down and buy the low cost electricity to power electric resistance heaters to provide heat only. Once wind energy output decreases or overall electricity demand increases, the CHP plants switch back to conventional CHP production (Andersen & Lund, 2007).

Add energy storage to the grid: Energy storage, taking up any excess electricity produced by wind farms, is another way to prevent wind curtailment. Options such as compressed air energy storage (CAES) and hydrogen generation through electrolysis & storage are being explored aiming at making energy storage economically feasible. It is important to consider that many of these storage technologies depend on local conditions, and it is likely that economic solutions will emerge through international cooperation.

Recommendations

Improving accuracy of power output forecasting	
Industry	Share best practices and technologies that enable better power output forecasting to enable learning and innovation
Policy	Further invest in R&D in this area to benefit both grid operators and the wind industry
Facilitating co-ordination of transmission and interconnection	
Policy	Ensure international collaboration on standards, regulation and agreements on the financing in order to facilitate interconnection projects
Encouraging dynamic load management	
Policy	International collaboration to share national approaches & facilitate learning
Adding energy storage to the grid	
Policy	Promote adaptation of smart grid technology and energy storage in the grid Promote R&D into smart grid and energy storage technologies Encourage international cooperation to support learning and innovation around the issue

4.4.4 Barriers to permitting of wind farms

Figure 17 presents a schematic of the process from investment decision to productive wind farm, presenting the two main permits that wind farms require: the consent to build the wind farm, and the permit required for grid access.

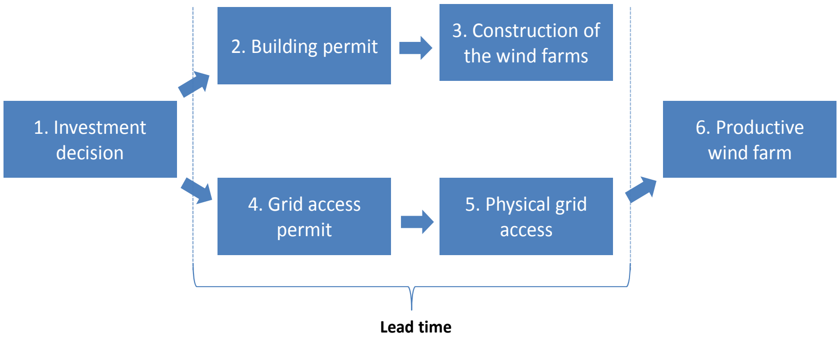

Figure 17: Process from permit to wind farm operation

Source: EWEA (2010)

When applying for these permits, wind farm developers face a range of barriers, which were assessed in great detail through the WindBarriers project coordinated by EWEA in 2010. Even though the study was conducted among the EU-27 countries, the general points are largely valid in other geographies.

Assessment

The key barriers identified in the administrative processes involved in issuing *building permits* are:

- Lengthy lead times resulting from administrative processes, spatial planning and environmental impact assessment
- Large number of authorities that have to be contacted by project developers
- High administrative costs
- Lack of transparency of the administrative procedure
- Generally negative attitudes of authorities.
- Lawsuits against the projects (40% of projects affected, 30% of all project cancellations are due to lawsuits)
- Answering questions from NGOs (30% of projects).

The main barriers identified in the administrative processes related to *grid access permits* are lead times before wind farms can actually be connected and connection costs.

Offshore-specific issues often relate to the fact that market structures, procedures and regulations for the permitting of offshore wind farms are in many cases still evolving. An additional complication is the specific seabed rights and permitting requirements that may be needed by different countries to allow cabling to cross coastal zones when several jurisdictions are involved (e.g. international EEZs) (IEA-RETD, 2011).

These barriers to wind development translate into bottlenecks in the supply chain, since delays in project timelines and the likelihood of aborted projects cause reluctance to invest in capacity expansion and improved technologies throughout the supply chain. The effect is felt most acutely in the supply chain that is local to the country or region that is experiencing the delays. Permitting issues mostly cause (sometimes lengthy) delays, though they are rarely showstoppers.

Mitigation

Assuming that project developers are putting forward appropriate projects for permitting and following the correct processes, the mitigation of this bottleneck lies largely with policymakers and public agencies. A series of measures could be taken to improve the speed and efficiency of wind farm permitting.

Reducing the number of authorities that have to be contacted. Governments should develop and implement a ‘one-stop-shop’ approach for project developers, enabling the latter to deal with one point of contact efficiently instead of having to communicate and follow up with several public bodies and their procedures (EWEA, 2010; IEA-RETD, 2011). For offshore wind special importance has to be given to international cooperation and synergies with other users of the sea, again to save project developers having to approach several different authorities and deal with potentially diverging processes (EWEA, 2010).

***Decreasing administrative lead times*.** Sufficient personnel should be allocated and trained to process the expected number of applications from wind farm developers. In addition, developers should be provided with a clear outline of the administrative processes, including all requirements such as environmental impact assessment and deadlines. EWEA propose that whenever deadlines cannot be met by the authority, the project should automatically advance to the next stage. This would give clarity and reassurance to project developers that timelines are highly likely to be met. Another important action that significantly decreases administrative lead times is to have performed detailed on- and offshore spatial planning to identify the most suitable wind development areas (EWEA, 2010).

***Reducing administrative costs*.** Poor knowledge management leads to duplication of actions which is not only a cause of capacity issues of public administrative bodies, but it also increases costs as financial resources are not used efficiently. Thus, of the most important actions for policy makers is to have firm knowledge management processes in place, which allows for results to be gathered for example from environmental impact assessments enabling learning from past projects. Such a bank of knowledge helps to limit administrative requirements to crucial issues that were identified in past projects, giving greater focus to the project application process and less costly duplication. As a corollary, the process guidelines given to project developers have to be updated regularly to reflect the most recent outcomes of completed projects (EWEA, 2010).

Designing efficient market structures for offshore wind farms. In order not to slow down offshore wind development, regulatory adjustments to streamline permitting and the connection to the grid may be required. An example is the creation of the UK's Offshore Transmission Network Owner (OFTO) regime, where an intermediary between the offshore wind farm owner and the national grid operator owns the rights to the transmission from the wind farm to the grid, and installs and operates this interconnection. This practice is regarded as driving down costs due to competitive tender processes to win the OFTO rights, but also as adding a level of complexity in that the wind farm owner, OFTO, and the national grid operator have to be coordinated (Utility Week, 2011).

Include local stakeholders in the project, potentially as investors. Local resistance is an important showstopper on a local level, so should be taken seriously. One way to generate local engagement and hence reduce resistance against wind farm projects is to create new financial models that give the opportunity for local stakeholders to participate financially in these projects.

Recommendations

Reducing the number of authorities that have to be contacted	
Policy	Implement a 'one-stop-shop' approach for developers, enabling the latter to deal with one point of contact efficiently instead of having to communicate and follow up with several public bodies and their procedures
Decreasing administrative lead times	
Policy	Allocate & train sufficient personnel to process wind farm applications Implement clear deadlines Perform detailed on- and offshore spatial planning

Reducing administrative costs	
Policy	Create knowledge management systems of crucial issues identified in the project application process Regularly update project application process guidelines to reflect latest information Design efficient market structures for offshore wind farms
Designing efficient market structures for offshore wind farms	
Policy	Adjust regulation so that permitting and the connection to the grid are streamlined. One option is to ensure that an intermediary actor exists between the offshore wind farm owner and the national grid operator that owns the rights to the transmission from the wind farm to the grid, and installs and operates this interconnection.
Including local stakeholder in the project, potentially as investors	
Industry	Ensure involvement of local stakeholder into wind farm projects in order to reduce resistance. One option could be to create financial models that give the opportunity for local stakeholder to participate financially in the projects.

4.4.5 Lack of production capacity for offshore wind transmission equipment

The first offshore wind turbines were connected to the onshore grid using adapted medium voltage onshore equipment. The advent of increasingly large projects further from shore required the development of higher voltage equipment, specialised offshore substations and advanced cable installation techniques (EWEA, 2011). Today, specialised offshore substations collect the power from the WTGs for export to the grid, which is mostly achieved using high voltage alternating current (HVAC) transmission technology. HVAC is the preferred technology for relatively short distances (<100 km) between offshore and onshore points of connection (IEA-RETD, 2011).

However, for the increasing number of offshore wind farm installations sited over 100 km from shore, high voltage direct current (HVDC) transmission technology is preferred over the incumbent alternative current technology (HVAC). HVDC transmission offers significantly lower transmission losses compared to HVAC (the longer the distance of transmission, the greater the difference in transmission losses between the HVDC and HVAC technologies), and at distances greater than 100 km the higher costs of HVDC cables and converters is offset by the gain in revenue through lower transmission losses (IEA-RETD, 2011). Another key advantage of DC over AC transmission is that wind farms could operate at frequencies that differ from the grid frequency. Higher frequencies for WTGs could reduce transformer size and cost – but to take advantage of synergies between WTG design and the export regime of electricity both have to be developed together (EWEA, 2011). DC transmission technology is, however, less mature than AC and there are fewer companies with DC equipment manufacturing and installation experience.

Overall, the penetration of HVDC is expected to increase with demand mainly from the UK's Round 3 offshore installations, German, and potentially US offshore wind farms (Renewable Energy Focus.com, 2011).

Assessment

For both HVAC and HVDC the main issues are related to lack of capacity for manufacturing and installing transmission infrastructure (Renewable UK, 2011; EWEA, 2011). Generally, the equipment needed for the electricity collection and export from offshore wind farms is produced by the same manufacturers also supplying to the onshore wind industry. For most items except for high voltage transformers and the specialised subsea HV cables, the capacity is deemed adequate.

Subsea HV export cables are widely regarded as the potentially most supply constrained of all wind energy components. A single cable extrusion line can produce approximately 200 km of cable core per year, with a total annual global capacity of cable extrusion of 2400 km in 2011. Translated into actual subsea cables this equates to approximately 1,200 km of 2-core HVDC, or 800 km HVAC (3-phase(BVG Associates, 2011). This means that12 cable extrusion lines were in operation in 2011[23].

According to Landberg (2012), each GW installed offshore requires an average of 150 km of subsea cable. In order to meet the BLUE Map Hi REN Scenario of 194 GW in 2025 and 917 GW in 2050, an average of 14 GW needs to be installed per year in 2025, and an average of 29 GW per year in 2050. Thus, assuming that this demand will be met by HVDC cables, and using the assumptions and data above, at least 22 extrusion lines will be required in 2025, and approximately 43 in 2050. Since AC cables would require more core extrusion, the number of future extrusion lines required may be even higher.

This would require a significant increase of cable production capacity, which will have to be met by expanding existing as well as building new facilities. Bringing such new cable production capacity online takes up to four years, which includes two years to construct the manufacturing facilities and two further years to test and type approve the cables. Capacity expansion of an existing facility requires 12 to 18 months. Lead times are also dependent on cable extrusion machinery manufacturers, a market dominated by a few specialized suppliers (Reinsalu, 2012). Although most suppliers have general expansion plans, they are unwilling to invest as firm long term commitments from customers are currently lacking. A further issue is that early supply from new lines or new suppliers is usually considered risky due to the lack of experience and track record (BVG Associates, 2011), which may initially hamper long term purchase commitments. Adding further complexity to the issue, due to the weight and size of cables there is a preference for production sited close to the demand. This may constrain the transition from demand (tender) driven production to continuous production for a globalised market (EWEA, 2011).

Mitigation

The main reason for the forecasted potential bottleneck related to HV cables and other equipment is the underlying insecurity about future demand along the HV cables supply chain. Essentially two main mitigation measures would contribute to reassuring the supply side about demand.

Recommendations

Signalling policy support to industry

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[23] The main established European suppliers of HV export cables are ABB (Karlskrona, Sweden), Nexans (Halden, Norway), and Prysmian (Naples, Italy). New entrants into the HV market are NKT (Cologne, Germany) and General Cable (Nordenham, Germany).

Policy	Support cable capacity expansion by credibly supporting the growth of offshore wind installation well into the future through mechanisms such as feed-in-tariffs and tax credits
Facilitating dialogues among industry players	
Industry	Further encourage and support dialogue between cable manufacturers and wind farm developers. If more trust and better communication can be established, the perceived risk of investment in new manufacturing facilities or capacity expansion can be reduced.

4.5 Medium criticality bottlenecks

4.5.1 Shortage of large casting and forging capacity for wind turbine components

The rotor hub, nacelle bedplate, main bearing housing and gear box housing, which are integral parts of the generator, are cast from steel. The main shaft, yaw bearing, other large bearings and tower section flanges are forged. Additionally, there is extensive machining involved in moving parts such as gears and bearings.

Today, there are only a few heavy castings and forgings manufacturers worldwide. The wind power industry has to compete with other heavy industries (for example, nuclear energy, thermal and hydro power generation, oil and gas) to access the available castings and forgings capacity. Rising demand and increasing sizes of turbines has led to a shortage of large casting and forging capacity available for the wind industry.

The shortage of large casting and forging capacity is caused by high barriers to entry resulting from:

- High technology requirements - Gearboxes are the biggest single cause of wind turbine failure and require precision. Similarly, large castings like rotor hubs and large forgings like rotor shafts require considerable skill in manufacturing.
- Size – There is a limited number of large casting / forging facilities in the world. With increasing size of turbines, the supplier pool becomes very restricted. Thus for a 6 MW turbine, whose rotor hub weighs about 40 tonnes, there are fewer than 30 casting suppliers in the world. Similarly, the diameter (up to 4.6 m) of rotor hubs further reduces the capable supplier pool (casting manufacturer, 2012a[24]).
- High levels of investment – It requires significant investment to add heavy casting and forging capacity as needed by the wind industry. Despite high levels of investment the margins are very low due to the cost pressures in the WTG industry. Manufacturers are therefore unwilling to invest unless very high (>80%) capacity utilization can be guaranteed – and currently there is not enough visibility or confidence in the demand from the wind industry.
- Cautious buyers – Another major reason for the limited number of new entrants in manufacturing is that WTG manufacturers are reluctant to contract new suppliers for critical

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[24] Information gathered through interview with key individuals from the industry who wished to remain anonymous.

components which affect the overall safety and performance of the turbine. This is manifested via restrictive procurement policies, time consuming and costly bidding processes, and high quality requirements.

Assessment

Casting: There are a large number of castings suppliers worldwide. However, as the size and weight of the required casting increases, the number of suppliers reduces exponentially. For example, only 30-35 suppliers can handle 20 tonne alloy castings. Among these, 26 suppliers can handle the more remunerative 50 tonne castings required by the hydro, thermal and nuclear power sectors. Thus, whilst global supply is not a constraint for a sub 2 MW turbine where the rotor hub casting weighs 8 to 10 tonnes; capacity is very limited for larger wind turbines' rotor hubs that can be as large as 4.6 m in diameter.

Tonnage for castings for various turbine sizes is not fixed. In Europe there is a tendency to prefer thinner castings while in Asia the trend is towards thicker castings. There are no standards in this regard (Table 1), but typically 5 MW turbines have rotor hub castings weighing more than 20 tonnes (casting manufacturer, 2012b[25]).

Wind turbine capacity	Size of rotor hub casting (Asia)	Size of rotor hub casting (Europe)
2.4 MW	20 tonnes	12 tonnes
5 MW	50 tonnes	35-40 tonnes

Table 1: Differences in rotor hub design and casting weights

Source: Avalon Consulting research and analysis

The size of the turbines, especially offshore, is increasing to 5 MW and above; for such turbines 150 tonnes of castings are required (Edwards, 2011). There are only approximately 12 companies capable of manufacturing the larger castings for turbines above 5MW as this requires a high level of capital investment and technical skill.

It is possible to mass produce castings for turbines up to 5MW, and there is a wider supplier base (more than 20 suppliers in the range 3-5 MW). Larger castings are normally produced individually. The typical lead time for a large casting is about a month if mould is to be made. Even with a pre-existing mould a hub of such size typically takes about 7 days to manufacture, with more than 20 hours spent on machining alone. Assuming a capacity addition of 16 GW in 2025 comprising offshore WTGs greater than 5MW, this translates to approximately 3,200 such heavy castings. Even an 11 GW capacity addition of such turbines in 2016-17 would require more than 2,000 such castings. In 2010, capacity addition was about 1 GW, which translates to maximum 200 such castings. Thus, a 10-fold increase in capacity available for wind turbine industry might be required in 5 years.

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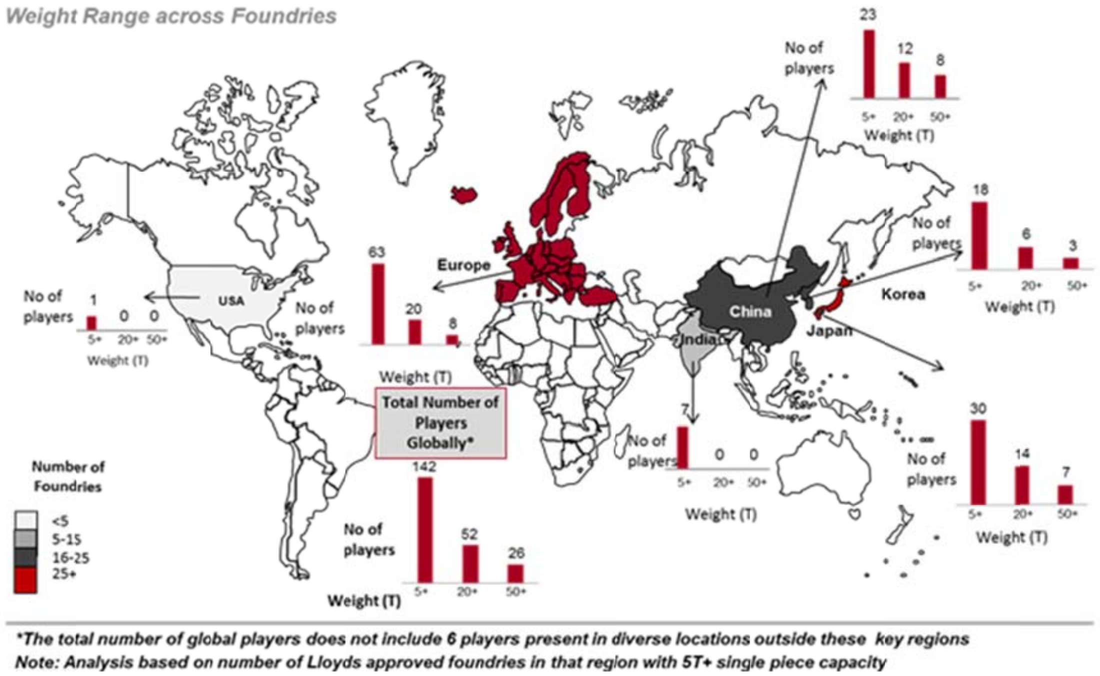
[25] Information gathered through interview with key individuals from the industry who wished to remain anonymous.

Currently 10 MW and higher capacity turbines are being discussed. This would stretch the capability of castings manufacturers based on the corresponding dimensions of castings that would be needed. For example, this might require rotor hubs that are close to 100 metric tonnes in weight if the design is not changed dramatically. Only a few foundries worldwide are able to produce these (Figure 18) and usually not in serial production but rather as piece by piece manufacturing. This could be a major constraint in the supply chain (EC-JRC, 2012). There are also fewer sectors where larger sized castings could be used – hence scope for sharing capacity with other industries is limited.


Weight Range across Foundries

*The total number of global players does not include 6 players present in diverse locations outside these key regions

Note: Analysis based on number of Lloyds approved foundries in that region with 5T+ single piece capacity

Figure 18: Weight range across foundries (T for tonnes)

Source: Avalon Consulting based on Lloyd data

The materials being cast also further reduce the available pool of suppliers. In order to reduce the weight and improve the properties, ductile iron is being replaced by ductile spheroidal graphite iron and high strength alloy steels (EC-JRC, 2012). Of the 106 suppliers capable of supplying 10 tonne plus castings, only about 50 can handle alloy castings.

Currently, casting size is limited by manufacturing processes that cannot scale up any further. The physical casting process is to a large extent a scaled-up version of what has been used for hundreds of years, and large castings are still produced piece by piece by in situ processes. Current foundry technology is increasingly unable to deliver the quantity, quality and sizes required by the wind industry. Today the geometry of castings is dictated by the actual manufacturing process and not by the designer. It is estimated that the rotor hub and bed plate weight could be decreased by up to 25% should process improvements be made.

In the longer term, shortage of large castings may cause major impacts at a global level. However, reduced demand from the nuclear sector following the Fukushima nuclear accident is expected to release some of the casting and forging capacity for other industries, providing short term relief to the wind industry.

Forging: In forging, while there are a number of components in the turbine, only the rotor shaft is large enough that size limits the number of suppliers (Table 2).

Component	% share of Forging as manufacturing process used	No. of components per unit	Weight of Forged Component(T)	
			< 2.5 MW	> 2.5 MW
Bearing Rings	100%	1	1	1
Rotor Shaft	**80%**	**1**	**7**	**15**
Low Speed Shaft	100%	1	2.5	3
Slewing Rings	100%	12	1.5	2
Gear Rim	100%	1	1.5	2
Sun Gear	100%	1	1.8	2
Planet Gear	100%	3	0.6	1
Lock Plate	100%	1	1.5	2
Rotor Brake Disk	100%	1	1.5	2
Blade Adaptor	100%	3	1.5	2
Clamping Unit (Main shaft to gearbox)	100%	1	1	1
Coupling (Gearbox to Genset)	100%	1	1	1
Tower Flange	30%	20	3	4

Table 2: Major forged components and their weight (indicative)

Source: Avalon Consulting research and analysis

Wind Turbines of 2.5 MW use rotor shafts weighing 10 tonnes (Figure 19), beyond which forgings are typically classified as “heavy” and for which the number of suppliers decreases. Globally, the supply of heavy (>10 tonnes) forgings is estimated at 150,000 tonnes as of 2011. Beyond 25 tonnes, (i.e. approximately 5 MW turbine) there are only a few vendors in the world capable of supplying such forgings.

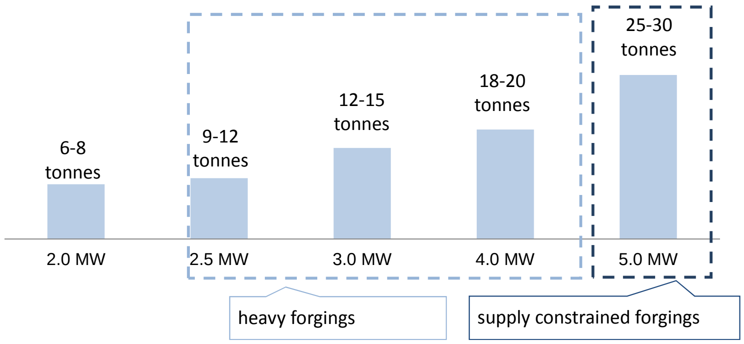


Figure 19: Rotor shaft size variation with turbine output

Source: E4tech/Avalon Consulting research and analysis

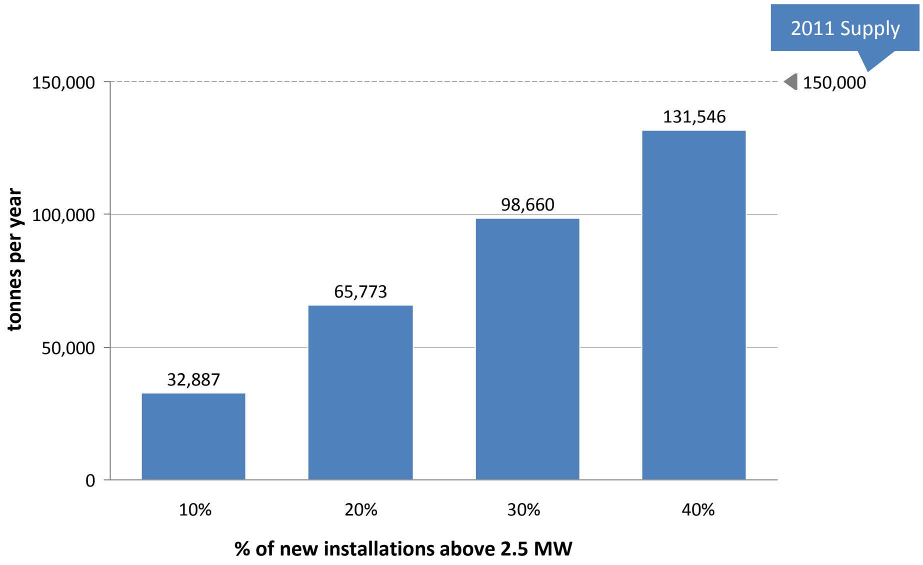


Figure 20: Forging requirement at various levels of deployment of high capacity turbines until 2016

Source: E4tech/Avalon Consulting research and analysis

In the assessment approach taken, it is assumed that deployment of high capacity turbines (>2.5 MW) will show strong growth in the coming years. However, even if that growth is half the expected share of 40% of all turbines, the wind industry will still consume 45% of the 2010 global heavy forging capacity resulting in supply stresses.

