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SCIENCE FOR POLICY BRIEF

Advanced materials for substitution in the clean energy sector

HIGHLIGHTS

→ Advanced materials play a crucial role in the development of clean energy technologies by enhancing performance, reducing costs and increasing sustainability. They foster innovation in industries and technologies, which can boost the EU economic competitiveness and growth.

→ Advanced materials also contribute to critical raw material substitution, thus potentially reducing the EU dependency on third countries. As such they are extremely important to increase the resilience of the relevant supply chains and the EU strategic autonomy, as well as to achieve full decarbonisation.

→ The impact of advanced materials substitution to reduce dependence on critical raw materials could be higher in sectors such as renewable energies and mobility, where demand is expected to grow or remain high, and European production potential is limited.

INTRODUCTION

Advanced materials [1] are engineered to possess specific properties that go beyond those of traditional materials. They offer superior cost and operational performance, can be more sustainable and recyclable, or replace strategic or critical materials used in a similar function. Many advanced materials have been successfully adopted by the markets and are now used in a wide range of applications. Examples include super-alloys, polymers, nanomaterials, carbon materials, optical, electronic and magnetic materials, superconductors, technical ceramics, composites and biomaterials, refrigerants, catalysts, coatings and adhesives. The continuous development of advanced materials is a driving force behind innovation. This involves a wide range of industries and research institutions and contributes to the creation of more efficient, sustainable and cutting-edge technologies. Advanced materials are also expected to offer efficient responses to addressing challenges related to circularity, zero-pollution, climate contribution, and traceability, aligned with the broader goals of sustainability [2].

New materials appear continually in the course of industrial progress, following more shallow or deep innovations. While advanced materials hold great promise for long-term innovation, their widespread implementation can face challenges and barriers that may hinder their adoption unless the right conditions are met. Challenges related to cost, scalability, compatibility, regulations, standards, risk aversion and market dynamics have to be considered.

Next-generation, solution-oriented advanced materials will play a relevant role and already have strategic importance for economic growth and the industrial competitiveness of the European clean energy sector. Europe is a global leader in advanced materials and processes, which make up 20% of its industrial base [3]. It is now imperative that this

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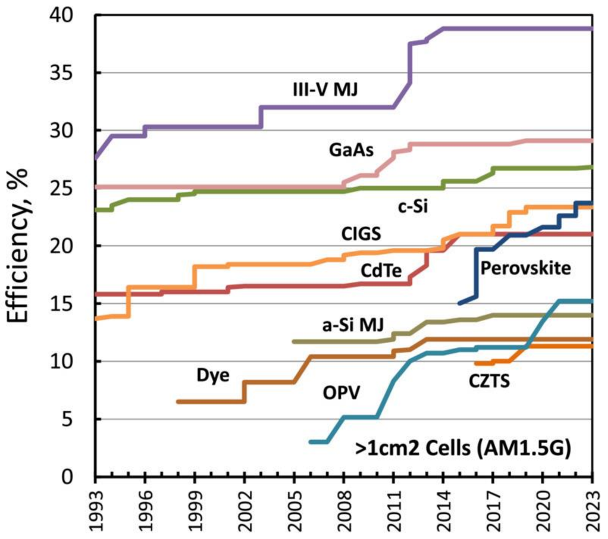
innovation advantage is used to underpin the acceleration of development of globally competitive clean energy technologies by the European industry. Research and innovation has a vital role to play in reducing the intensity of critical materials used, and developing high-performance advanced materials to substitute for them. Relevant initiatives include a new SET Plan Task Force which will explore circularity by design and the advanced materials needed for the production of renewable energy technologies [4], and design ways to embed all aspects of circularity systematically in the development phase.

ADVANCED MATERIALS FOR ENERGY-RELATED TECHNOLOGIES

Advanced materials are essential for the development of renewable energy technologies and low carbon energy solutions. For example (as shown in Fig. 1) advanced photovoltaic (PV) cells leverage innovative materials, structures and technologies to enhance the conversion of sunlight into electricity. These include thin-film cells, either based on cadmium telluride (CdTe) or copper indium gallium selenide (CIGS), which can offer several competitive advantages over traditional silicon-based solar cells. Multijunction cells and perovskites are highly promising technologies because they are on par with (or better than) crystalline silicon (c-Si) in terms of efficiency and can absorb light over a wide range of wavelengths [5]; for example, four terminal perovskite-silicon PV tandem devices were recently shown to surpass the barrier of 30% efficiency [6].

Figure 1 – Highest confirmed efficiencies for laboratory PV cells fabricated using different technologies between 1993 and 2021.



