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Special Issue on New Challenges in Energy Materials

Research on materials and renewable energy

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Abstract

In this paper, an overview on the subject of materials and renewable energy, mainly from the research point of view, is carried out. Energy and materials are nowadays driving science and technology. There is a search for cleaner, cheaper and more efficient energy production, and this is obviously related to the development of new and innovative materials. As energy is a top European priority, materials research can enable Europe to meet its future energy and climate goals. The importance of raw materials for the energy sector and the future of advanced materials for low carbon energy are addressed. Materials-based solutions to the energy problem and guidance on research in this field are also the aim of this paper.

Keywords: Materials; energy research; energy technology; critical materials.

1. Introduction

Different environmental and supply concerns related to fossil fuels have driven scientists to explore new technological solutions, looking for alternative means for energy production and storage. New and innovative materials are at the core of the new findings in this field [1]. The time when only a few materials such as steel, copper and concrete were the main components for energy technologies are long gone [2].

Materials are fundamental to industrial, social and economic development, and can be the trigger for the development of many new products and technologies [3]. There is a need to improve physical and chemical properties of materials in order to lead to new and competitive energy production [1].

One way to measure the progress of mankind is to take a look at the evolution of man-made materials, their development and use over time, their variety, quality and performance [4]. Furthermore, without continuous innovation in advanced materials the performance improvement, cost reduction and extended life time of energy technologies would not be possible [2].

Solar modules, wind turbine blades, batteries and wave power components, amongst others, all rely upon advanced materials, e.g. the efficiency of solar modules needs to increase, the weight of turbine blades must be reduced, batteries need longer life cycles and, in general, corrosion resistance must be improved [2].

The European Strategic Energy Technology Plan (SET Plan) aims to transform the way energy is produced and the use of energy in the European Union (EU), with the goal of EU leadership and the development of technological solutions for forthcoming energy and climate targets [2]. This plan aims to accelerate the development and deployment of low carbon technologies. The integrated SET-Plan is part of a new European Energy Research & Innovation (R&I) approach designed to accelerate the transformation of the EU's energy system and to bring promising new zero-emissions energy technologies to market. The SET-Plan comprises the SET-Plan Steering Group, the

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European Technology and Innovation Platforms, the European Energy Research Alliance, and the SET-Plan Information System (SETIS). Among other actions the SET-Plan identifies 10 actions for research and innovation, based on an assessment of the energy system needs and on their importance for the energy system transformation and their potential to create growth and jobs in the EU.
The Materials Information System (MIS), established in 2014, provides information on materials used in the SET-Plan technologies i.e. low carbon technologies as bioenergy, solar, wind, fuel cell, and hydrogen technologies, nuclear fission, electricity grids and carbon capture and storage. This includes information on the technologies; the materials supply chain; which materials, and their quantity, are used in each technology; the materials description; relevant references; and other info [2].
Sixty metals were identified as vital for the different energy technologies covered by the SET-Plan. About 70% of all technical innovations can be directly or indirectly attributed to the materials they use. The impact of advanced materials (fraction of growth attributed to these) for the energy sector is expected to reach 70% in 2030 [2].
A technical roadmap was published by the European Commission to establish what materials are needed in order to drive the next generation power sources or to make buildings more efficient [2].

2. Economic aspects of materials and energy

The Energy Materials Industrial Research Initiative (EMIRI), a pan-European initiative and an association that works for the future of advanced materials for low carbon energy (LCE) in Europe, identifies four key numbers as follows [5]:
1) >4 billion € in sales of advanced materials for energy;
2) >400 million € of investment in Research & Innovation (R&I) on advanced materials for energy;
3) >20,000 direct jobs in the manufacturing of advanced materials for energy;
4) >4000 researchers for R&I on advanced materials for energy.
Energy systems are changing profoundly, and the share of renewable and decentralized energy production in the energy mix is foreseen to increase. A wide range of advanced materials in sufficient quantities will be needed to modernize energy installations. However, several years of Research and Innovation (R&I) can be taken before the development and market uptake of these materials as every-day components. Long, capital-intensive development times, in combination with strong technology and marketing risks, means that it is very difficult to progress new materials from the lab to the industrial scale and, after this, to the markets [2].
In a 2012 study [6], carried out by Oxford Research AS for the Directorate-General for Research and Innovation of the European Commission, nearly 40% of the interviewed venture capitalists and private investors were willing to invest in early stages, or seed capital in advanced materials, for the energy sector, more than that for materials for other applications, showing the interest in investment on materials for energy. The total worldwide market for advanced materials is expected to grow to about 1100 billion € by 2050, with a share of 16% for materials for energy applications (176 billion €) [6].