Industry experts have highlighted that government commitments for domestic deployment have been a major factor in the rapid forging capacity development in China in the past decade. However, there is uncertainty over the actual demand from wind industry, especially in view of an anticipated reduction in demand from China. Additionally, a current freeze in nuclear power installations in many countries and fears of a double-dip recession are preventing heavy forging manufacturers from making any substantive investments on capacity.

Mitigation

Initiatives on both the demand and supply side can mitigate the potential bottleneck in casting and forging capacity. Improving visibility of demand would be the most pervasive measure, though several others are also relevant.

Demand visibility. For heavy castings and forgings, the wind turbine industry believes that if there is visibility of demand, capacity will increase following conventional industrial logic. The typical lead time for capacity addition is approximately 2-3 years.

Governments publishing roadmaps for wind energy deployment and declaring incentives and plans for wind power will generate confidence along the supply chain leading to capacity investments. These declarations need to be material and long term, since the level of investment is significant.

Supply-side incentives. Different supply side support options exist, which include:

- Tax incentives and measures for low interest or forgivable loans for setting up casting / forging capacity
- Creation of dedicated infrastructure such as supply parks for wind energy where infrastructure, knowledge and other resources can be shared among wind energy suppliers.

Increasing the supply base**.** The wind turbine industry could proactively encourage new vendors of medium to heavy forgings and castings by explaining the opportunity and requirements of the wind sector carefully.

Alternative materials. Alternatives to ductile irons are required in order to make more cost effective wind turbines in the future. Some of the materials with promise include high strength cast steel alloys, high strength cast ductile spheroidal graphite irons, high strength aluminium and magnesium alloys, titanium alloys and metal matrix composites (EC-JRC, 2012).

Process improvements. Research into improving the casting process for large items is needed to accommodate the industry’s needs in the coming years. This will allow the wind industry to use ductile iron as a construction material for longer and allow for improved efficiency of the nacelles and tower design. Additionally, process improvements could help reduce the weights of individual components up to 25%. As cast items represent approximately 60% of the total nacelle weight, this will result in reduced load, and hence, further design and cost optimization of structural parts (EC-JRC, 2012).

Split section castings and forgings**.** Large castings and forged components could be designed in sections and joined together.

Splitting large castings and forgings adds costs in terms of additional items for joining (like flanges, fasteners, welds etc.) and also may impact life and reliability. However, the industry feels that in the long run, as offshore turbine sizes continue to increase, sectional design would become common. Hence more research is needed in this area, working in close collaboration with the castings and forgings industry.

Recommendations

Increasing demand visibility	
Industry	Initiate dialogue with suppliers on the deployment roadmap and possible stresses on the supply chain
Policy	Provide clear deployment roadmaps with realistic interim goalposts and review checkpoints
Supply side incentives	
Policy	Tax incentives and infrastructure support (like supply parks) can be provided for manufacturing capacity built to cater to the wind energy demand
Increasing supply base	
Industry	Proactively develop and nurture additional suppliers for heavy castings and forgings
Research into alternative materials, process improvements and split design	
Policy	Provide grants / encourage research in the above areas and incentivize rapid deployment by the wind power industry
Industry	Invest in and sponsor research in the above areas to improve long term competitiveness and development of the industry, working closely with potential vendors

4.5.2 Limited availability of suitable vessels for offshore installations

Offshore wind farm installation and operation & maintenance require specialised vessels, remotely operated vehicles (ROVs) and platforms. These deliver services such as jack-up, craning, transport, accommodation, subsea works, cable installation, guarding and surveying. Vessel capabilities also have to match site requirements such as adequate draft for water depths, crane heights and specialized foundation requirements. Scheduling and forecasting demand for installation and maintenance vessels is difficult since wind and wave conditions affect installation times and can cause chain reactions of progressive delays (BWEA, 2007).

The demands of installing today's monopile foundations and up to 3 MW turbines and cables can in fact be met by many existing vessels used by the offshore oil & gas industry. This means that the offshore wind industry has to compete with the high day-rates customary in the offshore oil & gas industry, which are often unrealistic for the budgets of smaller offshore wind projects (Accenture, 2012).

Indeed, until today over 30 different vessel designs have been used for substructure and turbine installation (EWEA, 2011), but looking towards the future, increasing installation distances from land (and deeper water) and increasing sizes of turbines will require more purpose-built vessels (BWEA, 2007). There are few vessels currently available that are able to install 5 MW and larger turbines which will become the norm from 2016 onwards. Thus, overall it can be concluded that turbine installation vessels are the type of vessel that may be in short supply in the future, while vessels for the other tasks around wind farm construction are likely to be available.

An interesting issue arises when geographic mobilisation of vessels is required, e.g. to use vessels currently used in the North Sea in US East Coast wind farm installations. Certain jurisdictions restrict foreign-flagged vessels, which limits the deployment of fleets globally. An example of such legislation is the Jones Act in the USA (Gawthrop Greenwood, 2012). The impact of this is not yet known.

Assessment

In the North Sea area, the peak period for offshore wind deployment is expected from 2015 to 2020, which will coincide with the decommissioning stages of installations of many gas production platforms in the southern part of the North Sea area (Edwards, 2011). In addition, oil & gas industry demand for vessels increases with exploration activity, which is triggered by increases in oil & gas prices. This results in shortages of vessels and increased charter rates for both industries.

Fleet owners are able to respond to increases in demand for turbine installation vessels, but with lead times of two to three years for new designs (Carbon Trust, 2010). Vessel fleet owners will order specialised vessels if offshore wind developers show firm commitment for their projects, because only then can fleet owners secure the necessary financing. This is due to long payback periods of 8-10 years per vessel, and full booking of the vessels over that period can be more easily assured if vessels can be used both by the oil and gas as well as the offshore wind industry. Specialised offshore wind vessels would face more volatile returns if future offshore wind growth stalls (Carbon Trust, 2010). At the moment, many developers expect vessel fleet owners to build capacity without actually having confirmed contracts. This means that investors are hesitant to commit to new vessel orders/projects because of doubtful future returns, which in turn causes delays and ultimately affects project execution and profitability. If developers are not willing or able to assume the risk of unconfirmed projects in order to give security to fleet owners, governmental support is required to ensure that projects do go ahead (Accenture, 2012).

There are signs in the North Sea area that owners and contractors are initiating the acquisition of vessels able to service the installation of wind turbines. Most of these vessels are self-propelled and self-elevating, have a dynamic positioning system, cranes with heavy lift capacities and large deck space allowing them to install foundations, transition parts and turbines. As of April 2011, 16 of such ships had been ordered (KPMG, 2011) and by 2013 more than 20 specialised vessels are expected to have been deployed (Accenture, 2012). Even a year ago, this bottleneck would have seemed much more severe, while industry is already mentioning a potential “glut” of vessels by 2014-15. This is also confirmed in EWEA (2011), who expect a “good balance of supply and demand in the short to medium term”.

However, as installation continues beyond 2020, continued investment into specialised vessels must be sustained in order to avoid a serious installation vessel bottleneck later on (Accenture, 2012). The number of ship days required for turbine and foundation installation declines with increasing farm size (ORECCA, 2011).Assuming average turbine sizes of 5MW and farm sizes of 250MW, the 2025 BLUE Map Hi REN scenario annual capacity addition of 14GW offshore would mean that some 53 installation ships would be required during that period. This means an addition of around 33 vessels in the period 2015-2025. While this can be achieved, it does highlight the scale of investment required. It is clear that even with significant investment the use of non-specialised vessels will continue to be necessary in order to satisfy the demand from installations (BVG Associates, 2012).

Mitigation

Inevitable lead times for production of new vessels and retrofits mean that vessel fleet owners have to be confident that their investments will pay off through the higher future demand by the offshore wind industry. Establishing this trust should be at the centre of policy measures and industry action. Given that stimulating the industrial output of the traditional shipbuilding industry is in the interest of many governments, coordinated action between policy makers and industry groups could help inform shipyards of the opportunities and associated risks. Signals indicating strong and secure support for the wind industry from policy makers are needed in the long term to lower the overall investment risk in offshore wind.

Recommendations

Increasing demand visibility	
Policy	Provide firm deployment roadmaps with realistic interim goalposts and review checkpoints
Industry	Initiate dialogue with vessel suppliers on the deployment roadmap and possible stresses on the supply chain. Reliable industry forecasts are needed which translate roadmaps into needs for vessels and platforms. An example is KPMG (2011), which presents the opportunities for the German shipbuilding industry resulting from offshore wind activity in Europe and beyond.
Supply side incentives	
Policy	Provide tax incentives for ships built to cater to the wind energy demand
Demand side incentives	
Policy	Provide loan guarantees to ensure that projects go ahead for which developers cannot take the risk (e.g. Megaprojects)
International mobilisation of vessels	
Policy	Assess and enable the accessibility of national waters for offshore wind installation vessels

4.5.3 Limited availability of skilled personnel along the supply chain

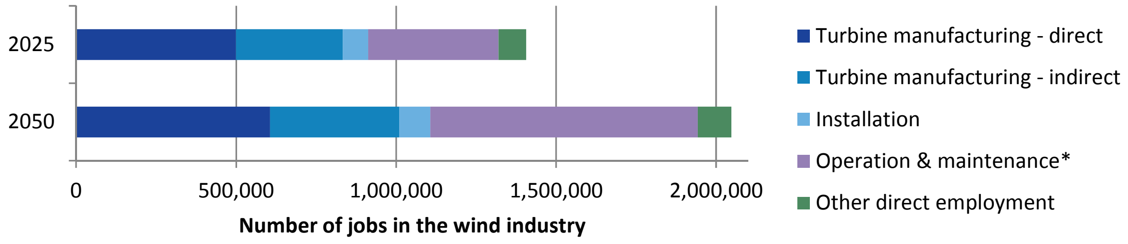
Wind is a manpower intensive industry and requires skilled human resources all along the wind supply chain and at all levels.

The wind industry has grown rapidly, which has exposed critical shortages in skilled personnel. Shortages already exist in design, engineering, testing and assembly of large wind turbines, as well as in the manufacturing of their specific components such as gearboxes, large bearings, electronic control, yaw and hydraulic systems. Power engineers with experience in substation work are also currently needed.

Equally, a shortage of locally available O&M professionals exists especially in remote areas (Wind Facts, 2009). This can lead to longer periods of wind turbines being switched off as a precaution when a lack of observation, diagnosis, and swift repair could lead to serious faults. The situation in the US serves as an illustration, where reportedly 60% of wind turbine generators currently are behind on their maintenance schedules. Many O&M teams of wind farms are actually so resource constrained that they are barely able to keep up with the unscheduled maintenance repairs (NREL, 2007; BVG Associates, 2011).

Assessment

The skill shortages are thought to be caused by the rapid expansion of the renewable energy sector, lack of public awareness of the opportunities in the (offshore) wind sector, lack of suitable training courses and retraining from other sectors, and strong competition from the offshore oil & gas sector. Wind farm developers and operators are looking for local labor and invest in their (international) training, but are struggling to find competent candidates (Canada Gov, 2007). In addition, adding untrained workers may actually reduce productivity, which means that ramping up production can be hampered by less experienced workers and engineers (Canada Gov, 2004).



*for total installed base

Figure 21: Expected number of jobs in the wind industry

Source: E4tech/Avalon based on EWEA (2009)

Figure 21 shows an estimate of the number of people working in the wind industry in 2025 and 2050, given the annual installations required for the IEA BLUE Map Hi REN scenario. At the end of 2010, the wind industry employed about 670,000 people (EWEA, 2010), which means that the number of people required by the industry would more than double by 2025.

Detailing these figures further, it is estimated that approximately 40% of people employed in the wind industry will be exclusively for offshore activities (EWEA, 2011). In addition, highly specific skills and knowledge may be required within the different job types shown in Figure 21. For example, since project managers are responsible for securing permits in the country of installation, besides excellent knowledge of the wind industry and project management, this also requires experience with the country's particular framework of wind park installations. This kind of knowledge is difficult to gain in short period of time and may results in the shortage of project managers (Wind Facts, 2009).

University-level education provides a range of generally qualified candidates. However, fresh graduates need additional specialization which is generally provided by wind sector companies due to the lack of specialized training. Secondary level education for developing skills such as O&M, health & safety, logistics and site management is insufficient (Wind Facts, 2009).

Overall this is a potential bottleneck which varies in its likelihood by country, with countries featuring under skilled or inflexible labor markets and/or high employment rates most likely to suffer first. However, given that the globally required workforce has to grow very quickly to meet the demand of the IEA BLUE Map Hi REN scenario, a lack of skilled people is likely to hinder deployment of wind energy.

Mitigation

***Meeting training needs*.** In order to meet the increasing demand for talent for the wind industry, various training and education needs for engineers and technical staff could be addressed jointly by industry, universities and policy makers (BVG Associates, 2011). Training needs include specific training in wind turbine generator manufacturing, component manufacturing, and project development, as well as in operation, maintenance and repair (Canada Gov, 2004), while training grants could help stimulate enrolment (Canada Gov, 2007).

Additionally, governmental assistance could include help with identifying appropriate staff, as well as training grants & incentives for expensive international training schemes required to transfer skills. With some skills overlapping between the offshore wind and the offshore oil & gas industry, much of the health, safety and environment processes can be shared and adapted. This could also provide the workforce with wider career options between the industries (Edwards, 2011). Encouraging the contracting firms for the offshore oil and gas sector into a wider offshore contracting role (including wind), could help in meeting the skills and training requirement for the wind industry.

***Developing internationally recognised profiles*.** For the required role, a standard profile should be generated, which may act as reference for developing global standard program for secondary training. The European Commission has funded the 'The Windskill Project' (www.windskill.eu/) to provide standard profiles in Europe (Wind Facts, 2009). This will also help in creating a mobile labour force, which can operate in different countries (Windskill, 2009b).

***Spreading awareness about wind opportunities*.** Programs should be created to increase the attention of younger generations in the wind opportunity. These could focus on both school and higher education. Also various job fairs, training centres and university employment offices can be helpful in reaching a potential candidate (EWEA, 2008). An example of this is the "Kent Schools Wind Energy Enterprise Challenge" in the UK, aiming at engaging young people in wind energy and related career opportunities (Wind Energy Network, 2012).

***Automation to reduce operation and maintenance needs*.** Wind turbine design can minimise the need for human interventions, for example by employing remote diagnosis to reduce the frequency of on-site service and maintenance. Reducing the need to visit turbines decreases the number of operational maintenance hours on and offshore, allowing the servicing of more turbines with less staff, while helping to reduce the health and safety risk to personnel (Renewable UK, 2011).

Recommendations

Meeting training needs	
Industry	Involve industry players (OEMs, component manufacturers, project developers) to communicate current and emerging needs for skills
Policy	Assist with identifying and providing training staff through grants and incentives Include alternate energy topics in colleges to improve awareness Provide training grants
Developing internationally recognised profiles	
Industry	Involve industry players to develop standardised profiles and job descriptions
Policy	Develop a body for developing standards Facilitate international cooperation around standards
Spreading awareness about wind opportunities	
Industry	Conduct job fairs and conferences to attract potential candidates
Policy	Provide grants for programs targeting all age groups (pre-career up to adult training
Automation to reduce O&M	
Industry	Invest in technologies that reduce the need for human O&M intervention

4.5.4 Limited availability of suitable port infrastructure for offshore installations

Ports are needed to service the installation as well as the operation and maintenance (O&M) phases of an offshore wind farm installation. A suitable port for the installation phase is one which offers relative proximity to offshore wind farm sites as well as several other factors: ample connections to land infrastructure; space for the establishment of suppliers in the vicinity; craning facilities able to cope with blades and foundations; free land area for lay-down and storage (approx. 8 ha, more for sites with greater weather restrictions); large sheds for storage of components and pre-assembly of WTGs; quayside access for vessels up to 140 m length, 45 m beam, 6 m draft without tidal or other access restrictions; overhead clearance to sea of at least 100 m to allow vertical shipment of towers; craning facilities and other logistics like heliports (DECC, 2009).

Ports are also needed to serve operation and maintenance (O&M) requirements on an on-going basis, though these do not need to have such extensive facilities and are not necessarily the same as those used to support installation.

Assessment

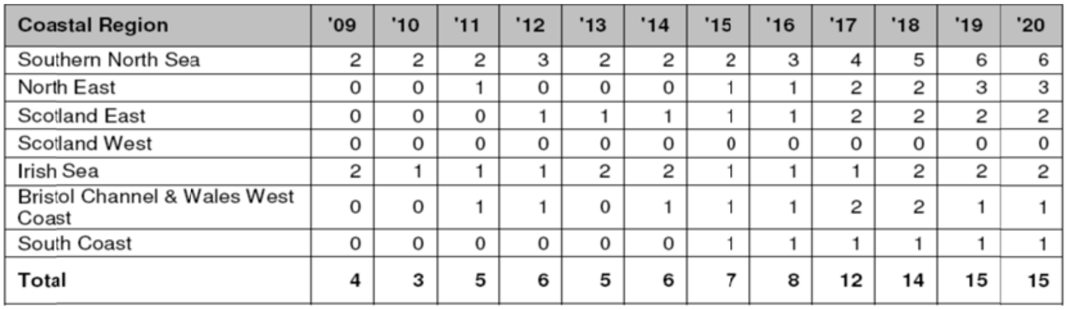
Ports for installation are a major concern in offshore wind (Reiche, 2010), though this issue should be considered regionally. Two of the main countries of concern are discussed below. Given that

O&M ports have to fulfil less stringent requirements, they are not considered to constitute a bottleneck.

United Kingdom. The UK Government has projected installation of offshore capacity of approximately 25 GW by 2020 in UK, of which about 6GW is currently in place. To achieve this target, about 5,000 turbines are planned to be installed, with expected average capacities of 5MW gradually increasing to 6MW in 2015. Currently, the UK has 5 wind enabled ports meeting current demand. By 2020, there will be a need for around 15 ports to satisfy the demand. Within the UK, new ports are needed in particular in the southern part of North Sea; the north east and eastern parts of Scotland (DECC, 2009). Currently, about 20 potential areas have been identified for port facilities to service the offshore wind industry, but since these are owned by private players, commercial viability alone may decide their availability in the future (DECC, 2009).

If the availability of ports is not improved in UK (Table 3), it will act as a major bottleneck from 2016 onwards. If sufficient ports are not developed in UK for the offshore industry, continental Europe may end up fulfilling this need for installations. However, this will increase the cost of turbine installations due to increased transport distances and weather risks; and impact the economic benefits for the UK offshore wind industry (DECC, 2009).

Since governments are more closely involved in funding ports in continental Europe, the lack of wind commercialisation is not expected to hamper development of ports the same way that it does in UK (Garret, 2011).



Coastal Region	'09	'10	'11	'12	'13	'14	'15	'16	'17	'18	'19	'20
Southern North Sea	2	2	2	3	2	2	2	3	4	5	6	6
North East	0	0	1	0	0	0	1	1	2	2	3	3
Scotland East	0	0	0	1	1	1	1	1	2	2	2	2
Scotland West	0	0	0	0	0	0	0	0	0	0	0	0
Irish Sea	2	1	1	1	2	2	1	1	1	2	2	2
Bristol Channel & Wales West Coast	0	0	1	1	0	1	1	1	2	2	1	1
South Coast	0	0	0	0	0	0	1	1	1	1	1	1
Total	**4**	**3**	**5**	**6**	**5**	**6**	**7**	**8**	**12**	**14**	**15**	**15**

Table 3: Indicative number of ports required by region in UK[26]

Source: DECC (2009)

USA. Currently, the US does not have any offshore wind farms, although the US Department of Energy (US-DoE) has published a scenario of 20% wind in the electricity mix by 2030 that includes an estimated 10 GW of offshore installations by 2020 and about 54 GW by 2030 (US-DoE, 2008; NREL, 2010). The Atlantic coast has been identified for major installations of offshore wind especially the states of New Jersey, Delaware, Maryland and Virginia (EWEA, 2011). Currently, there are no ports to service the installation of the offshore wind industry and so, given that ports are typically required to be in place 2 years before offshore operation can begin, this is a potential bottleneck (MCEC, 2010).

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[26] Assuming a typical installation capacity of 100 turbines per year per port

Rest of the world. European countries and the US are expected to have the lion's share of offshore capacity going forward (IEA, 2011b).

Outside Europe, offshore installations are limited and so is port infrastructure. China announced the installation of 5 GW of offshore wind power generating capacity by 2015 and 30 GW by 2020 (Economic Times of India, 2011). If wind enabled ports are not established in offshore wind potential areas, it may become a critical bottleneck in the next decade.

Mitigation

Availability of port infrastructure is a localised issue, since the ports should be available in the vicinity of the potential wind farm areas. Identifying the offshore potential and developing long term plans for port development need to be assessed by governments to facilitate the progress in port development (Reiche, 2010). This in turn relies on:

- Readiness of port owners, operators and wind industry players to share risks to develop facilities required for efficient construction of offshore capacity (mainly in the UK).
- Dialogue and co-ordination is needed between turbine manufacturers, port owners, offshore developers & offshore contractors.
- Prospective areas for port erection should be duly notified in advance so companies can look at opportunities accordingly.
- Public sector support would also be required for the port growth:
    - Governments can ensure that port capacities meet the desired targets since market forces alone are unlikely to ensure this in time.
    - More support from government to market prospective port facilities to developers would assist port owners to reach out to the prospective customers faster, especially for cases where developers have not yet identified a specific port for the project.
    - Ports with the ability to scale up to provide an offshore facility could mention this in their master plan. This would aid development planning.
    - Regional authorities could market the suitability of their sites to transform into offshore ports suitable for wind.
    - Appropriate competition and economic assessment would be required before embarking on new offshore port projects (DECC, 2009).

Recommendations

Developing port infrastructure plan	
Policy	Develop plan for port infrastructure development; including locations, feasibility studies, infrastructure requirements and time lines for development Provide financial support for port development and risk mitigation
Industry	Port developers, turbine manufacturers and wind farm developers should communicate closely, coordinating port facility development and potentially sharing risks

4.5.5 Overland logistics constraints for large wind turbine components

The increasing size and scale of wind turbine components like blades, towers and nacelles, may exceed the physical capacity of existing transportation means and related handling equipment such as large cranes (AWEA, 2009). Blades present challenges related to their size and nacelles due to their weight. The tower, another heavy component, is generally transported in sections, thus reducing the challenges.

Transportation is a regional issue and varies with state, country and continent. For example, for routes through Texas, infrastructure, routing and permitting are fairly straightforward. However, parts of Europe, California or the US North East are faced with older infrastructure, fixed structures such as low bridges, and tight turning radii (Redding, 2012).

There is a limited supply of trailers capable of hauling large wind turbine components, and a limited number of companies willing to make the investment to increase supply. This is due to high inherent cost and the fact that the specialized equipment used to haul wind turbine components often cannot be used for other hauling, which limits its usefulness (AWEA, 2009).

Transportation across different jurisdictions is one of the most challenging issues faced by carriers whether it is at a state level or at the county level in USA. Rising fuel cost and availability of trained drivers is also hurting the industry negatively (AWEA, 2009).

Assessment

Increases in the size of onshore turbines from 1.5 MW to 3 MW has hit the permissible transport limit in various US states, leading to alteration of transportation routes. This has increased the transportation cost of turbines by 10-25% and has been causing delays in installation (AWEA, 2009). The key issues faced by the industry are:

In the USA, different state jurisdictions require different permits. Transport firms select routes and apply for permits from the relevant state authorities. Often the route of choice is not permissible requiring time consuming adjustments and reapplications to multiple state authorities. As components become larger, the challenge to find safe and reliable routes is becoming more challenging (Redding, 2012). Challenging routing has added 20% to charges as contingency for 'out of route miles' in case of any unforeseen change of route (logistics company, 2012[27]).