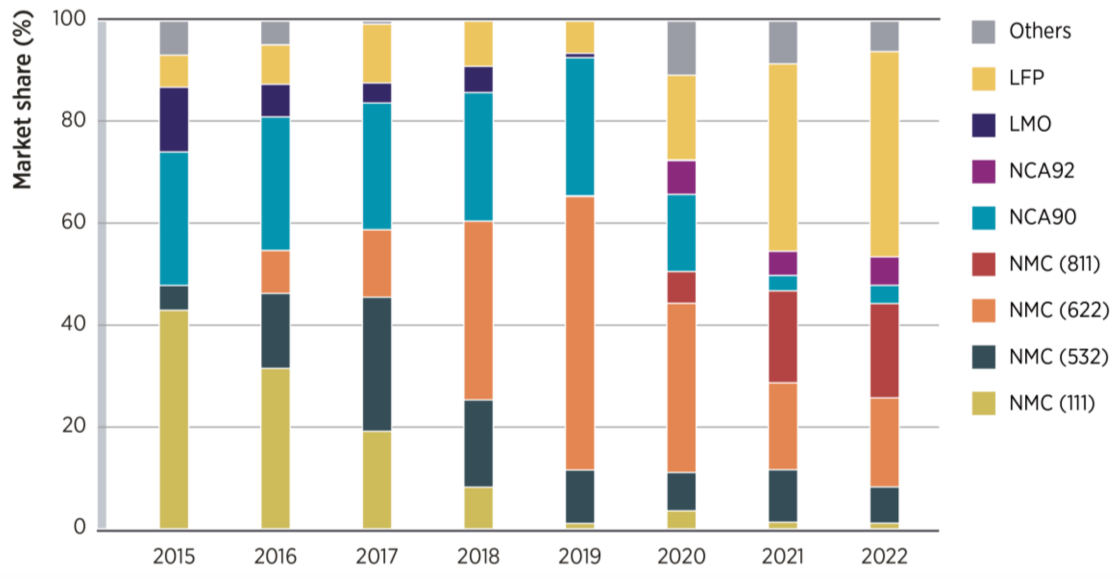
Source: Solar cell efficiency tables (Version 61) [7].

The use of advanced materials is also essential in the wind energy sector in order to overcome the unique challenges associated with offshore wind energy production, making it a viable and increasingly competitive renewable energy source. The trend in modern wind turbine generators involves a transition from traditional ferrite magnets to more advanced and higher-performing permanent magnets, particularly neodymium-based magnets. Since 2005, permanent magnet generators have gained popularity, especially in offshore turbines, as they allow for high power density and small size with the highest efficiency at all speeds, offering a high annual production of energy with a low lifetime cost [8,9].

The wind turbine blades contain complex composite materials – a combination of reinforced fibres and a polymer matrix/resins that is hard to break down and recycle. The core material of a blade is composed by balsa wood, sourced mainly from Ecuador (75-90% of the world's balsa wood demand). The use of such composites boosts the performance of wind turbines, since they allow for lighter and longer blades with optimised aerodynamics. However, their configuration poses challenges both for manufacturing and for recycling. Manufacturers look for alternative materials to increase circularity, avoid bottlenecks and increase efficiency. Characteristic examples are the use of recycled polyethylene terephthalate (rPET), biocomposites, and the use of special resins that dissolve at low temperatures. Similarly, the successful integration of advanced materials is expected to have a significant impact on the durability of wind turbine components (such as structural parts prone to erosion and corrosion and foundations and cables for offshore turbines) as well as on their circularity and sustainability [10].

Battery technologies have seen significant advancements in recent years, driven by innovations in materials science. These advancements often involve rapid changes in the chemistry of the battery, along with the integration of advanced materials driven, in the case of electric vehicle (EV) batteries, by the pursuit of improved energy density, longer range, faster charging, cost reductions and the reduction or elimination of the use of critical materials like cobalt or nickel (as shown in Fig. 2). Very recently, Northvolt claimed a breakthrough in sodium-based batteries, which provide a far cheaper alternative to lithium with a more abundant material [11].

Figure 2 – Evolution of global EV battery chemistries mix between 2015 and 2022. LFP batteries are nickel and cobalt-free, unlike NMC- and NCA-class batteries.



Source: BloombergNEF, 2022 [12].

Most of heat pumps currently use hydrofluorocarbon refrigerants, which are potent greenhouse gases with a typical Global Warming Potential (GWP) of around 2 000 times that of CO_2 [13]. The emissions are primarily caused by leakage and can vary depending on factors such as the model and maintenance. Typical average annual leakage rates of refrigerants are about 3.5% for residential heat pumps [14]. Fluorinated greenhouse gases will be phased down to near zero by 2030, according to a new regulation that will officially become law later this year [15]. While the market share of newer and more environmentally friendly refrigerants is growing, the heat pump industry needs time to scale up production. Transitioning to natural refrigerants like propane and CO_2 offers several advantages, including reducing greenhouse gas emissions and contributing to global warming mitigation. Moreover, using natural refrigerants presents an opportunity for the EU industry to differentiate itself from competitors and reduce dependence on non-EU suppliers.