3. The EMIRI initiative

The industry-driven initiative (IDI) promoted by EMIRI [5] calls for prioritization and action in R&I on advanced materials. Through collaboration between Industry, Research Organizations and Associations with the European Directorate-General Research & Innovation, a focused R&I program on advanced materials for LCE was defined. The IDI, aiming at bridging the gap between lab and market, focuses on 19 topics (Technology Readiness Levels (TRL) 4-7) over four key components (KC). These topics and KCs address the challenges of the European Energy System and contribute to the SET Plan. The four KCs are [5]:
KC1 - Advanced materials to increase energy performance of buildings;
KC2 - Advanced materials to make renewable electricity technologies competitive;
KC3 - Advanced materials to enable energy system integration;
KC4 - Advanced materials to enable the decarbonisation of the power sector.
Among the 19 topics promoted by this IDI, five are of interest to support Action 4 of the SET Plan (Increase the resilience, security and smartness of the energy system). These are [5]:
1 - Advanced materials for thermal energy storage (TES) - Next generation of TES technologies;
2 - Advanced materials for lower cost, high safety, long cycle life and environmental friendly electrochemical batteries (Li-ion batteries);
3 - Advanced materials for lower cost, high safety,

long cycle life and environmental friendly electrochemical batteries (next generation electrochemical batteries);
4 - Advanced materials for lower cost storage of energy in the form of hydrogen or other chemicals (power to gas, power to liquid technologies);
5 - Advanced materials to facilitate the integration of storage technologies in the grid.

These five topics are expected to contribute significantly to drive nine identified technology-related actions, as follows [5]:

Field of Advanced Research (5)
1 - Research and development of new materials for grid applications;
2 - Enhanced storage materials;
3 - New technologies for the next generation of central and de-central storage technologies of any scale;
4 - Improved second generation technologies for the next generation of central and de-central storage technologies of any scale;
5 - Storage systems interfaces.

Field of Industrial Research and Demonstration (3)
6 - Central and de-central storage technology demonstration of any scale;
7 - Storage manufacturing processes;
8 - Storage recycling.

Field of Innovation and Market Uptake (1)
9 - Closed storage material loop.

4. Materials and Energy

Impressive breakthroughs are taking place for electricity generation, mainly in the field of solar and fuel cells. As referred in [1], there are *"... entirely new classes of semiconductors… Inenergy-storage exciting developments are emerging from the fields of rechargeable batteries and hydrogen storage. On the horizon are breakthroughs in thermoelectrics, high temperature superconductivity, and power generation. Still to emerge are the harnessing of systems that mimic nature, ranging from fusion, as in the sun, to photosynthesis, nature's photovoltaic.*"

A published report on materials for emerging energy technologies, from the European Commission [3], states experts' recommendations on actions concerning energy/materials, and identified needs for:
a) Further research into the structure and properties of materials for energy;
b) Further research into new materials or materials solutions;
c) Advanced computer based complexity modeling.

Fig. 1. Photovoltaic solar panels (by By Kanadaurlauber, via Wikimedia Commons).

For example, the optimization of Li-ion batteries for low cost, high safety and long cycle life requires the development of new and lighter materials for e.g. electrodes, electrolyte separators, solid electrolytes, binders and optimized packaging materials. These Advanced Materials can lead to improved batteries with well specified Key Performance Indicators (KPI) for energy and power density, extended lifetime and significantly improved cost (one target is below 0.05 euro/kWh/cycle) while offering full safety. Typical cathode materials can be improved or novel lithium iron phosphate (LPF) and nickel-manganese-cobalt (NMC) types with current or increased voltages can be developed. Typical anode materials can be improved or micron/nano-sized Si, Sn composites can be developed. Solid-state developments by polymer or solid electrolytes may lead to higher safety levels. The wide range of new alternative storage solutions covers among others metal-air, lithium-sulfur, new ion-based systems (Na, Mg or Al), redox flow batteries (free of Vanadium) [5].