Availability and cost of blade carrying trailers. Onshore turbines are reaching 3 MW and the length of the blades is increasing beyond 50 m. The concern is that this increasing size can no longer be carried by the currently used 2 axle blade trailers. ATS Wind Energy Services added that they are already looking for modifications and better trailer designs with appropriate robustness and weight handling capacities (Redding, 2012). A related point is the high cost of such trailers, since they are mostly used during the warmer months and their lack of applications outside of the wind industry means that their costs cannot be easily defrayed by other uses (Redding, 2012).

Availability and cost of heavy component carrying trailers. Multiple axle trailers are used to carry nacelles. There is a limited supply of trailers capable of hauling very heavy wind turbine components and only a few companies willing to make the investment to increase supply. This is due to high inherent cost and the fact that the specialized equipment used to haul wind turbine components often cannot be used for other hauling outside the 'projects season', which limits its usefulness (AWEA, 2009). This results in high transportation costs for the largest components. Transportation costs per MW using 10 and 13 axle trailers with a capacity of up to 65 tonnes, as used for turbines below 1.5 MW, have actually fallen in the US since these are readily available. However, to carry the largest components for turbines of 2.5-3 MW, trailers with up to 19 axles and 75 tonnes capacity are required. These incur double the cost since they are not readily available (the US has an estimated total of 50 such trailers currently). Furthermore, very heavy turbine components for e.g. 6 GW WTGs could not be transported by the US trucking industry in anything other than very small numbers (Redding, 2012).

Road infrastructure. Specific highway lanes are approved for carrying oversized and heavy components. Travel outside that lane is generally not permitted for safety reasons. Any obstruction in the lane has to be dealt with by re-routing, therefore. In most cases suitable alternative options are not available for turning circle reasons. This can leave trailers stranded and causes delays in the supply of the key components. It also impacts the cost of transportation (US-DoE, 2010b).

Mitigation

Both global and regional strategies have to be adopted to cater to the increased challenges in onshore transportation, which is expected to be more severe with further increases in turbine size.

Modular components. Turbine components such as nacelles and blades can be divided into modules to match transport infrastructure. One such initiative is being taken by Gamesa whose G128-4.5 MW turbine suite has a 62.5 metre (the world's longest) modular blade, which is designed for land transportation (project management company, 2012[28]). The blade is transported in two parts and assembled directly on site. Once the blade is assembled a proprietary design crane mounts the blades on the wind turbine and no additional cranes are needed (Wind Energy Update, 2012).

***Communication and coordination between different stakeholders*.** A platform for different stakeholders is needed which would include turbine manufacturers, trailer manufacturers,

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[27] Information gathered through interview with key individuals from the industry who wished to remain anonymous.
[28] Information gathered through interview with key individuals from the industry who wished to remain anonymous.

component transportation companies and relevant government agencies. This would increase communication on different approaches used by players to improve transportation. This would also help in standardizing policies across a country or region with multiple jurisdictions (such as US or EU). A contribution to such communication is taking shape under the ‘AWEA Transportation and Logistics Working Group’ initiative. This will create a reference document for WTG design and sales teams to understand the US logistics infrastructure available so that this can be borne in mind as turbines are designed.

Developing alternate modes of transport. Developing water and rail transportation for WTGs would take some pressure off road transport and offers potential in some regions. It also has the potential to be more economical, where routes are compatible with infrastructure (AWEA, 2009). However, it should be borne in mind that waterways or railways do not provide a full substitute, since very few installations will be adjacent to river or railway tracks. Trailers will be needed for ‘last mile’ access to sites even if these modes of transport are employed. Nevertheless, this combined approach could reduce the burden on trailer companies as they need less equipment to undertake the shorter path.

On the other hand, large investment in loading and unloading equipment would be required in developing waterway or railway terminals. Laying railway line and dredging waterways is also costly, if required.

Recommendations

Developing modular components	
Industry	Developing nacelle and blade design with reduced weight and size respectively
Policy	Support testing facility for such projects
Communication and coordination between different stakeholders	
Industry	Sharing of key strategies used to transport heavy component turbine manufacturers, trailer manufacturers, component transportation companies and relevant government agencies
Developing alternate modes of transport	
Policy	Investment in developing waterways and railroad infrastructure
Reference document for OEM design and sales teams to identify transport limitations	
Industry	Create reference to OEM, regarding the logistic infrastructure available, before the turbine goes into mass production

4.6 Low criticality bottlenecks

4.6.1 Lack of wind turbines suited to cold weather conditions

Cold climates are defined as those regions that experience either icing events or temperatures lower than the operational temperature limits (-20^{o}C) of standard wind turbines (IEA Wind Task 19, 2011).

High masses of ice on the structure can bring about a change in the natural frequencies of the wind turbine components and cause a change in the behaviour of the whole turbine (DEWI, 2003). High air density at low temperatures and ice build-up on the blade reduces the power output of the turbine and the impact the aerodynamics of the blade (DEWI, 2003). Personal safety also becomes a major issue, in particular due to the risk of falling or thrown ice. Cold conditions also slow moving parts and increase the risk of materials failure.

Assessment

Currently installed wind capacity in cold climates is estimated at about 60 GW in 2008 (VTT, 2009). Although no global market study on the precise potential has been conducted, cold climates are expected to offer large opportunities. The Great Lakes area in the USA has for instance been estimated to have a potential of over 700 GW (NREL, 2010). A lack of proven and economical technologies for extreme cold climate conditions (below -30^{O}C) has limited the installation of WTG in some areas (Canada Gov, 2007).

Currently, no reliable solutions for heavy icing conditions are commercially available (IEA Wind Task 19, 2011). De-icing solutions allow the removal of ice, whereas anti-icing solutions help in reducing the icing occurrences in cold climatic conditions (IEA, 2005).Icing of blades adds to the risk of investment because it results in lower production of power in the peak winter season.

Overall the lack of turbines suitable to cold climate conditions is a potential bottleneck, which is likely to impact the deployment of wind in cold climatic areas.

Mitigation

To address the icing of blades, the aviation industry, which also faces equivalent conditions, may provide a solution. A few types of de-icing and anti-icing systems are being tested on prototypes, but are still under development. In one passive approach, anti-icing systems are being used - painting the rotor blades black facilitates the melting of ice once the blade gets heated up due to sunlight (DEWI, 2003). Active systems include heated blades which are already available but require further development.

Other effects of cold conditions are countered by design choices such as cold weather resistant steels and surface heated gearboxes, as well as using low temperature lubricants. Experience is growing with such approaches and further improvements are expected.

Recommendations

Developing de-icing and anti-icing technology	
Industry	Focused development and testing of de-icing and anti-icing systems
Policy	Supporting prototyping and testing facility

4.6.2 Deployment restrictions due to radar interference by wind turbines

Wind turbines can interfere with civilian and military radar due to Doppler interference resulting from blade rotation. The potential interference occurs when wind turbines, especially offshore and near airports, reflect radar waves and cause ghosting (false readings) or shadowing (dead zones) on receiving monitors. Radar interference thus raises national security and safety concerns (CRS, 2008).

Assessment

Globally, an estimated 20 GW of wind power projects, which is approximately 10% of the current global WTG installed capacity, are blocked due to concern over interference with radar systems. Due to security and safety reasons no new wind farms are installed within the radar line of sight (Ragheb, 2009).

This may significantly hinder the realisation of specific projects and lower the potential for wind power in some countries, but reaching the overall scenario projections of about 1,100 GW capacity additions till 2025 (IEA BLUE Map Hi REN) globally should not be seriously affected.

Mitigation

There are two technological solutions being considered:

***Stealth blades*.** Currently, research is in an advanced stage on 'stealth blades' for wind turbines. Cost effective and light weight stealth materials would need to be developed for rotor blades. Radar absorbing materials such as ferritic paints and parasitic claddings are the leading options. Prototyping is in process by the UK government and some manufacturers. The cost premium for stealth is estimated at 10-20% per blade (Ragheb, 2009).

***Changing Radar systems*.** Current radar systems at airport and military installations scan the movement of objects for a few milliseconds in a 4 second cycle. New radar systems can be developed, which will scan 10 times per second and illuminate a 3-dimensional image. The increased scanning frequency provides the Doppler resolution needed to distinguish between aircraft and wind turbines (Ragheb, 2009).

Recommendation

Developing stealth blade technology	
Industry	Focused development of stealth blades technology for rotor blades
Policy	Supporting prototyping and testing facility

4.6.3 Lack of internationally applicable health and safety standards

Description: Health and safety standards are of prime importance in the wind industry, both on and offshore. Hazards are mainly associated with the installation and maintenance of wind turbines, and can be related to the way wind turbines are designed. The risk is increasing with the increasing distance of offshore installation from land, increasing turbine heights, and difficult weather all of which create harder challenges for emergency response. However, health and safety regulations lack international consistency (Lawson, 2011), which translates into varying requirements across different markets for the design of wind turbine components and their operation and maintenance (O&M). The same applies to general quality requirements not directly related to health and safety.

Assessment

This lack of global homogeneity in safety and quality standards requires manufacturers to develop and produce specific components for different markets, which in turn requires installers and operators to adopt different practices in different regions (Lawson, 2011). However, standardisation of many of the components would be difficult to achieve due to different technical requirement such as the differences in grid frequency between the USA and Europe (Moser, 2012).

The establishment of common design standards would help the wind industry by:

- allowing manufacturers to increase standardisation and automation of production processes;
- providing a means for manufacturers and project developers to enter new markets without incurring additional costs for redesign and adoption of new practices.

Global standards for wind turbine design, installation and O&M could thus reduce complexity in the supply chain and ease manufacturing bottlenecks. However, the appropriateness of a one-size-fits-all approach must be considered carefully to ensure that the standards (and hence the costs) are not raised to meet the requirements of the most demanding market at the expense of all others.

This lack of international standards for technology and practices slows down the potential sector deployment and increases the cost of the technology and manpower.

Mitigation

Developing safety training standards. A common training platform could equip installation and O&M teams to be aware of the standards, significantly reducing the number of accidents (Lawson, 2011).

European key stakeholders (turbine manufacturers, operators, developers etc.) have started sharing incident data and have agreed on common European standards for safety training.

***Adoption of global health and safety standards*.** A pan European wind turbine standard (EN50308) is to be released in 2012. This standard specifically relates to health and safety issues that impact on design, operation & maintenance, and it refers to specific design standards already valid in Europe (Renewable UK, 2011). This standard could potentially serve as template for legislation to be passed in US and Asia. Similarly, other (non-health and safety) quality standards could also be coordinated globally.

Recommendations

Developing global standards through collaboration effort amongst Europe, US and Asian countries	
Policy	Governments of key countries / regions to collaborate for developing global standardization in safety training and also design related to health and safety.
Industry	Develop a common template for key components and quality standardization

4.6.4 Inadequate solutions for disposing of or recycling rotor blades

Rotor blades are composed of reinforcement fibres (glass fibres or carbon fibres), plastic polymer (polyester or epoxy), sandwich core materials (PVC or PET), coating (polyurethane), and lightning conductors. Rotor blades have a life of 20-25 years, after which they will have to be disposed of or recycled (MAVEFA, 2006). The main disposal options currently are landfill, recycling, or most commonly, incineration. (Larsen, 2009).

Assessment

Turbine blades contain approximately 30% organic material, mixed with fibres and fillers. While an increasing number of rotor blades are reaching the end of their useful life, landfilling is increasingly less viable as a disposal option. This is because countries such as Germany have already banned landfill disposal of materials containing a high organic content to prevent high methane emissions from landfill (MCDM, 2006).. The other seemingly straightforward solution of incinerating rotor blades is not feasible either when using current combustion technologies, as burning the resin causes the melted glass fibres to block the incinerator system (MCDM, 2006). In addition, up to 60% of the scrap is left as often contaminated ashes that would still have to be disposed of(Larsen, 2009).

Recycling as the third and most valid option for the end-of-life disposal of rotor blades is, however, currently challenging since:

- Blades have a complex composition of of thermosetting resin matrices reinforced with glass or carbon fibres (Job, 2010), which makes separation of close material compounds of a rotor blade is very difficult and energy intensive (Schmidl, 2010).
- Recycled materials cannot be remoulded due to the cross-linked nature of the thermoset resins (Cherringtona et al., 2012). In addition, the composite industry is wary of using recyclate as it is felt that they may pose a material risk and threaten guarantee certificates (Larsen, 2009)

The problem of recycling is not pressing, since there are currently limited volumes of decommissioned blades. However, quantities will increase substantially in the period from 2020 to 2034. In 2020, around 45 tonnes of end-of-life rotor blade material will be available globally, which is expected to increase to about 225 tonnes per year in 2035 at a CAGR of 12.2%.

Mitigation

New materials. A major step would be to consider the recyclability of materials in the design phase of rotor blades. While this may be secondary to the current R&D focus on performance of the blades, recyclability constitutes an important element of the multiple demands on blade materials. Examples include research into thermoplastic matrix composites and even bamboo shreds combined with epoxy or even bio-based adhesives in the future. Other R&D approaches include moving away from composites and using materials such as fully recyclable polyethylene terephthalate (PET) (Larsen, 2009).

Develop recycling processes. Given the challenges with recycling composite materials, further R&D and process trials are required in order to establish cost effective recycling processes. In one recent trial a hybrid shredder was built, capable of separating carbon fibres, with little internal damage.

This was then combined with special fibre upgrading methods aiming at removing impurities that make bonding of the fibres in new composites difficult. Other potential approaches to recycling include chemical recovery through solvolysis, or thermal and material recovery through pyrolysis and gasification (Larsen, 2009).

Establish end of life supply chain. To ensure the viability of any recycling process, reverse logistics of used blades will need to be set-up to aggregate volumes to economic quantities. This burden may fall upon WTG manufacturers as countries shift towards a 'producer responsibility' approach to end of life equipment. Also, markets for recycled fibre materials need to be developed to minimise net costs of recycling.

Recommendations

Developing recycling of organic material (PVC and polyester)	
Industry	Focused research on economically recycling organic material Developing reverse logistics to increase the volume Develop demand for recycled organic material in wind or other industry
Policy	Incentivizing OEMs for recycling of blades
Development and use of materials with recycling in mind	
Industry	Developing and using alternative materials that facilitate recycling
Policy	Support R&D in blade materials that focus on recyclability

5 Securing the supply chain of solar photovoltaics (PV)

5.1 Mapping of bottlenecks along the supply chain of PV

Key elements of the entire supply chain of PV, from raw material to end-of-life module recycling, are depicted in Figure 22. Even though the different PV technologies are manufactured in different ways, it is nonetheless relevant to map them onto the same generic supply chain.

Existing and potential supply chain bottlenecks have been identified and their likelihood of occurrence assessed following the approach described in chapter 3. These bottlenecks are mapped onto the supply chain using color coding in Figure 22.

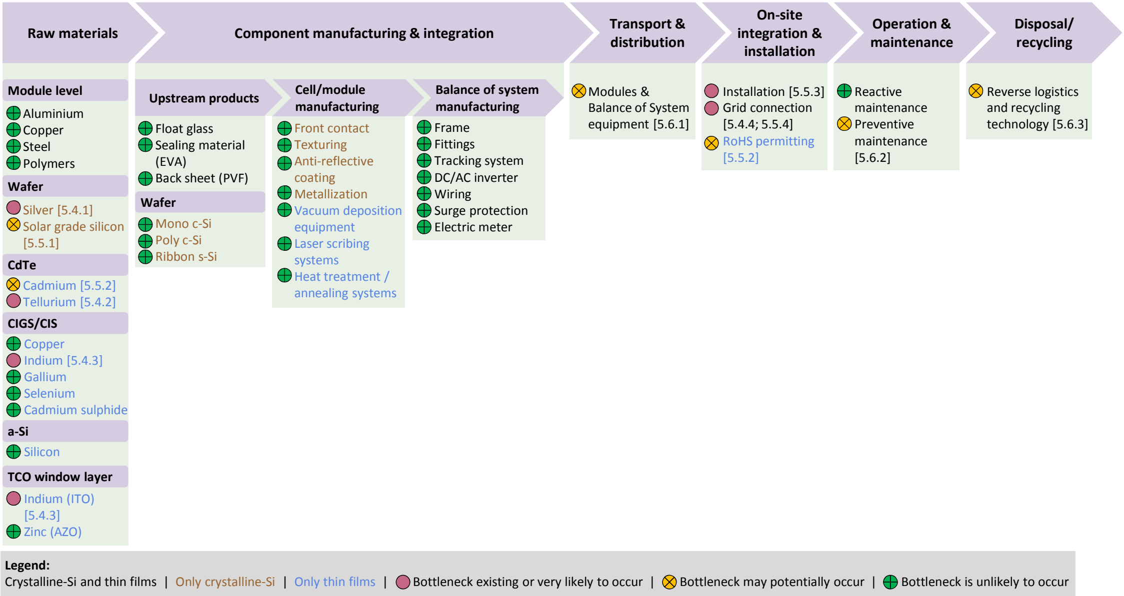

Figure 22: Likelihood of occurrence and location along the supply chain of identified PV bottlenecks[29]

Out of the 43 steps and activities that make up the PV supply chain, five of them have been identified as very likely to face barriers to large scale deployment of PV (see red dots in Figure 22)[30]. Out of these five, three are related to expected raw material supply constraints (silver, indium and tellurium), while the remaining two bottlenecks concern the on-site installation of PV systems and are related to human resources and grid connection issues.

A further six supply chain activities have been identified that could potentially face bottlenecks in the future (see yellow dots in Figure 22). Apart from the supply of solar grade silicon, all of these potential barriers are located downstream.

As seen in Figure 22, despite potential material supply limitations, the PV manufacturing industry itself (cell, module and component manufacturing processes) is unlikely to face significant issues that might constrain production. In other words, the PV industry should be able to meet the large scale deployment of PV if upstream and downstream bottlenecks are overcome. A lack of human

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[29] References to the sections where bottlenecks are described in the report are provided in square brackets.

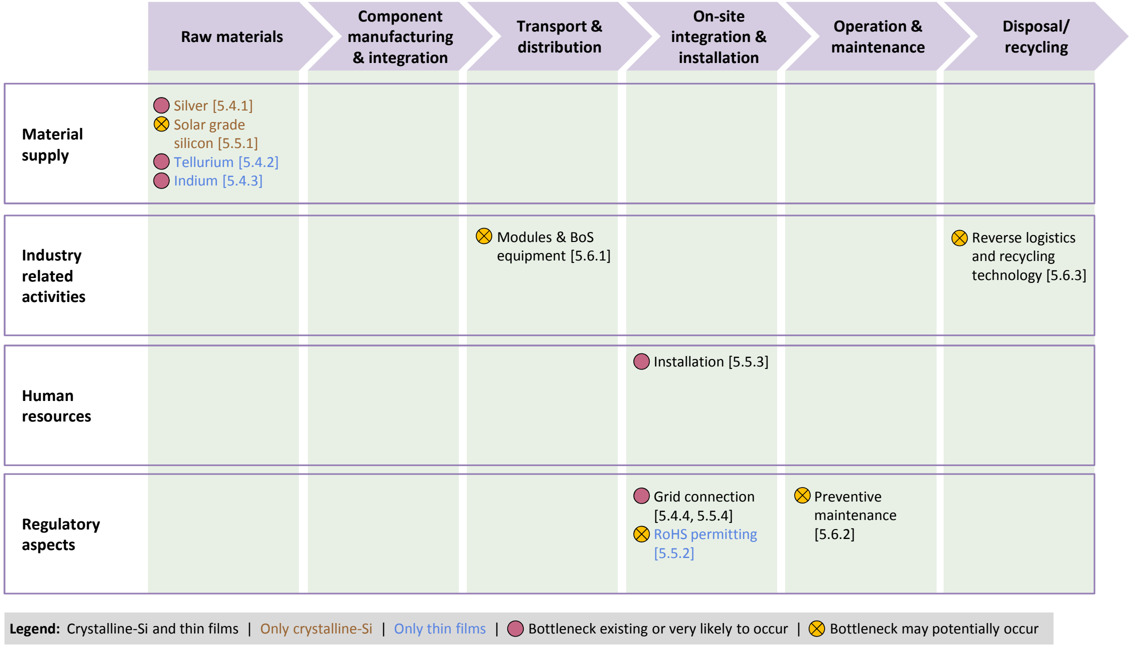
[30] Note that the 6 red dotted supply chain steps make only 5 bottlenecks, as the scarcity over indium appears twice as indium is used both in the front contact of thin film technologies, as well as in the absorber layer of the CIGS/CIS technology.

resources is ranked as a medium criticality issue, but was nevertheless analyzed in depth. Mitigation measures exist in principle, but in contrast to physical supply bottlenecks, which can be overcome by market mechanisms, the availability of skilled human resources in a given location requires concerted action and long term planning by policy makers.

Detailed descriptions, classification and criticality assessment of the bottlenecks identified are provided in section5.4 (high criticality), 5.5 (medium criticality) and 5.5.3 (low criticality) . The bottlenecks are presented in the order in which they arise moving along the supply chain.

5.2 Classification of bottlenecks

In order to facilitate a systematic approach for policy and framework discussion, the bottlenecks have been classified into the four categories "material supply", "industry related activities", "human resources", and "regulatory aspects" as discussed in (Figure 23).



	Raw materials	Component manufacturing & integration	Transport & distribution	On-site integration & installation	Operation & maintenance	Disposal/ recycling
Material supply	● Silver [5.4.1] ⊗ Solar grade silicon [5.5.1] ● Tellurium [5.4.2] ● Indium [5.4.3]					
Industry related activities			⊗ Modules & BoS equipment [5.6.1]			⊗ Reverse logistics and recycling technology [5.6.3]
Human resources				● Installation [5.5.3]		
Regulatory aspects				● Grid connection [5.4.4, 5.5.4] ⊗ RoHS permitting [5.5.2]	⊗ Preventive maintenance [5.6.2]	

Legend: Crystalline-Si and thin films | Only crystalline-Si | Only thin films | ● Bottleneck existing or very likely to occur | ⊗ Bottleneck may potentially occur

Figure 23: Classification of bottlenecks in the PV sector[31]

It comes as no surprise that the sourcing of material places several bottlenecks upstream in the supply chain. These are not current bottlenecks, but are expected to start constraining PV industry from the end of the decade onwards.

The lack of trained human resources is a recurrent issue throughout the downstream portion of the supply chain and that already affects PV deployment today on a country by country basis.

The lack of transparent and robust regulatory environment appears to be a major hurdle to the large scale deployment of PV. In particular, insufficiently clear regulatory frameworks regarding grid access and the uncertainty about possible environmental regulation over issues such as the use of water for panel cleaning and the possible ban over certain materials (e.g. cadmium), as well as the

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[31] References to the sections where bottlenecks are described in the report are provided in square brackets.

lack of long term power purchase agreements are the most cited issues that currently impact or might impact in the medium term on the PV deployment rate.

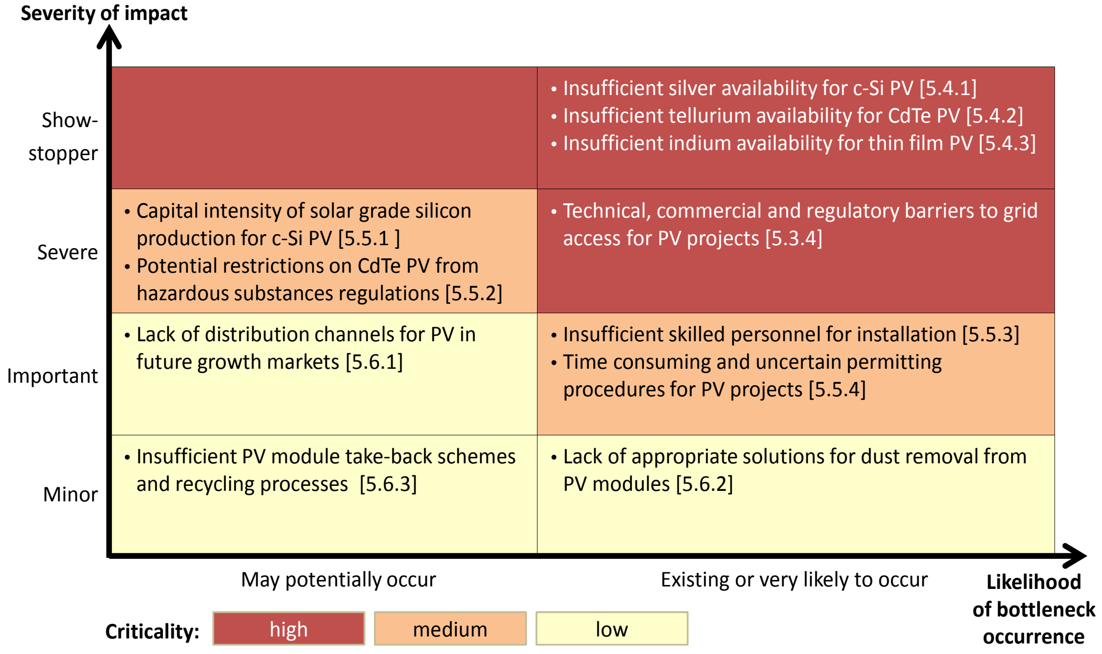
So far as industrial processes are concerned, the only identified barriers are related to the actual recycling of PV modules. The current lack of viable recycling processes is unlikely to affect the deployment of PV in the near future, but will become a growing concern that feeds back on raw material supply with increasing volumes of PV panels that reach their end-of-life.