Regarding materials for CO_2 capture, chemical solvents have been at the forefront of capture technologies for years, especially aqueous amine solutions such as monoethanolamine. Recently some alternative solvents have arisen in order to enhance the environmental and thermodynamic performance of amines. One of the most promising options is the use of ionic liquids, which have attracted interest as CO_2 capture materials due to their intrinsic properties (e.g., non-volatility and high stability), high CO_2 solubility and low energy requirements. Other capture technologies beyond absorption such as solid adsorbents are also promising, especially for newer applications such as direct air capture. Two relevant examples of these materials are zeolites and metal-organic frameworks, the latter being particularly interesting for their excellent thermodynamic stability and large-scale production capability.

ADVANCED MATERIALS FOR CRITICAL RAW MATERIAL SUBSTITUTION

Advanced materials research often aims to find substitutes for critical raw materials (CRMs), especially those that are geopolitically sensitive or subject to supply chain vulnerabilities. In 2011 the European Parliament adopted a resolution that proposes focusing research and development on the substitution of CRMs to support sustainable development and encourage growth in the European economy [16]. The European Innovation Partnership on Raw Materials addresses substitution among its commitments and priority actions [17]. The Critical Raw Materials Act states that increasing efficiency and uptake of material substitution, achieved by fostering production methods and research and development activities, will be supported at least under national research and innovation programmes [18].

Some advanced materials are designed to minimise or eliminate the use of CRMs from specific products. An example of this process was the evolution from fluorescent lighting technology to light-emitting semiconducting materials such as LEDs. The latter offer more efficiency and significant energy savings (up to 90%) and require 20 times less europium and yttrium and no terbium. By this the amount of critical rare earth metals needed is reduced. Moreover LEDs use gallium instead of germanium [19].

Decreasing or eliminating the use of CRMs reduces vulnerability to fluctuations in the global availability and pricing of these materials. This is limiting market power and challenging producer cartels, and contributing to a more stable and resilient supply chain at least in some applications [20]. Substitution with advanced materials is widely acknowledged as a strategic approach to address challenges related to CRMs and serves as a strategic tool for building resilient supply chains, to maintain and enhance sustainability and competitiveness in the EU [21].

A trend towards eliminating cobalt and nickel from electric-vehicle batteries has been taking place during the last few years as shown on Fig. 2. The resurgence in the popularity of Lithium Iron Phosphate (LFP) batteries, which are nickel and cobalt-free, is driven by their attractiveness for manufacturers seeking to reduce dependence on expensive and ethically challenging cobalt and to emancipate them from constrained or restricted supply chains. In general, an increase in the market share of LFP batteries implies lower levels of mineral security concerns due to the absence of cobalt, nickel and manganese, whose supply chains are more geographically concentrated and prone to disruptions [22].

Progress is also being made to reduce the content of rare earths in permanent magnet generators for wind turbines. In 2018, when such generators were used in nearly all offshore wind turbines in Europe and in approximately 76% of offshore wind turbines worldwide [23], Toyota Motor Corporation announced the development of a novel neodymium-reduced, heat-resistant magnet which does not use either terbium or dysprosium and where a significant amount of the neodymium has been replaced with lanthanum and cerium, two rare earths that are currently overproduced and are thus relatively cheap and easily available. Although to our knowledge Toyota's motor was never commercialized, since then Siemens Gamesa Renewable Energy and Goldwind have reduced the content of dysprosium in their generators to below 1% and, more radically, GreenSpur Renewables has developed prototypes of permanent magnet generators that do not contain rare earth elements [24].

The dynamic nature of substitution, influenced by factors such as technological advancements, market dynamics, and regulatory changes, makes it challenging to accurately predict future materials demand. The whole process (from initial research on the properties of materials to their practical implementation in a new product) encompasses various stages of development and can span several years or even a few decades [25,26]. However, substitution can happen quickly when the right conditions are met. Examples are the very rapid transition from SmCo to NdFeB magnets in the 1980s and the superalloys and special coatings for higher turbine temperatures and efficiencies [27,28]. More recently, the JRC estimated that developments in battery technology would have led to a reduction of 29% in the use of cobalt in EVs between 2017 and 2030 [29]. In fact, the recent increase in the market share of LFP batteries (Fig. 2) means that this reduction has most likely already been reached.

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