5.3 Criticality assessment of key bottlenecks in photovoltaics

Following the approach described in section 3.2, the severity of the identified bottlenecks has been estimated based on an assessment of the extent to which the relevant bottleneck can affect the overall deployment of PV in at least one of the technology mix scenarios considered (see 3.4.2, both in terms of severity and geographic expanse of the impact (whether regional or global).

5.3.1 Criticality matrix

The criticality matrix maps the severity rating against the likelihood of occurrence of the bottlenecks obtained in section 5.1 (Figure 24). The matrix helps to identify which are the most vulnerable steps and activities along the entire PV supply chain, which in turn should help decision makers prioritize actions to mitigate these barriers.



Severity of impact	May potentially occur	Existing or very likely to occur
Show-stopper	🟥	🟥 • Insufficient silver availability for c-Si PV [5.4.1] • Insufficient tellurium availability for CdTe PV [5.4.2] • Insufficient indium availability for thin film PV [5.4.3]
Severe	🟧 • Capital intensity of solar grade silicon production for c-Si PV [5.5.1] • Potential restrictions on CdTe PV from hazardous substances regulations [5.5.2]	🟥 • Technical, commercial and regulatory barriers to grid access for PV projects [5.3.4]
Important	🟨 • Lack of distribution channels for PV in future growth markets [5.6.1]	🟧 • Insufficient skilled personnel for installation [5.5.3] • Time consuming and uncertain permitting procedures for PV projects [5.5.4]
Minor	🟨 • Insufficient PV module take-back schemes and recycling processes [5.6.3]	🟨 • Lack of appropriate solutions for dust removal from PV modules [5.6.2]

Figure 24: Criticality assessment of bottlenecks in PV[32]

The following conclusions can be drawn from analyzing the criticality matrix:

- **High criticality bottlenecks (5.4)**. The most critical bottlenecks, which are found in the top right corner of the criticality matrix, are related to the supply constraints of rare materials (silver, tellurium and indium). Each of these materials could act as a showstopper in at least

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[32] References to the sections where bottlenecks are described in the report are provided in square brackets.

one of the technology mix scenarios considered for this analysis (see 3.4.2). This is because upstream bottlenecks have a much higher potential to globally affect the PV industry, unlike downstream barriers that are usually country dependent and thus have more restricted geographical impacts. Raw material scarcity is expected to start impacting the PV industry from the end of the decade onwards. Barriers to grid access and permitting issues impact on the deployment of PV already today with a potentially severe impact on future deployment. These two issues are discussed briefly, since they are only indirectly linked to the PV industry supply chain.

- **Medium criticality barriers (5.5).** Several barriers could prove critical either because of their high likelihood of occurrence or high impact severity. These are:
    - The grade silicon bottleneck observed towards the end of the last decade is now over, and there is currently no reason to fear a return of a supply shortage in the coming years. Nonetheless, the grade silicon industry remains one of the Achilles' heels of the PV supply chain, due to its high capital intensity and long lead time for ramping up new production capacities. The larger and the more mature the PV market becomes globally, the lower the criticality of a possible grade silicon bottleneck as not only will the market increase its capability to anticipate a possible shortage, thus reducing likelihood, but the impact severity of a given quantity of supply shortage will be a declining percentage of total capacity.
    - The exemption of PV from restrictions on the use of cadmium in electrical and electronic equipment in the EU (RoHS) has enabled the widespread of CdTe PV modules in the European market as well as globally. Even though scientific studies (e.g. Fthenakis, 2005) suggest that the risk of cadmium reaching the environment during product life is negligible, and despite the fact that the risk imposed by cadmium in end-of-life modules has been addressed by the industry with take-back schemes, a future ban of cadmium in certain countries or regions cannot be ruled out. Given that a potential cadmium ban would in principle only happen in certain regions/countries and basically only[33] affect the CdTe technology, it would therefore not act as a showstopper to the entire PV sector.
    - The lack of skilled manpower for the installation of PV systems and the grid connectivity issue are barriers that are already observed today in particular in new PV markets, where the regulatory framework has not been put in place and where the lead time to train professionals is longer than the time needed for the market conditions to develop. These barriers are expected to ease up as PV industries and markets mature.
- **Lower criticality barriers (5.5.3)**. Several potential barriers have been identified that are unlikely to affect the large scale deployment of the PV sector. These are the lack of established distribution channels in underdeveloped markets, high cost of dust removal on certain regions and a lack of recycling schemes for PV panels.

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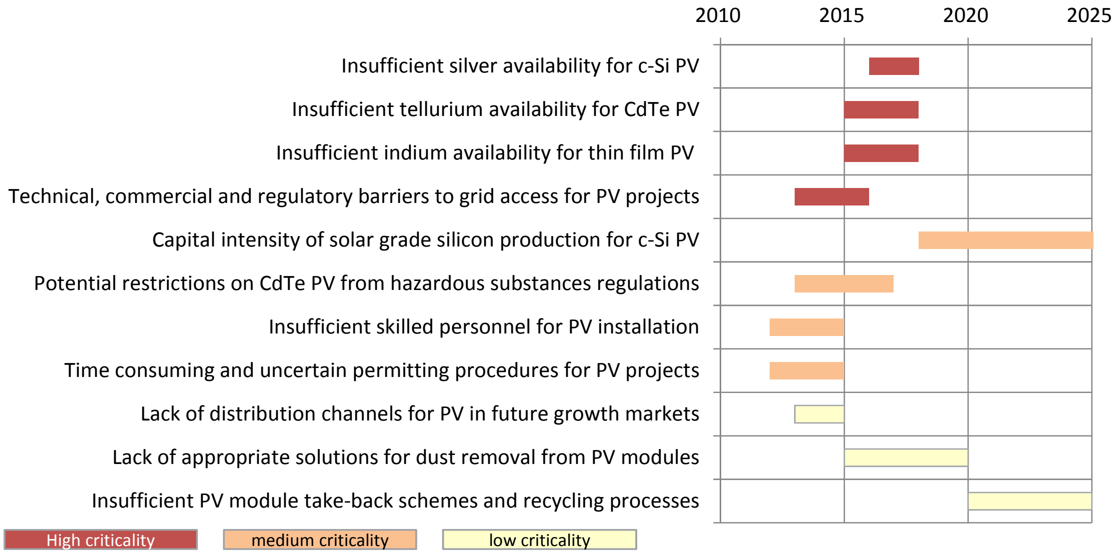
[33] CIGS/CIS technology uses cadmium in a buffer layer. However, the quantity used is significantly lower than in CdTe panels and alternative materials exist.

5.3.2 Time dimension of key bottlenecks in PV

With the exception of the lack of take-back and recycling schemes and the unlikely issue of a second shortage of grade silicon, all identified bottlenecks that may hit the PV industry would bite within a 1 to 6 year timeframe, irrespective of their nature (see Figure 24). Generally speaking, resource constraint on raw materials (silver, indium, tellurium) are medium term issues expected to appear after 2015, while downstream barriers are, again with the exception of recycling issues, shorter term or even current constraints (e.g. shortages of skilled personnel, permitting issue).



Note: Bars indicate the period over which the bottlenecks are expected to appear, in the absence of mitigation. The end of the bars reflects the latest when the issues are expected to appear, and not the time when the bottlenecks could be overcome by mitigation (the latter is too uncertain to predict).

Figure 25: Predicted timescale over which PV bottlenecks might start being felt in the absence of successful mitigation

5.4 High criticality bottlenecks

5.4.1 Insufficient silver availability for c-Si PV

Silver has been identified as the only raw material for which resource limitation may affect large scale deployment of crystalline silicon (c-Si) PV technology. Silver paste is used as the conducting material in the front electrodes. Excellent conductivity, adhesion, long term stability, and the ability to use simple screen-printing techniques for application have made silver paste the material of choice. Given that c-Si panels currently represent 85% of the PV market, a resource constraint on silver may seriously hamper the future PV deployment.

Assessment

Silver is very likely to suffer constrained availability for PV due to growing demand from multiple industry sectors.

Silver supply: Global silver reserves in 2011 were 530,000 (USGS, 2012) and primary silver production (from mining) reached 23,800 tonnes in 2011, up 3% from 2010. Secondary supply (from above ground silver, e.g. scrap) grew at 12% from 2010 and accounted for almost 8,000 tonnes in

2011 (Silver Institute, 2012). Silver is produced mainly as a by-product from lead-zinc, copper and gold mines; the main producers of primary silver being Mexico (4,500 tonnes per year), followed by China and Peru (each 4,000 tonnes).

***Overall demand for silver**:* Silver's properties are prized by many sectors, as shown in Figure 26.

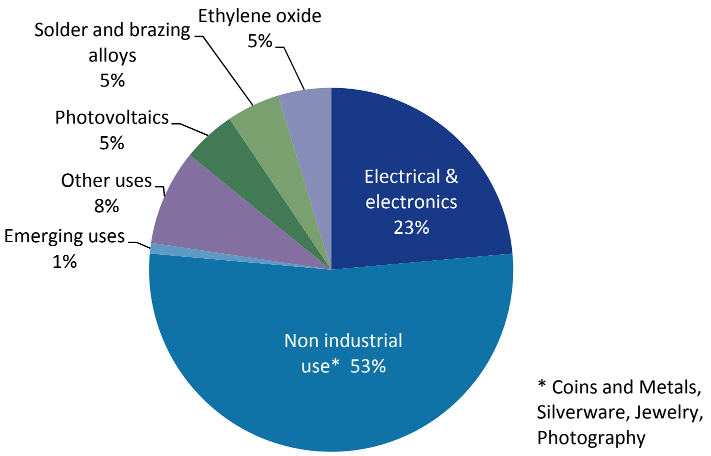


Figure 26: Global silver demand 2010

Source: E4tech/Avalon based on GFMS (2011) and Silver Institute (2011)

Demand from emerging uses is forecast to rise from 300 tonnes in 2010 to 1,300 tonnes per year in 2015, mainly driven by strong growth in demand from batteries, RFID (Radio Frequency Identification), solid state lighting and water purification. Some traditional silver applications such as photography and silverware have demanded less silver in recent years, and the specific use of silver per end product has reduced in some applications (e.g. TVs, cell phones). However, despite these reductions overall silver use grew continuously over the last decade and industrial demand for silver is forecast to grow at an CAGR of 6.4% to 20'711 tonnes in 2015, which is significantly (5'000 tonnes) above today's industrial demand (GFMS, 2011).

Demand from c-Si photovoltaics. Silver demand from the PV industry rose by over 70% year on year between 2001 and 2010 (GFMS, 2011). In 2010, c-Si technology typically used 77 g of silver per kWp (77 t/GWp)[34] (CTM Group, 2011). This figure translates into 2,000 tonnes during 2011, corresponding to 8% of global silver supply in that year[35]. Depending on the growth prospects for c-Si cells within the IEA BLUE Map Hi REN scenario, the PV industry would thus consume annually between 1,000 and 2,900 tonnes of silver by 2025, figures that would grow to 3,300-9,300 by 2050. Irrespective of the scenario considered, it is expected that, based on current technology, the demand for silver from the PV industry will grow significantly in the coming decades, and so will the market share that PV represents for the silver industry which by 2050 may reach between 14% and 39% of 2011's supply. Should silver supply not be augmented and should no alternative to silver use be found by the

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[34] Depending on layer thickness and finger width as well as on the pastes used, the silver use can vary between 50 and 120 g/kWp (Photon international, 2011). Assuming 16.6% module efficiency, this translates into 8-20 g of silver per m² of module area.

[35] Based on 85% c-Si market share (Mints, 2011) of a total of 29.7 GWp module shipments in 2011 (http://www.iwr.de/news.php?id=21128); 23'800 primary silver supply in 2011 (USGS, 2012)

different industries, the gap between supply and demand of silver would then reach 1,000 tonnes/year by 2025 and 7,400 tonnes/year by 2050.

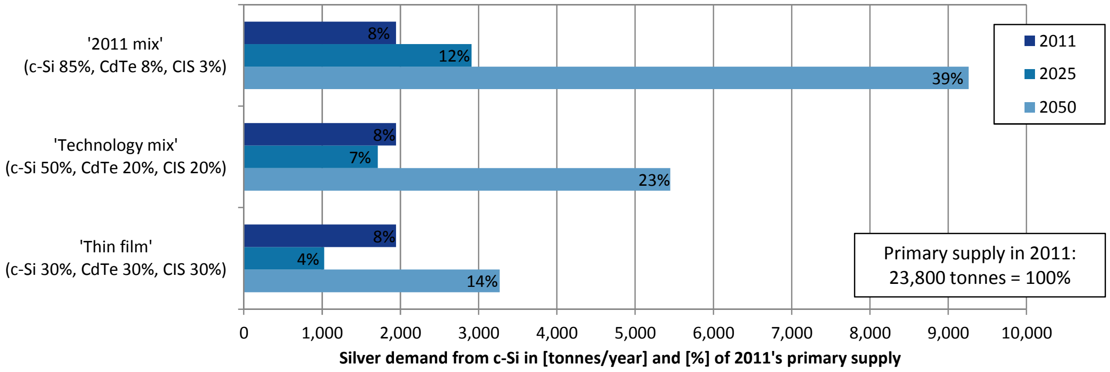

Figure 27: c-Si PV industry's silver demand scenarios

Source: E4tech/Avalon Consulting

Silver as a cost factor in c-Si: The average silver spot price (London Fix) increased at an annualized growth of 30% between 2005 and 2010. Analysts claim that price development is mainly driven by investor interest in silver, partly as a 'safe haven', and only to a small extent by growing industrial demand (Photon International, 2011). This makes future price development even more unpredictable and further growing silver prices threaten the competitiveness of c-Si PV in the medium term. Based on 2011's average silver spot price (US$ 1,129), silver already represents 6-14% of typical module production cost[36] (Photon International, 2011), any significant rise in the price of silver would affect the crystalline PV industry, as the sector is currently undergoing consolidation in a fiercely competitive environment.

Given the silver bottleneck is very likely to occur should no proactive mitigation actions be taken, and given that it would impact 85% of PV supply in the current technology mix, the silver bottleneck can be assessed as critical to the deployment of PV technologies in the medium and long run.

Mitigation

Three general strategies are being considered to alleviate the foreseeable silver bottleneck: Securing primary and increasing secondary silver supply; reducing silver intensity; and substituting silver by other more abundant materials.

Securing silver supply. PV companies are condemned to be price takers, being part of a cost-conscious industry which consumes only 8% of global production of silver. However, large cell manufacturers are already trying to soften the impact of abrupt price changes through long term supply contracts. Through the formation of buying consortia even smaller players can achieve better conditions and longer term supply contracts. This strategy reduces the risk of sudden price shocks, but it cannot avoid increased cost over time if silver continues to become more expensive.

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[36] Range of silver use per kWp: 50-120 g. Panel production cost: US$ 1000/kWp. Average 2011 silver price from http://www.silverinstitute.org/site/silver-price/silver-price-history/2011-present/

Increasing secondary silver supply. Silver is found in many end consumer appliances from which it can be recovered once these products reach the end of their useful life. Whether or not and how quickly items such as cell phones and computers reach recycling facilities, depends on the wide spread of take-back points as well as consumer awareness. While most countries have take-back schemes in place, the rate of collection is quite low. According to the U.S. Environmental Protection Agency, (EPA), only 8% of end-of-life cell phones were collected in 2009 (EPA, 2012) Education and information can be enhanced by governments and NGOs respectively. Campaigns can help inform end-consumers about the positive effects of recycling and concrete information about locations of free-of-charge take back points. This can subsequently help to increase supply of secondary silver and ultimately help to reduce pressure on silver supply.

The PV industry could recover silver from recycled end-of-life panels. This would require both recycling-friendly PV panels to be designed and recycling facilities to be in place. The former feeds back into the economic feasibility of the latter. A good illustration of how product design feeds back to the recycling technology is the initial recycling approach taken by the c-Si industry which aimed at reprocessing wafers from end-of-life modules. This approach was abandoned once the manufacturers succeeded in undercutting the critical wafer thickness of 240 µm which is the limit below which reprocessing wafers is no longer feasible.

Current industry efforts focus on feeding used silicon back into the crystallization process (energiezukunft, 2011). A pilot plant that recovers not only silicon, aluminum and glass, but also silver and copper is projected for 2012 (Spiegel Online, 2011). For the time being, PV panels remain exempted from the RoHS (2002/95/EC) and WEEE (2002/96/EC) regulation which is why lead containing solders for cell interconnections are still widely used. An important parameter of recycling costs is whether or not the PV panel contains hazardous materials which require more costly safety measures in recycling facilities (Spiegel Online, 2010).

As long as recycling of PV modules is not compulsory, NGOs could exert pressure by assessing PV manufacturers’ commitments to recycling. Manufacturers that implement best-practices early on could be publicly recognised, creating a source of competitive advantage. Recycling friendly panel designs are important and the earlier PV panel design is optimized for recycling, the earlier secondary silver from end-of-life modules can help securing the silver supply.

Experts estimate that a cost effective operation of a recycling facility requires at least 20’000 tonnes of scrap per year, equivalent to some 200 MWp. This level is expected to be reached between 2015 and 2020 (Spiegel Online, 2010). It is worth noting that even at a 100% recovery rate of silver, supply of this secondary silver from the PV sector would not be sufficient to meet demand as long as annual output is growing, which means that the volume of recycled modules lags behind the volume of newly produced ones. Nevertheless, recycling can start making a contribution to ease the pressure on the supply side in the 2025 perspective.

Reduce silver consumption per watt peak. Today, silver electrodes are commonly applied through screen-printing a silver paste which is subsequently fired. The challenge is to maintain the current conductivity level and high speed printability of pastes while trying to reduce the thickness the electrode fingers and bus bars. Currently the average thickness of electrodes is about 100 µm, although variance is high among manufacturers (CTM Group, 2011). New silver pastes with improved conductivity are currently under industrial development which may bring the electrode thickness down to 4-7 µm (Photon International, 2011). This could potentially bring specific silver consumption down to around 28 g/kWp by 2015 from current 77 g/kWp. Advanced application techniques such as evaporation or lithography are contemplated which could achieve even thinner silver fingers (Freundlich, 2008), but these will be constrained by conductivity limitations (Ballif, 2012).

Replace silver by less expensive / more abundant elements and materials. Using electroplated copper, to substitute for silver, is a promising path that is already being pursued by the PV industry, as it is not in principle associated with significant efficiency penalties (Solar Server, 2010), and could even bring an efficiency increase by allowing narrower more conductive lines (Ballif, 2012). Although attempts have been seen to integrate this new technology in commercial products, these have yet to fully succeed so this approach should still be considered as being in the development stage (Boydell, 2012). Critical techno-economic challenges remain, in particular:

- controlling the plating process remains difficult, as it is less accurate (Boydell, 2012) and generates higher stress in the plated electrodes (Ballif, 2012) than with silver screen printing techniques;
- an additional barrier layer (e.g. nickel) is needed between the copper and the semi-conducting layer to prevent copper from migrating into it, as this can damage the cell though creation of so-called recombination centres (Boydell, 2012).
- Copper oxidises much faster than is more susceptible to corrosion than silver. The impact of copper corrosion on the lifetime of the cell is likely to be very hard to estimate as there are no reliable accelerated ageing tests (Boydell, 2012). In this context, meeting IEC standard is likely to prove very difficult, which would hamper market deployment.

It is not obvious today whether the cost gain of using copper instead of silver can offset the added cost and complexity of the electroplating approach (Boydell, 2012). Furthermore, switching to copper would require large capital investments, which is likely to be a barrier at a time where there is excess capacity already and low or negative margins in cell and module manufacturing.

Industry experts expect the industry-wide replacement of silver to start in 2015, which potentially would reduce the specific silver consumption to 6 g/kWp by 2020 (CTM, 2011; Photon international, 2011). However, should the price of silver escalate in the near future, the switch from silver to copper could technically be achieved by the PV industry within 2 to 3 years if necessary (Ballif, 2012).

With extremely high conductivity reported, graphene is also discussed as a long term option to substitute silver. This approach is however still at the academic laboratory stage and has not yet passed proof of concept. Graphene is unlikely to reach the PV market before 2020, if at all.

Recommendations

Securing primary silver supply	
Industry	Form buying consortia that can enable even small players to sign long term supply contracts with key suppliers

Increasing secondary silver supply	
Policy	Introduce and/or ensure the wide take up of free-of-charge take-back schemes for consumer electronics
Industry	Improve recycling-friendliness of PV modules, e.g. through the use of lead free solders Make investments into recycling technology and facilities capable of recovering silver from end-of-life modules
NGOs	Run campaigns informing consumers about return of end-of-life products Monitor PV industry’s commitment to recycling, including recycling-friendly product design to reward manufacturers that implement best practices
Reducing silver consumption per watt peak	
Industry	Initiate collaboration to ensure that best-practice will be adopted industry wide and reduce the average consumption of silver per Wp significantly
Replacing silver by less expensive / more abundant materials	
Policy	Support targeted research and development activities aimed at silver-free production methods
Industry	Implement copper plating pilot lines into high throughput production facilities

Should these different mitigation strategies prove insufficient to prevent the c-Si PV industry from suffering from the silver bottleneck, the market could, in principle, rely more heavily on thin film PV technologies. Whether the thin film industry, which currently represents 15% of the PV market, could ramp up fast enough to bridge the gap would depend amongst other things on the ability of the market to interpret the price signals as well as on the risk appetite of investors who would need to support such a major technology switch.

5.4.2 Insufficient tellurium availability for CdTe PV

Tellurium is a semiconducting element. It is one of the rarest elements in the earth crust averaging 0.005 ppm (UniA, 2011). Tellurium together with cadmium forms the absorber compound of the Cadmium Telluride (CdTe) thin film PV cells. CdTe has the highest market penetration amongst thin film technologies and accounts for about 8% PV market share in 2011 (Mints, 2011), representing 1.8 GWp of shipments, more than a-Si and CIGS/CIS panels together. Cadmium Telluride (CdTe) technology is currently the least expensive PV technology on the market with production cost of US$ 0.74/Wp in Q3 2011 (Becker, 2011) and is expected to achieve further cost reductions leading to US$ 0.30/Wp - 0.50/Wp (ICEPT, 2011). However, it still has lower efficiency as compared to c-Si panels and therefore requires larger area for the same power which has implications to overall system cost (so called ‘area penalty’; Mints, 2011).

Assessment

Tellurium is considered as one of the most critical materials for the growth of thin film PV, since the production of CdTe panels today already consumes more than one third of the global tellurium supply. Further growth in CdTe would therefore require considerable growth in tellurium supply. A first sign of a supply stress is the 6-fold price increase of tellurium from US$ 60/kg in 2006 to US$ 360/kg in 2011, which has been attributed to the fast growing demand from the PV sector (USGS, 2012). Based on 2011's spot price, tellurium contributes about 5% to the manufacturing cost of CdTe panels. While total manufacturing cost (US$/Wp) are expected to further decrease, tellurium as a cost contributor is likely to increase, especially if tellurium prices continue to grow. It is therefore quite likely that the competitiveness of CdTe PV modules against tellurium free technologies will, to a growing extent, be driven by the tellurium supply cost.

Tellurium production: Tellurium is generally found as by-product of primary metals such as copper, lead, gold, nickel, platinum and zinc in different proportions.

- Around 90% of tellurium is produced as a by-product of copper mining (USGS, 2012). Tellurium can only be extracted from copper that is refined by the electro-winning process, a technique that is cost-effectively applied to high-grade copper ores (EC-JRC, 2011b). For refining lower-grade copper ores, the most economical process is the solvent-leach refining process, which is currently not capable of recovering tellurium. The global decrease in supply of high-grade ores may constrain the future supply of tellurium from copper (EC-JRC, 2011b).
- Around 10% of tellurium supply is tellurium recovered from lead refinery skimming and from the flue dust and gases of copper smelting (EC-JRC, 2011b).

Other potential future sources include two primary tellurium mines in China and gold mines in Mexico (George, 2012), along with nickel, platinum and silver mines (however, reserve estimates for these sources are not available). Total annual production of tellurium was at 545 tonnes of tellurium in 2010 (Fthenakis, 2012), while global reserves are estimated at 24,000 tonnes (USGS, 2012). This reserve estimate is based on the economic copper reserves only and assumes that less than half of the tellurium content of the copper ore is actually recovered (USGS, 2012). The availability of economically recoverable tellurium actually depends on the demand for copper as its parent metal. Mining tellurium as a primary material would drastically increase its cost.

Recycling*.* Very little recycled tellurium is currently available from traditional sources like selenium-tellurium photoreceptors. The leading CdTe manufacturer has a free of charge take back scheme for discarded PV panels in place. Once larger volumes of currently installed panels reach their end-of-life stage, they will serve as a feedstock for secondary tellurium or cadmium telluride. Pilot recycling facilities recover up to 95% of semiconductor material and can provide feedstock for future production of PV panels (EC-JRC, 2011b).

Applications of tellurium. As shown in Figure 28, the PV industry has the largest demand in the tellurium market and accounts for around 40% of the annual tellurium consumption. However, the demand pie has changed in last 5 years, with metallurgy reducing from around 30% to around 15%.

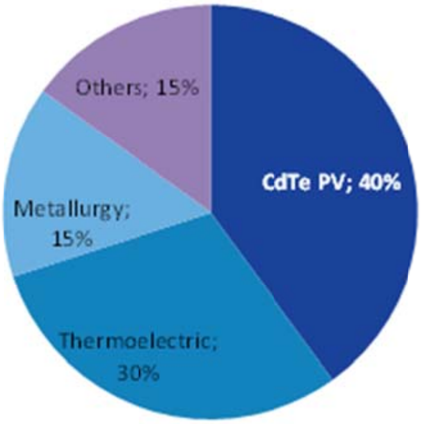

Figure 28: Demand of tellurium from different industries in 2010

Source: George (2012)

Traditionally, tellurium is used in *metallurgy* to enhance material properties in iron, copper and lead alloys (ICEPT, 2011). However, increase in price is expected to reduce usage in the future since alternative additives for both ferrous and non-ferrous metals have found substitutes (George, 2012). Apart from PV, another emerging use of tellurium is *thermoelectric cooling.* This refrigeration technology finds usage in electronics and military applications since it avoids moving parts and circulating fluids, smaller size and flexible shape. Typical applications are cooling of infrared detectors, integrated circuits, laser diodes, and medical instrumentation; all of these have experienced robust growth in recent years. Tellurium in *CdTe PV* is already today the largest user of tellurium, but still considered as an emerging application. The PV industry's demand is currently taking up 37% of global supply (545 tonnes per year) or 200 tonnes.

***Demand from PV**:* To estimated future demand from PV, the specific tellurium use in PV panels today of 85 tonnes/GWp[37] (Fthenakis, 2012) was combined with the PV growth scenarios discussed in 3.2. An average of 44 GWp per annum of PV capacity will be installed between 2020 and 2025. This is expected to increase 3 fold to 142 GWp per annum in the period 2026-2050. If CdTe contributes 8% to overall PV deployment in 2026-2050, 960 tonnes per year will be required (exceeding current annual supply by 76%). Should CdTe contribute as much as 30% of PV deployment (Thin film scenario), almost 7 times as much tellurium is needed per year than was produced in 2010 (Figure 29).

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[37] Absorber layer thickness: 3 µm; module efficiency: 11.7%; CdTe density 6,200 kg/m^3; molar fraction of Te: 53%

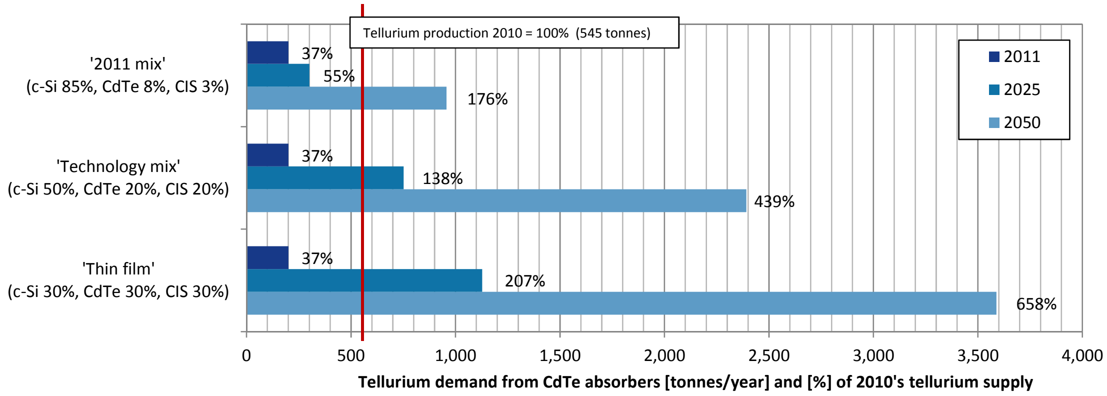

Figure 29: PV industry's tellurium demand scenarios

Source: E4tech/Avalon Consulting

If the supply of tellurium is not increased but remains at 545 tonnes/year, CdTe can achieve a maximum PV market penetration of around 14% in 2025 if the entire primary tellurium production is consumed by the PV industry. Between 2026 and 2050, if production is not increased, CdTe can only contribute 5% of annual PV production. These limitations indicate that a significant contribution of CdTe to overall PV deployment is likely to be constrained by the supply of tellurium.

Mitigation

In recognition of this looming resource constraint, several approaches are being pursued.

Increasing recovery during copper processing. Since tellurium is available mainly as the by-product of primary metals (copper, lead, gold, nickel, platinum and zinc), tellurium production is linked to the demand of these 'parent' metals. However, tellurium production can be increased by optimizing tellurium recovery during the primary (parent) metal refining process. Recovery of tellurium varies with the technical capability of the recovery system. Currently available tellurium recovery equipment allows recovery of up to 90%, but such processes are not systematically implemented (EC-JRC, 2011b). Generating interest from copper refiners may be the main challenge since tellurium refining is not their core business and is a negligible proportion of their overall income. Tellurium refineries could be attached to the copper production with incentives from CdTe manufacturers or governments. CdTe PV suppliers could consider directly or indirectly investing in installing and upgrading the recovery mechanism at copper refineries with the benefit of sourcing tellurium from copper refiners. Also, policies to incentivize higher recovery of tellurium during refining could support this.

Reducing tellurium usage per Wp. The usage of material can be reduced by either reducing absorber layer thickness or by increasing efficiency. The PV industry is continually putting efforts on both fronts. While a layer thickness of 2.1 µm was realized (ICEPT, 2011), further reduction to the physical limit of 0.5 µm could reduce tellurium consumption by 75%. Whether this is technically feasible remains to be seen.

Recycling and recovery of tellurium from end-of-life products. CdTe is a relatively new technology and large volumes of used panels are not yet available for large scale recycling. The recycling potential and volumes from end-of-life thermoelectric cooling equipment are also not yet clear. Recycling and recovery of tellurium could increase secondary supply over time, if such schemes succeed.

Substitution of tellurium in other applications. Research on alternative materials to substitute tellurium in non-PV applications could help to increase the tellurium availability for CdTe. However, since various alternative, tellurium-free PV technologies are available, arguably, technology switch within PV might be more effective than tellurium substitution within CdTe.

Recommendations

Increasing recovery during processing	
Policy	Provide access to capital for recovery mechanism
Industry	CdTe PV manufacturers to invest in installing and upgrading the indium recovery mechanism at copper refineries
Reducing tellurium usage per Wp	
Policy	Fund research on reducing absorber layer thickness and increasing efficiency
Industry	Conduct research, trials and implementation
Recycling and waste reduction	
Policy	Data collection on recycling of thermoelectric coolers
Industry	Research on recycling of thermoelectric cooler
Replacing tellurium in various applications	
Policy	Fund research on replacing tellurium with other elements/alloys
Industry	Research on replacing tellurium with other abundant materials

5.4.3 Insufficient indium availability for thin film PV

Indium is critical to copper indium (gallium) (di)selenide (CIGS/CIS) thin film PV cells, forming a major component of the absorber layer. CIGS/CIS has the highest demonstrated efficiency of all the thin film PV technologies, and is thus expected to rapidly achieve high volume, making these technologies particularly vulnerable to indium supply constraints.

CIGS/CIS absorbers, however, are not indium's only application for PV. Indium is used in indium tin oxides (ITO) that serve as the transparent front contact in thin film PV cells, letting sunlight through while being electrically conductive. However, different types of transparent conductive oxides (TCOs) exist, and leading manufacturers of both CdTe and CIGS/CIS prefer the lower price of indium free TCOs over the slightly better properties of ITO (Markowitz, 2009; Krustok, 2012). Yet, ITO is used commercially for certain amorphous silicon-based technologies, in particular for flexible panels as well as for micromorph and hetorojunctions cells. In addition ITO conductive layers are also used in organic PV and dye sensitized cells. These technologies have very limited market share today, but they almost exclusively use ITO as electrodes.

Assessment

Indium is a critical material for the PV sector, both in terms of severity as it is used in several thin film PV technologies, and in terms of likelihood of an upcoming indium bottleneck. This assessment is due to both uncertain total reserves relating to its parent metal zinc, coupled with geopolitical supply risks, as well as to a strong indium demand from other industry sectors as well as from PV. Each factor is discussed below.

Reserve constraints. Although indium is known to be three times more abundant than silver in the earth's crust, quantifying economic reserves has proven difficult. Indium is mined as a by-product mainly of zinc ores, implying that its availability actually depends on the production of zinc as its parent metal. Mining indium as a primary material for PV would drastically increase its cost. Primary indium production was 640 tonnes in 2011, which together with secondary supply (indium recovery from process equipment and used targets[38]) enabled a global consumption of 1,800 tonnes (USGS, 2012).

Competition over resource. More than half of indium demand is for Liquid Crystal Displays (LCD) (ICEPT, 2011) for the production of monitors, televisions and computers. With the widespread uptake of LCDs, indium use in the United States more than doubled within only five years from 2000 to 2005 (Graedel and Erdmann, 2012).The major ramp up phase of flat-panel display production can, however, be considered as completed and indium demand for LCDs is expected to only grow from 250 tonnes per year in 2011 to only 282 tonnes per year in 2020 (Indium Corporation, 2011). The LCD industry is looking into alternatives for ITO (e.g. graphene-based transparent conductors), but pressure to reduce cost can be considered lower compared to the thin film PV industry, which faces strong competition from indium free technologies.

Other, traditional uses of indium are alloys and solder. More recently indium demand from light emitting diodes (LEDs), laser diodes, electrode-less lamps and mercury alloy replacements emerged. Furthermore, indium is found in control rods for nuclear power plants (US-DoE, 2010a). Currently at about only 2 tonnes per year, indium demand from LED lamps is expected to grow the fastest and could reach 50 tonnes annually in 2020 which is roughly the indium consumption of the PV industry today (Indium Corporation, 2011).

Geopolitical supply security. About three quarters of economic reserves of indium and over 50% of refinery capacity are concentrated in China (USGS, 2011; US-DoE, 2010a). This geographic concentration, combined with China's recent lowering of export quotas on several rare materials including indium, has contributed to rising concerns about security of supply. China is anticipated to further tighten its indium export quota so that the growing domestic demand can be met (US-DoE, 2010a) and to support Chinese companies to develop value-added activities downstream of raw materials refining.

Growing indium demand in PV thin films. In 2011, CIGS/CIS thin films accounted for about 4% of global primary indium supply, growing rapidly from only 2% in 2010 (Fthenakis, 2012, EC-JRC, 2012).

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[38] Only about 30% of an ITO target is deposited onto the substrate, whereas the remaining indium can be recovered from the walls of the sputtering chamber and the spent target (USGS, 2009).

The indium embodied in CIS PV modules is currently about 27 g/kWp[39], while it is slightly lower in CIGS panels[40]. Thin film panels that use indium tin oxide (ITO) as a front contact contain between 25 g/kWp[41] and 40 g/kWp[42] depending on the panel's efficiency and the thickness of the ITO layer. Taking into account the material efficiency in the process and recovery rate of indium from process equipment, actual indium use is 15% to 300% higher[43].

Currently, CIGS/CIS thin film technology has only a 3% PV market share, but has experienced rapid growth in recent years and is expected to be the fasted growing indium application in the next 8 years (Markowitz, 2009). CIGS/CIS has the highest efficiency among all thin film technologies, and it is therefore likely that the technology uptake will continue to grow quickly. Figure 30 shows indium demand from CIS thin films under different technology scenarios 'wafer', 'technology mix' and 'thin films' (see section 3.2). A CIGS/CIS market share of 20% ('technology mix' scenario) would, in 2050, require 766 tonnes/year of indium which is 130 tonnes more than the total primary supply of indium in 2011. In the 'thin film' scenario, by 2025, PV would require about as much indium as the LCD industry consumes today, implying an additional need of 300 tonnes/year or 50% more than current primary indium production.

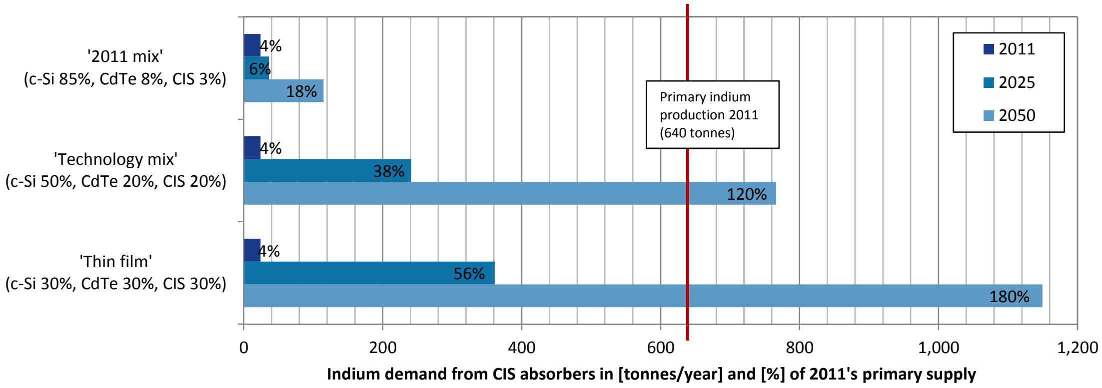

Figure 30: PV industry's indium demand scenarios for indium in CIS thin film absorbers (gallium free)

Source: E4tech/Avalon Consulting

The above scenarios assume that indium is only contained in the absorber layer, and it is worth noting that avoiding indium in thin film TCOs continues to be a high priority. Were ITO be additionally used as the front contact (TCO) in all thin film technologies, annual demand for indium in ITO in 2050 would outgrow 2011's total primary supply even in the '2011 mix' scenario. About 2,500 tonnes/year would be needed to cover the needs of the thin films scenario in 2050. This would require a fourfold increase in current primary indium production just to cover PV's needs. Overall this is unlikely as acceptable alternatives to indium are already being commercialised in the main thin film PV types.

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[39] Calculation based on following parameters: Absorber layer thickness: 1.6 µm; Panel efficiency at STC: 11.5%; Assumption: No indium losses in manufacturing process. Taking into account material yield losses, 52 g of indium per kWp are estimated (US DoE, 2012)

[40] In demand scenarios gallium free CIS is used for calculation. Indium demand for CIGS is about 20% lower than for CIS

[41] Calculation based on following parameters: ITO composition: 90% InO_3, 10% SnO_2; layer thickness: 500 nm; Panel efficiency at STC: 11.7% (typical for CdTe); Assumption: No indium losses in manufacturing process.

[42] Calculation based on following parameters: ITO composition: 90% InO_3, 10% SnO_2; layer thickness: 500 nm; Panel efficiency at STC: 6.8% (typical for a-Si); Assumption: No indium losses in manufacturing process.

[43] Material efficiency in ITO sputtering process is only about 30% if no recovery of indium takes place.

In an environment of constrained indium supply and growing competition from high value electronic consumer products, the thin film PV industry is likely to suffer from its inability to pay much higher prices for indium. Indium material alone contributes already up to 5% to the manufacturing costs of CIGS PV panels[44]. Even at stable indium prices, the cost share of indium is likely to increase as other cost factors are lowered. Reducing the use of indium (and other materials) per Wp is one key element of module manufacturers' cost reduction strategies. An increased indium price may eat up these efforts and threaten the competitiveness of indium-containing PV, which faces intensive competitive pressure from all types of PV. Therefore manufacturers have a limited opportunity to pass on increased cost of indium material supply.

Mitigation

Depending on whether indium is used in the absorber layer (CIGS/CIS cells) or in the front contact (TCO), different technological mitigation strategies to reduce dependency upon indium have been suggested. These are discussed below.

Alternative materials in CIGS/CIS. One approach being pursued by the CIGS/CIS industry to reduce its dependency on indium is to reduce the thickness of the absorber layer while maintaining conversion efficiency. However, prospects are limited since a reduction by factor two appears to be the most optimistic projection (ICEPT, 2011; Fthenakis, 2009)[45]. More promising routes are found by substituting indium (and gallium) by more abundant materials such as zinc and tin, although efficiency loss is still a critical barrier and requires significant R&D effort. In particular, the copper-zinc-tin-sulphide-selenide (CZTSSe) semi-conducting compound has already demonstrated conversion efficiencies up to 10.1% in the laboratory (NREL, 2011), and some CIGS/CIS players are aiming to switch their production lines to CZTSSe in the medium term (Solar Frontier, 2010). The timeline for a complete industry shift away from current indium-based to CZTSSe-based technologies is hard to predict, (Herring, 2012), but could happen within a 10 years timeframe if the indium price increases significantly (PV industry expert, 2012[46]). Knowledge of the actual performances of CZTSSe cells is still very limited, in particular regarding thermal behaviour. Applied research regarding homogenous layer deposition and the right mix of elements that would optimise cost and efficiency is only starting and is likely to take decades (Herring, 2012). While the CIS/CIGS industry is confident that the most significant challenges will be solved in the long run (Herring, 2012), it remains however widely disputed amongst PV experts whether the CZTSSe technology will actually be able to bridge the significant efficiency gap with CIS/CIGS[47] cells.

Recycling of indium from CIGS/CIS. Despite a rapid growth in CIGS/CIS manufacturing capacity, the CIGS/CIS share of the 2011 global PV market was estimated to be only 3% (Mints, 2011). As the technology has only very recently reached commercial stage, recycling methods that recover indium or the indium containing compounds have not yet been investigated in depth (ICEPT, 2011). In any case, recycling would only contribute a minor share to indium supply once CIGS industry growth has picked up, given the long lifetime of PV panels.

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[44] Based on manufacturing cost of US$ 0.92 per Wp (Goodrich, 2012) and an indium input of 52 mg/Wp (US DoE, 2012) and an indium price of Based on US$ 785 / kg (Spot price on 31/12/2011, www.mineralprices.com/)

[45] From 1.6 micrometers in 2008 to 0.8 micrometers in 2020+

[46] Information gathered through interview with key individuals from the industry who wished to remain anonymous.

[47] Best research cell efficiencies: CIGS/CIS 20.3%; CZTSSe: 10.1%

Reducing indium use in ITO based TCOs. It is considered that the ITO conductive layer cannot be reduced any further as it would result in lower conductivity and hence lower cell efficiency (Boydell, 2012; Ballif, 2012; Varema, 2012). A similar 'non-solution' is to improve the utilisation efficiency during TCO deposition. Although there is room to significantly improve material utilization as only about 30% of the ITO material is actually deposited on the target substrate (ICEPT 2011), this would however not alleviate the indium supply issue, as most of the 70% of indium that is currently wasted during the process is already being collected and reprocessed (USGS, 2009)[48].

Replace indium in TCOs for PV applications. Several options to fully replace ITO by more abundant materials are available or in the development stage. The most promising near term solutions are TCOs consisting of doped zinc oxide (typically AZO) and doped tin dioxide (Freundlich, 2008) which are already used in commercially available modules (CIS/CIGS and CdTe respectively), while graphene is also being considered (USGS, 2011), but would only be a long term option.

Alternatives like AZO come with a minor conductivity penalty (Meissner, 2012), but more importantly, their requirements for the encapsulation material are much more demanding when a 20+ years lifetime is aimed at. Compared to ITO, AZO typically requires an up to 25 times less permeable encapsulation to protect from moisture and oxygen (Coyle, 2011). As long as modules are sandwiched between glass (or glass and aluminium foil), the barrier is sufficient to use AZO. Glass free, light weight and flexible thin film modules would however require a high barrier encapsulation material, typically based on several consecutive layers of sputtered oxides (e.g. SiO_2, Al_2O_3) and polymers (Fahlteich, 2010). Those special materials are not expected to become competitive with glass in the medium term (Meissner, 2012), and could thus only be used as a way to mitigate a significant increase in the price of indium. This qualitative trade-off between encapsulation cost and TCO cost is illustrated in Figure 31.

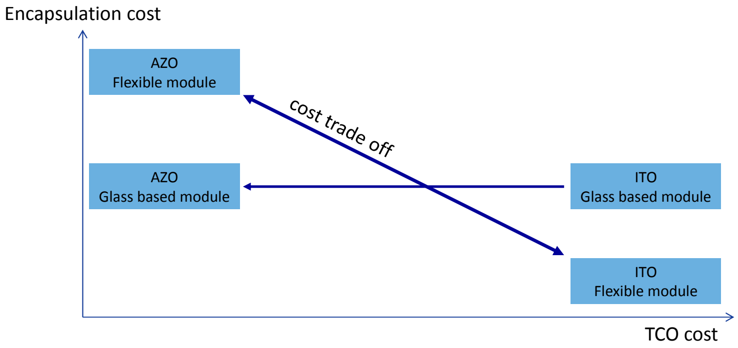

Figure 31: Qualitative trade-off between encapsulation cost and TCO cost

Source: E4tech/Avalon Consulting

Although getting away from glass as an encapsulant has the potential to significantly increase the competitiveness of thin film PV technologies against incumbent crystalline silicon cells in the longer term, the current alternatives to glass are either cheap encapsulants that do require the use of indium-based ITO, or novel TCO materials such as AZO but with the need for expensive encapsulant. R&D efforts are thus required to reduce cost.

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[48] 85 to 93% of the wasted indium can currently be reprocessed and be reused a secondary indium

Recycling of indium from ITO. Indium recovery from ITO deposition equipment is common already and is the major source of secondary indium supply. Contradictory views of the recycling potential of indium or ITO from end-of-life LCD displays are presented in literature (Graedel and Erdmann, 2012; ICEPT, 2011)[49]. Even though take back schemes for consumer electronics such as flat screen televisions and monitors are in place in most countries, consumer reluctance is still a barrier to high return and recycling rates (EPA, 2012)[50]. Furthermore, recovery of indium from end-of-life products is still in the research and development stage (Itoh and Maruyama, 2011). It should be kept in mind that indium recycling from PV panels would not contribute significantly to the indium supply in the next decades, given the strong growth of the PV sector and the long lifetime of PV panels (Boydell, 2012).

Recommendations

Substitution of indium in CIGS/CIS absorbers	
Policy	Provide targeted funding to support research and development activities that focus on the efficiency improvement of CZTSSe absorber based solar cells
Industry	Conduct feasibility studies on the transition of CIGS/CIS production processes towards indium free CZTSSe and invest in pilot production lines for CZTSSe
Recycling of indium from CIGS/CIS	
Policy	Enforce increased efforts in recycling and recovery of indium (and other materials) through including PV in electronic waste regulations such as the WEEE
Industry	Develop indium recovery processes for CIGS/CIS PV panels
NGOs	Monitor PV industry's commitment to recycling-friendly product design to reward manufacturers that implement best practices
Replacing indium in TCOs for PV applications	
Policy	Provide targeted funding to support research and development activities that focus on high barrier encapsulants and cost reduction of their production processes (this can enable the use of indium free TCOs in flexible modules)
Industry	Cost reduction of high barrier encapsulates to enable the use of indium free TCOs in flexible modules Conduct sensitivity analysis of the cost factors indium and encapsulant to define a critical indium price in the framework of a long term technology strategy

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[49] Medium low recycling potential for monitors, televisions and computers (Graedel and Erdmann, 2012), up to 92% from LCDs (ICEPT, 2011).

[50] According to the EPA, only 8% of end-of-life cell phones were collected in 2009

Recycling of indium from ITO	
Policy	Introduce and/or ensure the effectiveness and widespread use of free-of-charge take-back schemes for consumer electronics in which ITO is used (LCDs) Provide targeted funding to support research and development activities that focus on indium or ITO recovery from TCOs in LCDs
Industry	Invest in IP or start-ups that develop processes for indium recovery from TCOs (e.g. in LCD displays)
NGOs	Launch campaigns that inform consumers about return of end-of-life products Monitor PV industry's commitment to recycling-friendly product design to reward manufacturers that implement best practises

5.4.4 Technical, commercial and regulatory barriers to grid access for PV projects

Certainty over grid connection is a key factor in investment decisions for PV projects. Grid connection may be unsuccessful due to administrative and regulatory barriers, grid capacity limitations or technical grid connection issues.

Grid capacity limitations. Today's grid infrastructures were built to dispatch the electricity produced by large centralized power plants. Grid reinforcement is often needed at an additional cost which no one wants to pay for, thereby impacting the economic viability of PV projects. This is particularly the case for remotely located small capacity PV systems where grid upgrades can result in very high cost per kWh transmitted due to low utilization. Within Europe as a whole, the transnational electricity network is not sufficiently developed to sustain a large penetration of solar PV (ECORYS, 2010).

Technical constraints to decentralised generation. A large-scale introduction of decentralized generation may result in bi-directional power flows and complex reactive power management issues. This can lead to thermal management issues and instabilities in the voltage profile, with potentially severe consequences on the grid safety and reliability (ECORYS, 2010). In connecting PV generation systems to the grid, utilities are concerned about overheating, voltage rises, harmonics and unintentional Islanding.

Administrative and regulatory barriers. Country or even utility specific regulations make applications for grid connection challenging. In particular, insufficient legal provisions favouring renewable energy systems often mean that grid operators refuse the connection of (utility scale) PV systems onto the grid, even if technical requirements are met (ECORYS, 2010). In addition, long lead times for grid connection increases the risk for investors.

Assessment

At a global level, unlike wind, intermittency of power production is not a major structural issue in solar PV. This is because in most of the high solar potential regions (e.g. Sun Belt), the peak production (typically 12 – 3 PM) also corresponds with peak demand due to operation of air conditioning etc. The supply demand mismatch is more of an issue only in intermediate and low solar potential regions (e.g. Northern Europe) where electricity consumption peaks in winter evenings.

Grid capacity, availability and technical connectivity are region- or country-specific and are therefore not global issues as such. Many established PV markets provide or even guarantee grid connectivity. However, local grid capacity is a growing area of concern in high solar penetration markets (e.g. South East Germany where 1 GWp per 1 million inhabitants has been reached in the Passau area). A severe lack of grid access is likely to occur at a regional level and may have a significant impact when specific projects fail to get off the ground.

Amongst the technical issues faced by the grid in regions with high PV penetration are both the voltage and the temperature rises. The voltage rise is faced even at low PV penetration levels and is already a problem in many medium-high deployment regions (Premm, 2012). Voltage rise is a function of distance from the interconnection point. The cable and transformer heating issues are expected to become critical at higher levels of penetration (Figure 32).

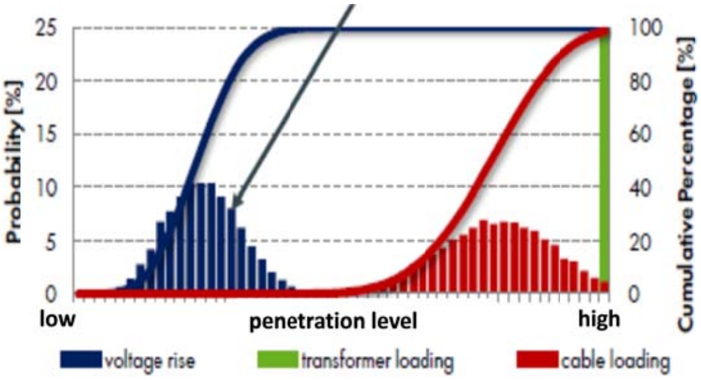

Figure 32: Probability of occurrence of various faults in the grid with increasing levels of penetration of distributed PV

Source: Premm (2012)

Additionally, in many of the high solar potential regions, like North Africa, India, South East Asia or Latin America, the grid itself needs to be enhanced to cover more human settlements as well as generation locations. Alternatively, local mini-grids need to be set up in remote locations to absorb and supply power to small local communities (EPIA, 2010). Thus, grid connectivity may actually also impact PV penetration on a global level if major future markets such as China and India fail to overcome grid connection issues.

Administrative and regulatory barriers vary significantly between and within countries, but these are diminishing as PV becomes more widespread and best practices are shared.

Mitigation

Grid capacity and technical barriers. Smart grid technologies are widely recognized as being a cornerstone of the technical solution that will enable large-scale penetration of renewable electricity (ECORYS, 2010). In this sense, measures to accelerate deployment of those smart grid technologies which enable the integration of decentralized power generation and a two-way distribution of electricity will contribute to accelerate uptake of PV. PV inverters are becoming especially important in smart grids by supplying reactive power, managing voltage fluctuations and reducing harmonics issues (Premm, 2012)

In this regard, specific technical solutions to overcome grid capacity limitations include the following:

- Choosing alternative grid connection points, preferably closer to the generation point. Technical guidelines defining the requirements for the interconnection of generating plants can be standardized globally
- Splitting output over more than one grid access point
- Reinforcing local electricity grids to increase capacity
- Using appropriate inverter and filter selection to reduce issues related to harmonics

However, smart grids should not be considered to be the unique and universal solution. Grid reinforcement through technical equipment or new transmission lines will also be needed, in particular in remote areas lacking suitable grid infrastructure.

Administrative and regulatory barriers. National and regional governments can play a strong role in designing appropriate framework conditions to facilitate grid connection for PV installations, in particular they could consider:

- Reducing the complexity and lengths of grid connection procedures.
- Creating transparency regarding cost sharing arrangements for grid connections (EPIA, 2009).
- Establishing clear and strong regulations regarding the obligation for grid operators to connect PV systems (e.g. up to a certain rated capacity), associated with an efficient system of sanctions in case of violation of such obligations (ECORYS, 2010).

Recommendations

Defining grid and grid connectivity standards	
Policy	Enable global dialogue between equipment manufacturers, utilities and regulators to evolve standards
Industry	Initiate global dialog on best practices and evolve standards
Reducing the complexity and lengths of permitting procedures	
Policy	Ensure that regulators facilitate permitting of PV projects through reducing administrative cost, burden and lead time
Industry	Utilities should proactively take steps to improve lead times and simplify procedures for obtaining permits

Guaranteeing sustainable levels of financial support	
Policy	Provide transparent long term outlook on incentives to support infrastructure creation and also encourage developers to take up additional investments if required
Creating transparency regarding cost sharing arrangements for grid connections	
Policy	Ensure that regulators provide clear guidelines regarding cost sharing for additional investments in case of additions required in the grid
Establishing clear and strong regulations regarding the obligation for grid operators to connect PV systems	
Policy	Ensure that regulations are in place that force grid operators to connect PV systems, and that exclusions from the obligation are clearly defined and monitored

5.5 Medium criticality bottlenecks

5.5.1 Capital intensity of solar grade silicon production for c-Si PV

Silicon is the second most abundant element in the earth's crust[51]. Despite this virtually endless raw material potential, the solar industry witnessed a major shortage of solar grade silicon in the years 2007-2008, as PV demand outgrew the availability of high quality silicon which until then had been mainly sourced from 'scrap' from the semiconductor industry. This caused severe disruption to the entire PV supply chain. Large high grade silicon (known simply as 'grade' silicon) manufacturing capacity has been ramped up since, mainly in Asia, and current global supply can now be considered secured for at least up to 2013-2014. The silicon bottleneck is thus over for now. However, to meet the deployment targets in the IEA BLUE Map Hi REN, significant investments and capacity addition will be required in the long term perspective towards 2050.

Assessment

The production of silicon, be it metallurgical, solar or electronic grade, is highly capital intensive. A facility with 10 kilo tonnes yearly output, which would enable the production of 1.4 GWp of c-Si PV modules, requires an investment of about US$ 1 billion (Chemicalstechnology.com, 2011). The set-up of new grade silicon production lines takes about 3 years which makes investments even more risky given the uncertainty in the current subsidy-driven demand for PV (Chemicalstechnology.com, 2011).

Given the risk structure of this business, it is not surprising to see that the global solar grade silicon industry is concentrated among 10-15 very large players, in sharp contrast to the several hundred module manufacturers downstream. The small number of players combined with the high capital intensity and high risk of the sector makes the PV industry particularly vulnerable to this segment of the supply chain.

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[51] Georgia State University http://hyperphysics.phy-astr.gsu.edu/hbase/tables/elabund.html Accessed 9 Dec 2011

Although there is currently no reason to fear a silicon bottleneck within the foreseeable future, grade silicon manufacturing remains one of the potentially most vulnerable steps in the c-Si supply chain as supply constraints might find their origin in the availability of capital and risk appetite of the investors for individual projects.

The larger and the more mature the PV market becomes globally, the more capable it will be to both anticipate a possible solar grade silicon shortage and ramp up new production capacity, and the smaller the impact of delayed construction of individual silicon plants.

In summary, silicon bottlenecks are going to be difficult to predict but could potentially occur between 2020 and the outlook horizon of this study (2050). Their impact on the c-Si PV sector will taper off over time as the effect of a given quantity of supply shortage will be a declining percentage of total capacity.

Mitigation

Solar grade silicon manufacturing is highly complex and thus benefits from large economies of scale, which makes it an intrinsically capital intensive sector. There is therefore not much scope to reduce capital intensity. Strategies to reduce the probability or the severity of future silicon bottlenecks are thus to be found outside the silicon industry. The main mitigation measures to consider are the following:

- Any measures that ensure strong and predictable growth for the PV market would lower the risk perceived by financiers and corporations that might otherwise prove reluctant to invest in a high risk capital intensive sector. Predictable, long-term incentives such as robust feed-in tariff schemes typically encourage market growth.
- Recycling of solar grade silicon could potentially contribute to supply which would create a buffer in the demand for silicon produced from raw materials in the future. Wafers contained in of end-of-life PV panels reaching the recycling market now and in the years to come contain thicker wafers than the currently produced wafers. To some extent this relationship can reduce the mismatch between the lower number of incoming end-of-life wafers and the current and future production of new wafers. Further development of recycling technologies and building of large scale silicon reprocessing plants is however needed.

Recommendations

Ensuring long term growth predictability of the PV sector	
Policy	Ensure that newly introduced incentives supporting PV deployment aim at moderate but continuous growth to avoid overheating of the market and create confidence in long term investments
Industry	Smaller module manufacturers which lack the size to vertically integrate silicon processing in their business can team up with other companies and build consortia that either invest in silicon capacity or jointly sign long term contracts with silicon suppliers to lower their risk in longer term investment.

Increasing recycling of wafers and recovery of silicon	
Policy	Introduce and ensure the effectiveness and wide application of free-of-charge take-back schemes for end-of-life PV panels, including inducement to recovery silicon instead of disposal
Industry	Improve recycling-friendliness of PV modules, e.g. through the use of lead free solders Invest in recycling technology and facilities capable of recovering silicon from end-of-life modules
NGOs	Monitor PV industry's commitment to recycling-friendly product design to reward manufacturers that implement best practices

5.5.2 Potential restrictions on CdTe PV from hazardous substances regulations

Worldwide, different regulations restrict the use of hazardous materials. The potential risk related to the use of cadmium, a toxic heavy metal, in PV has long been discussed. The cadmium-telluride (CdTe) PV technology contains about 74 g of cadmium per kWp[52]. To a much lesser extent (~0.2 g/m²) cadmium is also used in the CdS buffer layer of the CIGS/CIS PV technologies (EAGLABS, 2009).

The risk of cadmium release into the air or water during manufacturing and usage of the module has been investigated for many years (NREL, 1998). While the release of cadmium during production and recycling (if modules are collected properly) can be controlled, a release during the use phase of the modules is subject to less predictable risks. Although the cadmium is sealed between two glass plates and cannot reach the environment during standard operation conditions, it may be released during extreme conditions such as fire. However, it has been shown that under typical residential and commercial fire conditions (1,100°C) the top and back glass plate of the CdTe modules melt together quickly enough to retain 99.96% of the cadmium inside the module (Fthenakis, 2005).

Assessment

No restriction on the use of cadmium in PV modules has been enforced to date. In Europe, which is currently the largest PV market, the EU RoHS Directive[53] restricts the use of six hazardous substances in electrical and electronic equipment, including lead, mercury and cadmium , but PV modules have so far been exempted, even in the 2011 revision of the Directive.

RoHS regulations are nonetheless revised periodically, which means that a potential future ban or restriction on the use of cadmium in PV is always possible, which could seriously hamper the deployment of the CdTe technology in given regions. This could impact overall PV deployment, depending upon the future market share of cadmium-containing technologies and the ability and pace of the market to switch to alternative technologies. Given sufficient lead time, however, it is

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[52] Calculation based on following parameters: Absorber layer thickness: 3 µm; Panel efficiency at STC: 11.7%; Assumption: No cadmium losses in manufacturing process.

[53] Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment 2002/95/EC

unlikely that removal of CdTe as an option from the EU market would make a significant impact as numerous alternative PV technologies exist.

Mitigation

Several alternatives have been suggested to replace cadmium in the CIGS/CIS cells (Hariskos, 2005), but are still in the research and development stage. The situation is different for CdTe cells, given that this technology is based on the use of cadmium as the semiconductor compound CdTe. The use of cadmium could however be further reduced by decreasing the thickness of the absorber layer. While the physical limit is 0.5 µm (NREL, 1998), the technical potential of reducing the layer thickness is forecast at 1 µm in the most optimistic case (Fthenakis, 2012). However, a reduction of cadmium use would not address a potential ban.

Recommendations

Switching to alternative materials in CIS/CIGS technology	
Policy	Provide clarity about intentions to change cadmium legislation and provide support for R&D into alternatives for CdS buffer layer
Industry	Conduct R&D into alternative materials
Preparing for a potential ban of cadmium in PV panels	
Policy	Provide clarity about intentions to change cadmium legislation
Industry	Prepare contingency plans for technology choices in EU if intentions are signalled by policymakers

5.5.3 Insufficient skilled personnel for PV installation

Through the introduction of incentives, policy makers have the power to establish new PV markets overnight. PV modules and related system components are available on the global market and supply can respond to abrupt demand changes in individual countries quite quickly. However, the lead time to train the local labour force for planning and installing PV systems is typically much longer and can take several years. Without careful planning this can result in a shortage of personnel required for an accelerated deployment of renewable energy. Even with engineers and technicians on the labour market, project developers report that their growth has sometimes been slowed down because potential candidates consider traditional sectors such as the automotive industry to be more attractive than the PV sector, which is seen as more volatile due to changing incentive policies (Weindl, 2012).

Assessment

The PV industry considers the lack of qualified professionals as one of the most significant mid- and long term challenges (EPIA, 2009). A lack of trained installers and system planners may significantly delay PV deployment at a regional level. Should no proactive measures be taken to anticipate a rapid demand increase for skilled resources resulting from new government PV incentives, the deployment curve of PV could lag several years behind the actual demand curve (Meissner, 2012) –

equivalent to an approximate cumulative global shortfall of several tens of GW by 2020. A delayed start cannot easily be compensated by faster growth.

Furthermore, if appropriate training is not secured or if certification systems are not in place to reference qualified professionals, the deployment still occurs but through unskilled resources, which has already resulted in poor quality installations in some locations (e.g. sub-optimal orientation and system sizing, poor fixing). Although difficult to assess quantitatively, this does impact on the total electricity output per kW installed, as well as on the lifetime of the installed systems. Poor quality installations also affect the image of PV, which has a ‘boomerang effect’ on demand (Closset, 2012) and can disrupt an entire PV market (Martin, 2012). Such issues have been largely observed in Southern European markets, but also, to a lesser extent, in regions such as Germany and Switzerland which are normally known for their high quality standards (Closset, 2012; Martin, 2012).

The situation differs significantly between emerging and established PV markets. In emerging markets, the skillset and experience required for PV system planning and installation is naturally more scarce, while competition for the workforce can be an additional hindrance. In established markets, the skills and expertise are in principle available, but competition among PV companies as well as with other industry sectors may hamper hiring.

A notable exception is know-how in DC wiring of PV systems, which is novel even for engineers (Hengerer, 2012). The DC part of a PV system requires most attention and care from specialists as failures can be fatal (Martin, 2012). Through the guidance of senior team members, established companies are able to convey such knowledge and skills to new hires ‘on the job’ (Weindl, 2012). In contrast, small and start-up companies often seek qualified workers with previous experience in the PV sector to build up internal knowledge. However, in an overheated PV market, as observed in Germany in the past three years, recruiting of more experienced people has proven very difficult for small players (Martin, 2012).

In emerging PV markets where PV incentives are new and regulations are not yet well framed, expertise in system planning and installation is naturally scarce. For instance in Canada in 2009, a labour shortage was identified of around 78% for installation and 51% for design and integration, while the main professional-level shortages were in project management (40%), and engineering (40%) (EDCTEO, 2011). PV companies that are based in a robust core market (e.g. Germany), could - in the past - afford to start branches in neighbouring countries and accept longer lead times while building up local knowledge (Weindl, 2011). In contrast, it is very difficult for local start-ups to achieve a sustainable growth when long term dependability of incentives (e.g. feed-in tariffs) is not given.

Mobility of human resources from established markets to emerging markets is quite low for PV technicians, who are less open to accepting positions in foreign countries than industry specialists and academics (ENN, 2008; Martin, 2012). In addition, local standards and regulations may be highly country specific and knowledge of local language is a pre-requisite to understand these and the requirements of local utilities, even in harmonized markets such as the EU (Martin, 2012). Therefore the overall potential of increasing the mobility of skilled workers from developed PV markets is rather limited.

Mitigation

Knowledge and experience are not scarce in principle, but to a large extent concentrated within the main developed PV markets. Several measures are suggested to secure the supply of skilled human resources, ranging from inter-country exchange of expertise to launching of local educational programs, and from adapted product design to vertical integration.

Inter-country exchange of and knowledge through intensive training courses. In order to sustainably mitigate a labour shortage, only local education programs offer sufficient relief. Teaming up with foreign experts to set up professional exchange programs can speed up knowledge transfer. Since overall capabilities are in principle available, but inadequately distributed, developed markets can help emerging markets through sending experts to trigger the local training or temporarily work abroad. Companies active in both established and emerging markets already transfer knowledge internally, which gives them a competitive advantage (Weindl, 2012; Martin, 2012). PV companies, even with modest budgets, can create internal photovoltaic academies so that the workforce can constantly receive training and updates on legal, technical or technological fields (Martin, 2012). To also give small companies access to foreign experts, industry associations, e.g. EPIA, could act as a coordinator by teaming up with regional associations (Closset, 2012). In addition, the harmonization of regulations and standards internationally would make the transfer of know-how much more efficient (Martin, 2012).

***Launch of training programs aligned with renewable deployment targets*.** Education programs for renewable energy engineering and management on all levels (vocational schools and academia) can help to mitigate shortages in the medium and long term. The industry suggests that adapted policies regarding education and training are put in place (EPIA, 2009). New programs should focus on the most recent technological developments, safety, regulations and smart grid systems (Martin, 2012). A dual system of vocational training (e.g. as in place in many sectors in e.g. Switzerland, Austria, Germany) should be favoured since it enables mobility between academia and vocational schools (Hengerer, 2012). Concerted planning of education programs and the launch of PV incentives is required to avoid a lag between labour demand and release of first graduates to the labour market. In Austria, for instance, a new study program specifically designed for the PV industry was launched while European PV markets were booming. However, the first batch of graduates entering the labour market in 2012 now faces a phase of industry consolidation (Meissner, 2012).

Planning dependability and design of incentives. Introduction of generous feed-in tariffs followed by abrupt cuts later on have discredited the long term dependability of the PV sector. This is one major reason why talented professionals may prefer a traditional industry sector such as automotive over PV. For a continuous and smooth growth of the PV sector, newly introduced incentives should therefore rather aim at moderate but continuous growth to avoid overheating of the market. A stable industry perspective may ultimate attract more highly skilled professionals. Another related factor is whether or not an incentive rewards system optimization. In markets where PV systems are incentivised exclusively through upfront subsidies, companies are often not encouraged to build knowledge about system optimization and grid connection, which can result in lower performance (Closset, 2012). Policy incentives should therefore always include rewards for the actual electricity generation (e.g. through feed-in tariffs) rather than capacity installation. This forces project developers and installers to optimize systems and ensure quality of installation. This in turn improves the overall skill levels available to the PV sector.

Overall it is worth noting, that with the slow disappearance of feed-in tariffs as PV has begun to reach grid parity in many regions, demand in emerging markets is likely to ramp-up more smoothly than the booming markets triggered in the past by generous government incentives. This would also give more time to the market to equilibrate supply and demand for labour (Closset, 2012).

Installation-friendly design of PV systems ('plug & play'). Another way to approach the lack of skilled workforce is to work on the installation-friendliness of PV systems, so that a less specialized work force can conduct installations. 'Plug & play' may be a future key selling proposition which the PV industry is already aware of. Hence, the industry has already embraced this challenge (Hengerer, 2012).

Vertical integration of PV companies downstream*.* Vertical integration downstream is one way for module manufacturers to gain control over quality of installations. It can also be of interest in order to profit from higher margins in those segments of the value chain. Module manufacturers are keen to have the final assembly done in key target markets and thus participate in the local training of personnel (Hengerer, 2012). For established PV companies that are already vertically integrated from distribution down to planning and installation, expanding the distribution channels to new markets has proven to be a quick route to internationalization. Knowledge about local regulations and specialities evolves gradually and the local branch can launch activities further downstream the value chain step by step (Weindl, 2012).

Recommendations

Inter-country exchange of knowledge through skills transfer	
Industry	Develop emerging PV markets by establishing skills transfer mechanisms
Policy	Provide support for outward and inward skills transfer
Providing education and training programs aligned with renewable deployment targets	
Industry	Work closely with policymakers to predict skills needs and develop skilled personnel in line with requirements
Policy	Work closely with industry to understand needs and develop appropriate education
Providing incentives for PV deployment to create smooth growth	
Policy	Consider the need for smooth and sustainable growth in creating policies to support PV
Designing installation-friendly PV systems	
Industry	Consider skills aspects in product design, in particular through provision of more 'plug and play' type systems

5.5.4 Time consuming and uncertain permitting procedures for PV projects

Administrative processes related to the permits for a PV system can be a serious challenge for PV project developers. Delays and uncertainty expose the developer financially, which means that investment suffers, which in turn creates uncertainty along the supply chain about the strength of the market. Examples of these barriers are the administrative processes required to secure building permits, spatial planning, electricity production licenses or environmental impact assessments. They become a serious burden when they are opaque, overly complicated or progress slowly. In the case of residential rooftop PV systems, administrative processes can create excessive burdens for private households and thus may prevent the residential rooftop PV market to develop at all (EPIA, 2012a).

Assessment

In some EU countries these issues can be traced back to a lack of training and availability of public officials, the necessity to contact and deal with a multitude of public authorities, as well as legislation that neither favours nor takes into account the specific nature of PV installations. Other markets with a longer track record of PV installations (e.g. Germany, Portugal), have simplified administration for small scale systems (EPIA, 2012a).

PV permitting barriers vary significantly between jurisdictions. Another key factor is the infancy of most PV markets. This means that the severity of this bottleneck varies significantly between countries. In the *PV Legal* project, several European countries were assessed regarding permitting of PV (EPIA, 2012a). Figure 33 highlights the substantial waiting times in many countries. These can have severe implications for PV developers and their investors, which creates negative feedback along the supply chain.

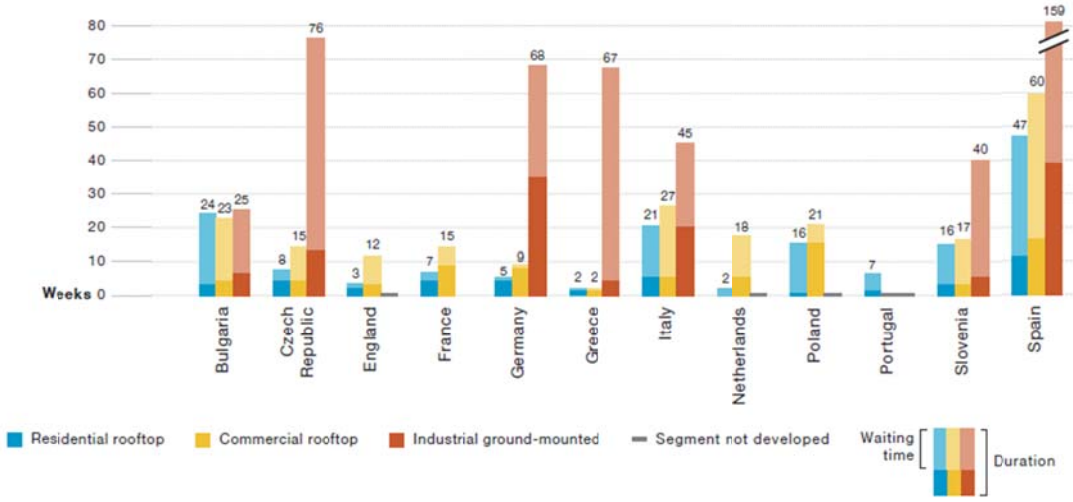

Figure 33 –Cumulative average durations of PV project permitting processes for different EU countries

(Source: EPIA, 2012a)

The often substantial time spent on administrative permitting processes reflects the difficulties that many public authorities have in dealing with the requests for PV system permits. These difficulties are rooted in staffing and capacity issues, lack of training, and/or complicated procedures that have to be followed.

Mitigation

National and regional governments can play a strong role in designing appropriate framework conditions to facilitate the permitting of PV installations.

***Design and enforce lean and appropriate permitting procedures*.** This will reduce the burden on PV developers and public administrations alike. It is important to differentiate requirements for residential rooftop and large scale ground mounted systems. Additionally, permitting procedures should have a clearly spelled out legal grounding so that administrative bodies have limited discretionary authority and the outcome of the permitting process is more predictable or can be challenged in independent courts (EPIA, 2012a).

***Create a "one-stop-shop" approach*.** This would reduce the number of public bodies to be contacted and involved and drastically reduce the administrative burden for project developers. An example of good practice is found in Portugal, where all permitting procedures for residential rooftop installations are handled online by a single authority (EPIA, 2012a).

***Design and adhere to "hard deadlines"*.** Deadlines for different stages of the permitting process help to make them more transparent. Deadlines with associated compensation payments to PV developers may help to create more confidence that they will be met (EPIA, 2012a).

Recommendations

Creating and enforcing appropriate PV permitting processes	
Policy	Design and enforce lean and appropriate permitting procedures Create a "one-stop-shop" approach Design and adhere to "hard deadlines"

5.6 Low criticality bottlenecks

5.6.1 Lack of distribution channels for PV in future growth markets

So far the main PV markets have been concentrated among a few countries in Europe, as well as in Japan and North America. Module manufacturers and suppliers of balance of system components have built up distribution networks in these countries driven mostly by feed-in tariff schemes. A lack of subsidy-driven market pull for PV in new market regions, in particular in those sunnier regions where PV has a large deployment potential but where the capital barrier is high (e.g. North Africa), may hinder the pace of development of distribution channels and the creation of proper market structures.

Assessment

Distribution channels are lacking in countries that have a limited track record of PV incentives and/or deployment. Consequently, it is considered a potential bottleneck which may delay large scale deployment at regional level. On a global level, the impact can however be considered minor.

Mitigation

National programs to support the uptake of PV can pave the way for foreign PV companies to enter and local organizations to develop. Where the cost of PV electricity would not yet be at grid parity or where the capital barrier is too high, country specific subsidy schemes such as feed-in tariffs or buyer incentives may be needed to overcome these barriers.

Recommendation

Developing PV markets through roadmaps and subsidies	
Policy	Announce incentives and roadmaps for PV energy development in advance to give PV manufacturers time to plan distribution networks

5.6.2 Lack of appropriate solutions for dust removal from PV modules

Since most PV deployment to date has been concentrated in the temperate climatic zones of Japan, Europe and North America, dust deposition on module surfaces has not been a significant consideration so far. However, moving PV deployment to the drier regions of the globe will require the sector to address this challenge cost-effectively. Studies of PV systems in the Middle East, India and Southeast Asia have shown that dust deposition can lead to a significant drop in performance depending upon the kind of dust - finer dust is more critical than coarser particles - and geographical factors such as frequency and intensity of precipitation *(Mani, 2010)*.

Assessment

Although panel cleaning has not been observed as a bottleneck to PV deployment so far, it may potentially occur due to one or more of the following issues:

- lack of appropriate semi-automated cleaning equipment
- unknown manpower costs over lifespan of PV systems
- difficulties in sourcing softened water in Sun Belt regions.

Should cleaning be required on a regular basis (weekly or monthly), maintenance costs over the module lifetime are currently difficult to estimate and increasing the perceived investment risk. From today’s perspective, this issue is, however, likely to have only a minor impact at a global level. As a rule, the higher solar irradiation in sunbelt regions may offset performance losses to a certain extent.

Mitigation

Due to underdeveloped PV markets in potentially affected countries, field studies that quantify the impact are still lacking. Technological solutions to decrease the impact include special coatings for solar PV modules designed to reduce dust accumulating and increasing the effectiveness of rain washing, but further research and development in this area is still required.

Recommendation

Research on the impact of dust accumulation and technological solutions	
Industry	Conduct research on impact of dust on PV modules and investigate cost-effective technical and manual alternatives. Sponsor research on technologies to reduce the impact, e.g coatings

5.6.3 Insufficient PV module take-back schemes and recycling processes

Module take-back and recycling will be key to achieving long term sustainability in the PV sector, and may become a regulated requirement. Currently the first generation of modules deployed at large scale are still in the middle of their product life span. Large quantities of end-of-life modules can be expected from 2020 onwards. In principle, the amount of take-back modules will be a function of the rate of installations and so corresponding recycling capacities will be needed.

Assessment

A lack or absence of take-back schemes of end-of-life modules would ultimately make the apparently “green” PV technology unsustainable by creating an ever growing amount of waste and depleting limited raw materials included in these wastes which in turn increase the pressure on material bottlenecks (see 5.4.1, 5.4.2 and 5.4.3).

Potential bottlenecks may derive from:

- Insufficient take-back schemes (free of charge demounting and transport) and reverse logistics.
- Poor economics of recycling based on current technology and lack of appropriate recycling capacity.

Take-back schemes and reverse logistics are mainly a question of regulation. While the PV industry in the EU has historically been exempted from the Waste Electrical and Electronic Equipment Directive (WEEE) Directive[54], Solar modules were included in the Directive in January 2012 (EU Parliament, 2012) and EU member states will now transform this into national legislation.

For the past four years, the PV industry had hoped to escape from legal obligations and instead worked on a voluntary take-back scheme. Most European manufacturers have joined the PV Cycle[55] organization which aims to build up reverse logistics and recycling plants. PV Cycle originally planned to accept modules from any manufacturer, but the long term financing of the programme has proven difficult to agree on.

Thanks to enforcement of strict obligations in today’s major markets, and due to the (usually rising) value of materials incorporated in modules, it can be expected that on a global scale take-back schemes will be in place in most regions by the time large quantities of end-of-life modules come on the market. However, a lack of reverse logistics may have a significant impact at a local level.

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[54] European Community directive 2002/96/EC on Waste Electrical and Electronic Equipment Directive

[55] http://www.pvcycle.com

Due to limited quantities of end-of-life PV modules, dedicated recycling plants are not yet commercially viable. Automated plants can be viable at 20,000 tonnes per annum capacity (Choi and Fthenakis, 2010). In the near future Europe is likely to see a rise in end-of-life PV modules from 7,700 tonnes in 2010 to 132,000 tonnes in 2030, making automated plants potentially viable if sufficient panels can be treated at a single plant.

Pilot facilities for recycling of panels are found in Germany (CdTe in Frankfurt, and c-Si in Freiberg). The process of recycling c-Si modules includes the burning of plastic components in a semiconductor-protecting process at 600°C, whereas remaining materials such as solar cells, glass and metals are separated manually and recycled conventionally. New solar cells are re-etched to recycled wafers, but damaged cells with edge chippings or micro cracks can so far not be remanufactured, limiting the recovery rate. In addition, the thickness of the original wafers influences the recovery yield; wafer thicknesses of 400 μm allow for recovery of up to 76% while an original thickness of below 200 μm is currently not providing an economic recovery yield (GFMENCNS, 2007).

A lack of economic raw material recovery technologies potentially could, in the long term, have an important impact on raw material supply, especially that of the rare metals (Table 4).

Material	C-Si	Thin Film		
		a-Si	CdTe	CIS/CIGS
Glass	74%	86%	95%	84%
Aluminium	10%	<1%	<1%	12%
Other components (incl rare earths)	16%	14%	4%	4%
Other key materials within other components (>1% by overall weight)	EVA, Tedlar backing film, silicon, adhesive	Polyol, MDI	EVA	EVA
Rare metals included	silver	indium, germanium		indium, gallium

Table 4: Key materials used in a typical PV module (in weight %)

Source: ECDGEnv (2011)

Mitigation

For a sufficient supply of end-of-life PV modules for recovery, co-ordination between end-user, manufacturer and recycler is required. In markets where regulators do not obligate module manufacturers, the industry could offer free-of-charge take-back schemes voluntarily. In terms of raw material recovery, research and development of recovery processes should be intensified in the medium term.

Recommendations

Encouraging recycling	
Industry	Implement viable take-back schemes to make recycling trouble-free for end-users
Policy	Enforce recycling of PV modules through regulations
NGOs	Build awareness and encourage recycling, especially in case of PV modules
Building reverse logistics and recycling infrastructure	
Industry	Ensure coordination between manufacturer, recycler and end-user; build cross-industry reverse logistics systems
Encouraging recycling research	
Policy	Support R&D into higher yielding recycling technologies

6 Conclusions and recommendations

This study sets out to identify current and potential bottlenecks in the supply chains for wind and solar photovoltaics (PV), in order to inform decision makers about the mitigating actions that are required to meet global deployment targets. Overall the study finds that the supply chains of both wind and PV are currently likely to be constrained by a range of bottlenecks that may critically impact the deployment of these technologies.

6.1 Wind and PV-specific conclusions are discussed in dedicated sections later in this chapter. A number of higher level conclusions can also be drawn, which are discussed first.Overall conclusions about bottlenecks

Number of bottlenecks. A considerable and surprisingly similar number of bottlenecks were identified for the wind and the PV sectors: 14 for wind and 11 for PV. There are, however, few commonalities between the two sectors. The large number of bottleneck in the PV sector is as a result of several different cell technologies, each having its own supply chain and hence its specific upstream supply constraints. The numerous bottlenecks identified for wind reflects mainly the downstream challenges associated with offshore wind deployment.

Commonality of bottlenecks. There are nonetheless three bottlenecks that are common to both wind and PV at generic level, though they differ when specifics are considered. Access to grids, permitting of new installations and availability of suitable skilled personnel are challenges requiring solutions that have some common features across wind and PV, though with careful consideration of their differences.

Type of bottlenecks. Many of the bottlenecks identified are related to supply-demand imbalances (supply not being able to ramp-up at the same rate as fast-increasing demand), while some bottlenecks are due to absolute constraints on material resources, and some to regulation.

Likeliness of occurrence of bottlenecks. Out of the 25 bottlenecks identified in this study, 9 are already being felt or very likely to occur. This underlines the urgent need for mitigation actions, which is strengthened by the fact that 7 of the 9 highest severity issues have a high likelihood of occurrence.

Criticality of bottlenecks. The most critical bottlenecks, i.e. those most likely to occur and capable of showstopper impact at global level, are to be found in the PV sector. These bottlenecks all relate to materials shortages (silver, indium, tellurium), for which alternatives are either unavailable or unproven at industrial scale. Both wind and PV face major bottlenecks relating to grid access and permitting, and wind also faces critical bottlenecks in several vital materials and subsystems.

Time horizon of bottlenecks. With the exception of the lack of take-back and recycling schemes and the unlikely issue of a second shortage of grade silicon, all identified bottlenecks that may hit the wind and PV industries would bite within a 2 to 6 year timeframe, regardless of their nature. Generally speaking, raw material (upstream) bottlenecks seem to be medium term constraints expected to start occurring after 2015, while downstream barriers are, again with the exception of recycling issues, shorter term or even current constraints (e.g. shortages of skilled personnel).

Most short term constraints are related to demand and supply imbalances which, by nature, are difficult to forecast in the longer run. Such supply constraints should normally not last for more than 1-2 years as market dynamics are expected to resolve these, although issues requiring addition of very capital intensive production capacity (large casting and forging or carbon fibre for wind industry) may last slightly longer.

There is greater predictability for physical resources than for personnel, allowing longer term predictions. However, bottlenecks in material availability are likely to manifest themselves through the price mechanism long before being absolute resource constraints, which makes it difficult to predict the time horizon for the occurrence of such bottlenecks. Amongst other factors, this is because of the growing demand from competing industries which often have a general ability to pay higher prices for these rare materials than the wind and solar sectors do. However, it is likely that most resource issues identified would either occur before 2020 or not occur at all, as the industry would already have moved away from these critical materials by then (e.g. silver, indium).

6.2 The need for action

The negative message is that 25 bottlenecks were identified across the wind and PV sectors which could severely constrain the deployment of these renewable energy technologies in the short to medium term.

The positive message is that the impact and the likelihood of occurrence of almost all of the bottlenecks identified can be reduced significantly, if not eliminated, by mitigating activities at policy and industry level. While supply-demand imbalances can mostly be mitigated by ensuring robust long term policies are being put in place that secure demand, most constraints on raw materials can be resolved by switching to alternative more abundant materials.

As discussed above, almost all wind and PV bottlenecks could appear within a 2 to 6 year timeframe, regardless of their nature. Some are actually already being felt today, such as the lack of skilled human resources. The time to act is now, therefore, since many of the mitigating actions involve long lead times.

This report recommends 137 actions, synthesised in appendices 0 and 0, that principally require industry or policy makers, and to a lesser extent NGOs, to take steps in the near term. Immediate steps range from carefully monitoring potential problems, to strengthening existing efforts, or initiating new activities.

6.3 Overall conclusions about mitigation

Type of mitigation actions. Many bottlenecks, in particular those related to supply-demand imbalances and raw material constraints, can be diminished by clarity from policy makers about the intended growth of renewable energy and the frameworks to support this, combined with clear communication of these along the supply chain by industry and policy makers. This will trigger the investments needed at industry level into both additional production capacities and R&D efforts.

Mitigation by location of bottlenecks. The nature of suitable mitigation measures largely depends on their location along the supply chain. Generally speaking, the more upstream a constraint the more global its impact, hence the more relevant an industry-wide technology solution becomes, implying the need for R&D and/or capacity expansion as a mitigation strategy. The more downstream the bottleneck, the more national/regional the impact, hence the more likely that national/regional policy measures may contribute to solving the issues.

Mitigation by nature of bottlenecks. The type of mitigation strategy also depends on the actual nature of the bottlenecks considered. Generally speaking, while regulatory issues or lack of human resources can best be addressed by policy measures, bottlenecks that are related to industrial processes or upstream shortages of materials or components can largely only be addressed by the industry itself (although sectoral measures may help in certain instances). Also, several bottlenecks are found in very capital intensive steps of the wind and solar supply chains so it is crucial to consider how effective measures will be in ensuring that private capital is attracted to the wind or PV industry and their supply chains. Capital risk reduction, by the implementation of long term policies and contracts, is thus a very important mitigation strategy. This will also reduce the need to design 'bottleneck specific' policies, i.e. a separate policy for each problem, as the industry and market will be more prepared to invest.

Importance of demand signals. In every bottleneck in which industry can play a role, mitigation becomes significantly easier if there is a strong demand signal. Industrial actors take investment decisions on the basis of risk and reward, both of which are heavily influenced by policymakers. There is a need for clear, predictable and long term commitments from policy makers, not just financially, but also in terms of sectoral support. Roadmaps and credible targets also assist in this regard.

Generic bottlenecks and mitigation. In addition to the many renewable energy focused mitigation steps discussed in this report, there is a strong role in the wind and PV sectors for all of the disciplines of supply chain professionals. These include risk analysis of geographic pinch points and multi-sourcing where appropriate. 2011 brought strong examples of the need for these approaches when the Fukushima disaster was followed by the floods in Thailand, leaving automotive supply chains particularly disrupted.

6.4 Wind power conclusions and recommendations

The key findings and conclusions for wind energy are as follows:

- Offshore wind suffers from many more barriers to deployment than onshore wind, with 9 out of 14 bottlenecks applying wholly or largely to offshore wind. Only overland logistics problems for large components are unique to onshore wind.
- The shortage of critical materials is very likely to constrain wind energy deployment by the medium term (beyond 2015) if no pro-active mitigation steps are taken. However, none of these are absolute constraints but demand-supply mismatches which can be remedied with planning and capacity augmentation.
    - In the case of carbon fibre, the short-to medium term capacity constraint is driven by low yields in the manufacturing process and the high investment needed in production of the main precursor, Polyacrylonitrile (PAN). Thus, mitigation should involve close collaboration or upstream integration between carbon fibre and PAN suppliers, together with research to develop alternatives to carbon fibre and to

precursors to PAN, as well as on process improvements to minimize losses in carbon fibre manufacturing.

    - In the case of rare earth metals, very strong focus should be placed on developing mining and refining capacity globally, along with encouraging recycling and development of alternatives for permanent magnets. Several new facilities are already being developed and decision makers are recommended to watch these initiatives very closely.

- Wind projects are already being affected by three bottlenecks which will have a severe impact on global deployment levels if not addressed very soon.
    - Two of these, permitting and grid integration of new projects, are delaying the rate at which projects are approved and connected meaning that deployment levels are already being affected. The solution lies largely with policymakers who should create regulatory systems that match their ambitions for wind energy deployment.
    - The lack of production capacity for offshore transmission infrastructure will be an increasing bottleneck over the next 5 years which requires industrial investment now to prevent it having a severe impact. Clarity is therefore needed about the volumes of such equipment that will be required in the coming years, which in turn relies upon policy to a large extent.
- Two further bottlenecks could be severe, though they are less certain to occur in view of the activities that are currently underway:
    - The wind turbine generator manufacturing industry might suffer from capacity shortages for very large cast and forged components in the medium term, as turbine sizes grow. Close collaboration is needed along the supply chain to ensure timely capacity addition, together with R&D into alternative materials and alternative designs to allow large components to be split into sections in the long term.
    - Until recently it was felt that there would be a near term shortage of vessels suitable for deeper water installations. Several such vessels are being built and, combined with recent delays in offshore wind projects, this may allow time for additional capacity to be added before this becomes a bottleneck. Without further capacity additions this bottleneck would severely constrain off-shore wind deployment.
- Three bottlenecks are being felt already, though their severity is lower than those mentioned above as their effect is more localised:
    - The wind industry is suffering from a shortage of skilled personnel in manufacturing, installation, and also operation and maintenance. This is felt most strongly in ‘difficult’ locations (e.g. offshore, remote areas) where the sector has grown quickly from a low base. Rapid training and skills transfer are needed in the near term. Skills planning by industry and supportive education policy are longer term requirements.
    - Port infrastructure to support offshore wind installation is lacking in several countries (e.g. UK, Eastern US) and requires a long term approach by policymakers and industry to ensure that this does not become a greater bottleneck.

    - Overland transportation of increasingly large turbine components is challenging in countries where installation takes place far from ports or manufacturing sites, such as the US. Policymakers can assist by removing regulatory barriers, and industry should collaborate along the supply chain to predict capacity needs for critical equipment.
- Two bottlenecks relating to turbine design may become important on a localised basis if ongoing efforts do not succeed:
    - The lack of wind turbines suited to very cold conditions precludes access to the large wind resource at high latitudes (e.g. Labrador, Scandinavia). Turbine designs are being explored to overcome the challenges, though further research, development and testing is needed.
    - There is no proven solution to radar interference from wind turbines , meaning that projects cannot be placed within line of sight of radar facilities. Technical approaches are being developed and tested to avoid this impact.
- Two bottlenecks were found to be of only minor importance during the preparation of this report:
    - The lack of internationally applicable health and safety design standards already leads to proliferation of specific designs, raising costs and complexity along the supply chain. Some efforts are underway to harmonise standards within Europe.
    - Current approaches to rotor blade disposal and recycling are inadequate, though there is time for research efforts to bear fruit before this becomes a bottleneck.

A table summarising all of the recommendations for decision makers in wind energy is found in Appendix 0.

6.5 Photovoltaics conclusions and recommendations

The key findings and conclusions for PV are as follows:

- Of the 11 bottlenecks identified, 6 are common to all PV types, 2 apply to c-Si PV and 3 to thin film PV. Amongst the showstoppers, there are 2 for thin films and one for silicon.
- Shortages of critical materials (indium and tellurium for thin film technologies, and silver for c-Si cells) are very likely to be showstoppers for PV deployment from 2020 onwards if no pro-active mitigation steps are taken. This is aggravated by increasing demand for these metals from competing industries (e.g. consumer electronics), which generally have an ability to pay higher prices for these materials, unlike the PV sector which faces shrinking margins. Whether alternative more abundant materials can potentially substitute for these standard PV materials depends to a large extent on their actual role in the cells:
    - The critical materials used as conductors in the front electrode, namely indium and silver, can in principle be substituted with more abundant materials. While indium used in transparent conductive oxide of different thin film PV cells has already largely been replaced by e.g. zinc, the replacement of silver used in the conductive grid of crystalline silicon cells is proving more difficult to achieve. Given the lack of

    readily available mitigation against the silver bottleneck and given that silver is used in 85% of the PV panels sold today, the constraint over silver supply can be considered one of the most critical bottlenecks in the PV sector.

  - The critical materials used in the semiconducting layer, namely indium in CIS/CIGS cells and tellurium in CdTe cells, cannot easily be replaced as this would imply changing the very heart of the active photo-electric process upon which these technologies are based. While alternative semiconductors exist for CIS/CIGS which could solve the indium issue within a decade, no substitute currently exists for tellurium in CdTe cells. Both CIGS/CIS and CdTe technologies are likely to face supply constraints and hence higher prices of indium and tellurium in the medium term, unless increases in the supply of these critical materials can be achieved.

- Grid connection of PV systems is already holding back deployment levels and will have a serious impact if improvements cannot be made to grid capacity limitations, technical grid connection issues and administrative and regulatory barriers. Regulation to ease PV connection and enforce the upgrading of grids at fair cost is needed, in conjunction with widespread smart grid infrastructure.

- Two further bottlenecks would have a severe impact were they to occur, though this is not certain:

  - The recent shortage of grade silicon caused a major crisis in the PV sector, but this has been overcome by capacity additions. With clear market demand signals more highly capital intensive silicon production will be planned and brought on stream as demand increases. This bottleneck should not recur under these conditions.

  - A ban on cadmium that would include PV applications has been contemplated in the EU, and could occur elsewhere. Were this to be put in place it would require a significant switch from CdTe PV, which accounts for a significant share of EU supply. This could be achieved, given sufficient lead time, but would be disruptive.

- Two bottlenecks are already being felt, but with a more localised impact:

  - Insufficient skilled personnel are available for PV installation, especially as PV moves to growth markets where sunshine levels are high but skill levels are lower overall. This requires careful skills planning and transfer, supported by education policies.

  - Time consuming and uncertain permitting procedures are delaying the deployment of PV projects in some countries and there is scope for transferring lessons learned in permitting across PV markets.

- A potential bottleneck which only affects some markets is the absence of distribution infrastructures, particularly in developing countries. Long term planning and collaboration between policymakers and industry would allow this to be avoided.

- Two bottlenecks were found to be of only minor importance:

  - The cost of dust removal is already a problem for some PV installations, and this will increase as more sun belt locations are exploited. Research, development and testing of different approaches is required to find a cost-effective method.

  - PV module take-back and recycling is immature and, although development is important to recover critical materials and protect industry image, there is time for ongoing activities to bear fruit.

A table summarising all of the recommendations for decision makers in photovoltaics is found in Appendix 0.

6.6 Recommendations for further work

The work carried out for this study could be used to provide further value, by extending it along one or more of several possible dimensions.

Further examination of bottlenecks in wind and PV. The methodology, existing analyses and contacts network could be used to provide additional value on wind and PV supply chains by, for example:

- Annually revisiting the key bottlenecks to assess whether their criticality has altered in the light of changing demand, supply or mitigating actions. This would require updating the current report or key sections of it such as the criticality matrices.
- Similarly, key indices on e.g. critical materials demand and supply could be published regularly by IEA, for example within IEA Energy Technology Perspectives or as a special supplement to that publication.

Applying the methodology to other areas. The same approach could be applied to new areas, for example:

- Assessing adjacent systems that are relevant to wind and PV supply chains, for example energy storage, smart grids, international shipping.
- Considering other renewable energy technologies such as concentrating solar power, geothermal power and bioenergy.
- Broadening the assessment to include non-supply chain matters such as financing and environmental regulations

Enabling mitigations that are within IEA's remit. Many of the recommended mitigating actions within this study could be assisted by IEA-RETD or other parts of IEA. For example:

- IEA-RETD could provide best practice guides and case studies for policymakers on how to design regulation that overcomes listed bottlenecks, drawing upon the experience of member countries.
- Several recommended industry initiatives require collaboration yet may be held back by concerns about 'prisoner's dilemma' sharing with competitors or 'free riding' by non-participants. The IEA Energy Technology Platform and/or technology-specific Implementing Agreements could use their convening power to draw together key stakeholders in a non-competitive environment in order to address challenges in a mutually beneficial way.

7 Appendices

7.1 Interviewees

The list of sector experts that were interviewed during the course of this project is given below. In addition to that list a further nine interviews were contacted with industry experts, who wish to remain anonymous.

Wind

Axel Braskamp, ABO Wind

Mark Carlson, Badger Transport Inc.

Cash Fitzpatrick, U.S. Department of Energy

Rudolf Hadorn, Gurit Group

Gareth Hatch, Technology Metals Research

Jürg Hutter, Gaia

Bjorn Leimar, Heavycast

Julian Lowe, Toho Tenax Co. Ltd.

Kim Kronborg Christiansen, Vestas

Scott McCollister, Plambeck Neue Energien AG

Dan Nadav, Gamesa Wind

Pierre P. Neatby, Avalon Rare Metals

Jane Paju, Molycorp Silmet AS

Alan Redding, ATS Wind Energy Services

Andres Reinsalu, Prysmian Group

Alfred Zhu, Ningbo Riyue

Photovoltaics

Christophe Ballif, Swiss Federal Institute of Technology (Lausanne)

Marcie Black, Bandgap Engineering

Philippe Boydell, DuPont

Chiara Candelise, Imperial College

Alexandre Closset, VHF-Technologies (founder & former CEO)

Micheal W. George, USGS

Roland Hengerer, Trina Solar

Brooks W. Herring, Solar Frontier

Jüri Krustok, Tallinn University of Technology

Kevin Martin, Yangden Solar GmbH

Dieter Meissner, crystalsol GmbH

Tiit Varema, Tallinn University of Technology

Josef Weindl, Soleg GmbH

Trond Westgaard, REC

7.2 Summary of recommendations to address wind power bottlenecks

Bottleneck [section #]		Recommendation	Policy	Industry
Insufficient supply of carbon fibre for rotor blades [4.4.1]	1.	**Partnership of wind turbine manufacturers with carbon fibre manufacturers**		
		Capital investment by turbine manufacturer in developing carbon manufacturers' facility with supply guarantee		X
		Expertise sharing to co-develop the required type of material		X
	2.	**Securing Polyacrylonitrile (PAN) supply**		
		Backward integration investment by the carbon fibre and/or blade manufacturers into new precursor production capacity		X
	3.	**Developing alternative precursor for carbon fibre**		
		Support for targeted research and development activities into development of alternative precursors	X	
		Implementation and pilot projects with the alternative materials		X
	4.	**Technology development on improving actual production vs. nameplate capacity of carbon fibre**		
		Rewarding manufacturing facility with higher plant efficiency	X	
		Sponsoring research on improving manufacturing process efficiency	X	
		Focused research on increasing carbon fibre yields		X
	5.	**Developing alternative to carbon fibre**		
		Collaborated effort of turbine manufacturers with material suppliers to develop alternative materials, which meet the required specifications for large wind turbines		X
		Support research with focus on alternative materials to carbon fibre	X	
Insufficient supply of rare earth metals for wind turbine generators [4.4.2]	1.	**Accelerating new mining and refining capacity outside China**		
		Capital availability for funding the projects, loan guarantees for high risk projects, tax incentives for exploration and mining activities	X	
		Supply chain collaboration and industry consortia to give investors confidence about future REE demand		X
	2.	**Improving material efficiency of mining, processing and magnet production**		
		Focus on improving the recovery rates of neodymium and dysprosium mines, as well as processing steps further downstream		X
		Provide R&D support to the rare earth mining sector to enhance recovery rates and to the PM manufacturing industry to improve materials efficiency of processes	X	
	3.	**Promoting recycling of permanent magnets**		
		Provide policy frameworks to encourage and support PM recycling and recycling friendly designs	X	
	4.	**Exploring alternative drive train designs**		
		Support R&D programmes of PM free drive trains	X	
	5.	**Encouraging R&D in materials science**		
		Support R&D programmes in materials science	X	

Bottleneck [section #]		**Recommendation**	**Policy**	**Industry**
Difficulty in integrating variable generation into the grid [4.4.3]	1.	**Improving accuracy of power output forecasting**		
		Share best practices and technologies that enable better power output forecasting to enable learning and innovation		**X**
		Further invest in R&D in this area to benefit both grid operators and the wind industry	**X**	
	2.	**Facilitating coordination of transmission and interconnection**		
		Ensure international collaboration on standards, regulation and agreements on the financing in order to facilitate interconnection projects	**X**	
	3.	**Encouraging dynamic load management**		
		International collaboration to share national approaches, facilitate learning, develop and share best practices	**X**	
	4.	**Adding energy storage to the grid**		
		Promote adaptation of smart grid technology and energy storage in the grid	**X**	
		Promote R&D into smart grid and energy storage technologies	**X**	
		Encourage international cooperation to support learning and innovation around the issue	**X**	
Barriers to permitting of wind farms [4.4.4]	1.	**Reducing the number of authorities that have to be contacted**		
		Implement a 'one-stop-shop' approach for developers, enabling the latter to deal with one point of contact efficiently instead of having to communicate and follow up with several public bodies and their procedures	**X**	
	2.	**Decreasing administrative lead times**		
		Allocate & train sufficient personnel to process wind farm applications	**X**	
		Implement clear deadlines	**X**	
		Perform detailed on- and offshore spatial planning	**X**	
	3.	**Reducing administrative costs**		
		Create knowledge management systems of crucial issues identified in the project application process	**X**	
		Regularly update project application process guidelines to reflect latest information	**X**	
		Design efficient market structures for offshore wind farms	**X**	
	4.	**Designing efficient market structures for offshore wind farms**		
		Adjust regulation so that permitting and the connection to the grid are streamlined. One option is to ensure that an intermediary actor exists between the offshore wind farm owner and the national grid operator that owns the rights to the transmission from the wind farm to the grid, and installs and operates this interconnection.	**X**	
	5.	**Including local stakeholder in the project, potentially as investors**		
		Ensure involvement of local stakeholder into wind farm projects in order to reduce resistance. One option could be to create financial models that give the opportunity for local stakeholder to participate financially in the projects.		**X**

Bottleneck [section #]		Recommendation	Policy	Industry
Lack of production capacity for offshore wind transmission equipment [4.4.5]	1.	**Signalling policy support to industry**		
		Support cable capacity expansion by credibly supporting the growth of offshore wind installation well into the future through mechanisms such as feed-in-tariffs and tax credits	**X**	
	2.	**Facilitating dialogues among industry players**		
		Further encourage and support dialogue between cable manufacturers and wind farm developers. If more trust and better communication can be established, the perceived risk of investment in new manufacturing facilities or capacity expansion can be reduced.		**X**
Shortage of large casting and forging capacity for wind turbine components [4.5.1]	1.	**Increasing demand visibility**		
		Initiate dialogue with casting and forging suppliers on the deployment roadmap and possible stresses on the supply chain		**X**
		Provide clear deployment roadmaps with realistic interim goalposts and review checkpoints	**X**	
	2.	**Supply side incentives**		
		Tax incentives and infrastructure support (like supply parks) can be provided for manufacturing capacity built to cater to the wind energy demand	**X**	
	3.	**Increasing supply base**		
		Proactively develop and nurture additional suppliers for heavy castings and forgings		**X**
	4.	**Research into alternative materials, process improvements and split design**		
		Provide grants / encourage research in the above areas and incentivize rapid deployment by the wind power industry	**X**	
		Invest in and sponsor research in the above areas to improve long term competitiveness and development of the industry, working closely with potential vendors		**X**
Limited availability of suitable vessels for offshore installations [4.5.2]	1.	**Increasing demand visibility**		
		Provide firm deployment roadmaps with realistic interim goalposts and review checkpoints	**X**	
		Initiate dialogue with vessel suppliers on the deployment roadmap and possible stresses on the supply chain. Reliable industry forecasts are needed which translate roadmaps into needs for vessels and platforms. An example is KPMG (2011), which presents the opportunities for the German shipbuilding industry resulting from offshore wind activity in Europe and beyond.		**X**
	2.	**Supply side incentives**		
		Provide tax incentives for ships built to cater to the wind energy demand	**X**	
	3.	**Demand side incentives**		
		Provide loan guarantees to ensure that projects go ahead for which developers cannot take the risk (e.g. Megaprojects)	**X**	

Bottleneck [section #]		**Recommendation**	**Policy**	**Industry**
Limited availability of suitable vessels for offshore installations [4.5.2]	4.	**International mobilisation of vessels**		
		Assess and enable the accessibility of national waters for offshore wind installation vessels	X	
Limited availability of skilled personnel along the supply chain [4.5.3]	1.	**Meeting training needs**		
		Involve industry players (OEMs, component manufacturers, project developers) to communicate current and emerging needs for skills		X
		Assist with identifying and providing training staff through grants and incentives	X	
		Include alternate energy topics in colleges to improve awareness	X	
		Provide training grants	X	
	2.	**Developing internationally recognised profiles**		
		Involve industry players to develop standardised profiles and job descriptions		X
		Develop a body for developing standards Facilitate international cooperation around standards	X	
	3.	**Spreading awareness about wind opportunities**		
		Conduct job fairs and conferences to attract potential candidates		X
		Provide grants for programs targeting all age groups (pre-career up to adult training)	X	
	4.	**Automation to reduce O&M**		
		Invest in technologies that reduce the need for human O&M intervention		X
Limited availability of suitable port infrastructure for offshore installations [4.5.4]	1.	**Developing port infrastructure plan**		
		Develop plan for port infrastructure development; including locations, feasibility studies, infrastructure requirements and time lines for development	X	
		Provide financial support for port development and risk mitigation		X
		Port developers, turbine manufacturers and wind farm developers should communicate closely, coordinating port facility development and potentially sharing risks	X	
Overland logistics constraints for large wind turbine components [4.5.5]	1.	**Developing modular components**		
		Developing nacelle and blade design with reduced weight and size respectively		X
		Support testing facility for such projects	X	
	2.	**Communication and coordination between different stakeholders**		
		Sharing of key strategies used to transport heavy component turbine manufacturers, trailer manufacturers, component transportation companies and relevant government agencies		X
	3.	**Developing alternate modes of transport**		
		Investment in developing waterways and railroad infrastructure	X	

Bottleneck [section #]	Recommendation		Policy	Industry
Overland logistics constraints for large wind turbine components [4.5.5]	4.	**Reference document for OEM design and sales teams to identify transport limitations**		
		Create reference to OEM, regarding the logistic infrastructure available, before the turbine goes into mass production		X
Lack of wind turbines suited to cold weather conditions [4.6.1]	1.	**Developing de-icing and anti-icing technology**		
		Focused development and testing of de-icing and anti-icing systems		X
		Supporting prototyping and testing facility	X	
Deployment restrictions due to radar interference by wind turbines [4.6.2]	1.	**Developing stealth blade technology**		
		Focused development of stealth blades technology for rotor blades		X
		Supporting prototyping and testing facility	X	
Lack of internationally applicable health and safety standards [4.6.3]	1.	**Developing global standards through collaboration effort amongst Europe, US and Asian countries**		
		Governments of key countries / regions to collaborate for developing global standardization in safety training and also design related to health and safety.	X	
		Develop a common template for key components and quality standardization		X
Inadequate solutions for disposing of or recycling rotor blades [4.6.4]	1.	**Developing recycling of organic material (PVC and polyester)**		
		Focused research on economically recycling organic material Developing reverse logistics to increase the volume Develop demand for recycled organic material in wind or other industry		X
		Incentivizing OEMs for recycling of blades	X	
	2.	**Developing and using materials with recycling in mind**		
		Developing and using alternative materials that facilitate recycling		X
		Support R&D in blade materials that focus on recyclability	X	

7.3 Summary of recommendations to address photovoltaics bottlenecks

Bottleneck [section #]	Recommendation		Policy	Industry
Insufficient silver availability for c-Si PV [5.4.1]	1.	**Securing primary silver supply**		
		Form consortia that can enable even small players to sign long term supply contracts with key suppliers		X
	2.	**Increasing secondary silver supply**		
		Introduce and/or ensuring the effectiveness and widespread of free-of-charge take-back schemes for consumer electronics	X	
		Improve recycling-friendliness of PV modules, e.g. through the use of lead free solders		X
		Make investments into recycling technology and facilities capable of recovering silver from end-of-life modules		X
		Run campaigns informing consumers about return of end-of-life products.	NGOs	
		Monitor PV industry's commitment to recycling, including recycling-friendly product design to reward manufacturers that implement best practices	NGOs	
	3.	**Reducing silver consumption per watt peak**		
		Initiate collaboration to ensure that best-practice will be adopted industry wide and reduce the average consumption of silver per Wp significantly		X
	4.	**Replacing silver by less expensive / more abundant elements and materials**		
		Support of targeted research and development activities that aim on silver free production methods	X	
		Implement copper plating pilot lines into high throughput production facilities		X
Insufficient tellurium availability for CdTe PV [5.4.2]	1.	**Increasing recovery during processing**		
		Provide access to capital for recovery mechanism	X	
		CdTe PV manufacturers to invest in installing and upgrading the indium recovery mechanism at copper refineries		X
	2.	**Reducing tellurium usage per Wp**		
		Fund research on reducing absorber layer thickness and increasing efficiency	X	
		Conduct research, trials and implementation		X
	3.	**Recycling and waste reduction**		
		Data collection on recycling of thermoelectric coolers	X	
		Research on recycling of thermoelectric cooler		X
	4.	**Replacing tellurium in various applications**		
		Fund research on replacing tellurium with other elements/alloys	X	
		Research on replacing tellurium with other abundant materials		X

Bottleneck [section #]		Recommendation	Policy	Industry
Insufficient indium availability for thin film PV [5.4.3]	1.	**Substitution of indium in CIGS/CIS absorbers**		
		Provide targeted funding to support research and development activities that focus on the efficiency improvement of CZTSSe absorber based solar cells	**X**	
		Conduct feasibility studies on the transition of CIGS/CIS production processes towards indium free CZTSSe and invest in pilot production lines for CZTSSe		**X**
	2.	**Recycling of indium from CIGS/CIS**		
		Enforce increased efforts in recycling and recovery of indium (and other materials) through including PV in electronic waste regulations such as the WEEE	**X**	
		Develop indium recovery processes for CIGS/CIS PV panels		**X**
		Monitor PV industry’s commitment to recycling-friendly product design to reward manufacturers that implement best practices	**NGOs**	
	3.	**Replacing indium in TCOs for PV applications**		
		Provide targeted funding to support research and development activities that focus on high barrier encapsulants and cost reduction of their production processes (this can enable the use of indium free TCOs in flexible modules)	**X**	
		Cost reduction of high barrier encapsulates to enable the use of indium free TCOs in flexible modules		**X**
		Conduct sensitivity analysis of the cost factors indium and encapsulant to define a critical indium price in the framework of a long term technology strategy		**X**
	4.	**Recycling of indium from ITO**		
		Introduce and/or ensure the effectiveness and widespread use of free-of-charge take-back schemes for consumer electronics in which ITO is used (LCDs)	**X**	
		Provide targeted funding to support research and development activities that focus on indium or ITO recovery from TCOs in LCDs	**X**	
		Invest in IP or start-ups that develop processes for indium recovery from TCOs (e.g. in LCD displays)		**X**
		Launch campaigns that inform consumers about return of end-of-life products.	**NGOs**	
		Monitor PV industry’s commitment to recycling-friendly product design to reward manufacturers that implement best practises	**NGOs**	
Technical, commercial and regulatory barriers to grid access for PV projects [5.4.4]	1.	**Defining grid and grid connectivity standards**		
		Enable global dialogue between equipment manufacturers, utilities and regulators to evolve standards	**X**	
		Initiate global dialog on best practices and evolve standards		**X**
	2.	**Reducing the complexity and lengths of permitting procedures**		
		Ensure that regulators facilitate permitting of PV projects through reducing administrative cost, burden and lead time	**X**	
		Utilities should proactively take steps to improve lead times and simplify procedures for obtaining permits		**X**

Bottleneck [section #]		Recommendation	Policy	Industry
Technical, commercial and regulatory barriers to grid access for PV projects [5.4.4]	3.	**Guaranteeing sustainable levels of financial support**		
		Provide transparent long term outlook on incentives to support infrastructure creation and also encourage developers to take up additional investments if required	**X**	
	4.	**Creating transparency regarding cost sharing arrangements for grid connections**		
		Ensure that regulators provide clear guidelines regarding cost sharing for additional investments in case of additions required in the grid	**X**	
	5.	**Establishing clear and strong regulations regarding the obligation for grid operators to connect PV systems**		
		Ensure that regulations are in place that force grid operators to connect PV systems, and that exclusions from the obligation are clearly defined and monitored	**X**	
Capital intensity of solar grade silicon production for c-Si PV [5.5.1]	1.	**Ensuring long term growth predictability of the PV sector**		
		Ensure that newly introduced incentives supporting PV deployment should aim at moderate but continuous growth to avoid overheating of the market and create confidence in long term investments	**X**	
		Smaller module manufacturers which lack the size to vertically integrate silicon processing in their business can team up with other companies and build consortia that either invest in silicon capacity or jointly sign long term contracts with silicon suppliers to lower their risk in longer term investment.		**X**
	2.	**Increasing recycling of wafers and recovery of silicon**		
		Introduce and ensure the effectiveness and wide application of free-of-charge take-back schemes for end-of-life PV panels, including inducement to recovery silicon instead of disposal	**X**	
		Improve recycling-friendliness of PV modules, e.g. through the use of lead free solders		**X**
		Invest in recycling technology and facilities capable of recovering silicon from end-of-life modules		**X**
		Monitor PV industry's commitment to recycling-friendly product design to reward manufacturers that implement best practices	**NGO**	
Potential restrictions on CdTe PV from hazardous substances regulations [5.5.2]	1.	**Switching to alternative materials in CIS/CIGS technology**		
		Provide clarity about intentions to change cadmium legislation and provide support for R&D into alternatives for CdS buffer layer	**X**	
		Conduct R&D into alternative materials		**X**
	2.	**Preparing for a potential ban of cadmium in PV panels**		
		Provide clarity about intentions to change cadmium legislation	**X**	
		Prepare contingency plans for technology choices in EU if intentions are signalled by policymakers		**X**

Bottleneck [section #]		Recommendation	Policy	Industry
Insufficient skilled personnel for PV installation [5.5.3]	1.	**Inter-country exchange of knowledge through skills transfer**		
		Develop emerging PV markets by establishing skills transfer mechanisms		**X**
		Provide support for outward and inward skills transfer	**X**	
	2.	**Providing education and training programs aligned with renewable deployment targets**		
		Work closely with policymakers to predict skills needs and develop skilled personnel in line with requirements		**X**
		Work closely with industry to understand needs and develop appropriate education	**X**	
	3.	**Providing incentives for PV deployment to create smooth growth**		
		Consider the need for smooth and sustainable growth in creating policies to support PV	**X**	
	4.	**Designing installation-friendly PV systems**		
		Consider skills aspects in product design, in particular through provision of more 'plug and play' type systems		**X**
Time consuming and uncertain permitting procedures for PV projects [5.5.4]	1.	**Creating and enforcing appropriate PV permitting processes**		
		Design and enforce lean and appropriate permitting procedures	**X**	
		Create a "one-stop-shop" approach	**X**	
		Design and adhere to "hard deadlines"	**X**	
Lack of distribution channels for PV in future growth markets [5.6.1]	1.	**Developing PV markets through roadmaps and subsidies**		
		Announce incentives and roadmaps for PV energy development in advance to give PV manufacturers time to plan distribution networks	**X**	
Lack of appropriate solutions for dust removal from PV modules [5.6.2]	1.	**Research on the impact of dust accumulation and technological solutions**		
		Conduct research on impact of dust on PV modules and investigate cost-effective technical and manual alternatives.		**X**
		Sponsor research on technologies to reduce the impact, e.g. coatings		**X**
Insufficient PV module take-back schemes and recycling processes [5.6.3]	1.	**Encouraging recycling**		
		Implement viable take-back schemes to make recycling trouble-free for end-users		**X**
		Enforce recycling of PV modules through regulations	**X**	
		Build awareness and encourage recycling, especially in case of PV modules	**NGO**	
	2.	**Building reverse logistics and recycling infrastructure**		
		Ensure coordination between manufacturer, recycler and end-user; build cross-industry reverse logistics systems		**X**
	3.	**Encouraging recycling research**		
		Support R&D into higher yielding recycling technologies	**X**	

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9 List of Acronyms

a-Si	Amorphous Silicon
AC	Alternating Current
AN	Acrylonitrile
AZO	Aluminium doped zinc oxide
BoS	Balance of System
c-Si	Crystalline Silicon
CAGR	Compound Annual Growth Rate
CdTe	Cadmium-Telluride
CIGS/CIS	Copper-Indium-Gallium-Selenide / Copper-Indium-Selenide
CPV	Concentrated Photovoltaics
CZTSSe	Copper-Zinc-Tin-Sulphide-Selenide
DC	Direct Current
EPA	U.S. Environmental Protection Agency
EEZ	Exclusive Economic Zone
ETP	Energy Technology Perspectives
EU	European Union
GW	Giga watt
GWp	Giga watt peak
HTS	High Temperature Superconductor
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IEC	International Electrotechnical Commission
ITO	Indium tin oxide
LCD	Liquid Crystal Displays
LED	Light Emitting Diode
MW	Mega Watt
NdFeB	Neodymium Iron Boron (magnet)
NGO	Non-Governmental Organization
O&M	Operation and Maintenance
OECD	Organization for Economic Cooperation and Development
OFTO	Offshore Transmission Network Owner
PAN	Polyacrylonitrile
PET	Polyethylene terephthalate
PM	Permanent Magnet
PV	Photovoltaic
PVC	Poly Vinyl Chloride
R&D	Research & Development
RE	Renewable Energy
RETD	Renewable Energy Technology Deployment
RoHS	Restriction of Hazardous Substances

ROV	Remotely Operated Vehicle
rpm	revolutions per minute
TCO	Transparent conductive oxide
TWh	Terra Watt- hour; unit of measurement for energy
US DoE	US Department of Energy
WEEE	Waste Electrical and Electronic Equipment Directive
WTG	Wind Turbine Generator