Fig. 2. Full electric car (by evgonetwork (eVgo Network), via Wikimedia Commons).

One of the main concerns is the development of new materials for TES in order to achieve the next generation of TES technologies. So, there is a need to develop new thermal energy storage technologies with better performance, availability, durability, safety and also lower costs. The challenges are to identify/develop advanced TES materials for sensible, latent and thermochemical storage technologies having increased energy storage density for buildings and industrial waste heat including sensible heat storage and latent heat storage. The optimization and development of new phase-change materials (PCM) and their integration in building element materials or industrial applications is foreseen. PCM properties need to be improved to encourage their use, such as increasing the lifetime without physical properties degradation, increasing their liquid stability at high temperatures, limiting liquid expansion during fusion, and encapsulation [5].

In the field of lower cost storage of energy in the form of hydrogen or other chemicals, advanced materials innovation will focus on high capacity durable proton-exchange membranes (PEM) and solid oxide electrolysis cell (SOEC) electrolysers for hydrogen production. Other topics also to be included are the development of cost efficient tank materials for high-pressure storage of hydrogen and the development of materials to support catalysts in presenting longer lifetime and improved efficiency [5].

To facilitate the integration of storage devices in the electrical grid there is the need of high capacity new material cables and superconductors, materials for smart electrical accessories, new materials for extreme conditions, sensor materials and surface treatment of existing materials to protect and improve performances. These new materials will enable a significant enhancement of power supply reliability, management and ensure connection of renewable energy sources to increase grid efficiency [5].

Regarding PV, flat solar panels for thin film technology allow for lightweight constructions and offer a wide range of architectural design possibilities, which is in contrast to the heavier traditional silicon-based panels that require a stable underframe [2].

In the field of concentrated solar energy, graphite foams impregnated with PCMs could be key materials for the capture, storage and release thermal energy in concentrated solar power infrastructures [7]. Another possibility is the introduction of nanomaterials (e.g. silica, alumina) in the storage component [8], or the use of mixtures of carbonates and nitrates of lithium and cesium [9], and the use of lithium-based salts and copper foams [10]. Future research is needed in the development of new porous and reticulated ceramic foams for the reaction chambers of new solar chemical reactors.

For wave energy converters, new materials to reduce the device's weight and biofouling effects on the marine environment are needed, as well as materials quality improvement for reduction of capital and maintenance costs [11].

Also included in the field of materials and energy is the production and test of materials using energy, as, in the use of the high temperatures obtained with Concentrated Solar Energy. Several examples of this can be mentioned:

- Industrial level: The cement industry is an energy-intensive one, in which calcium carbonate decomposition and clinkering at temperatures of 900-1450ºC needs to be performed. Direct calcination in one single step avoids gaseous contaminant formation, and lowers CO_2 emission [12];
- Laboratory level: Synthesis of fullerenes and carbon nanotubes; synthesis of carbides, carbonitride and nitrides; steel superficial hardening; copper and alumina sintering; aluminium foam production [13][14]; solar sintering of complex cordierite ceramics [13][14];
- Materials testing: Testing of space engineering materials (atmosphere reentrance) [15].

5. Raw materials supply

A study published in 2011, called Critical Metals in Strategic Energy Technologies revealed potential bottlenecks in the deployment of LCEs (nuclear fission, photovoltaics (PV), wind, bioenergy, carbon capture, and storage and grids, related with shortages of certain metals. Hence, a European Innovation Partnership on Raw Materials was set up in 2012 [2].

The 2014 EU list of the twenty critical raw materials includes [2]: borates, chromium, coking coal, magnesite, phosphate rock, silicon metal, antimony, beryllium, cobalt, fluorspar (fluorite), gallium, germanium, indium, magnesium, natural graphite, niobium, platinum group metals, heavy rare earths, light rare earths and tungsten. Some of them are called high-tech metals. From these, eight metals were classified as critical: dysprosium, europium, terbium, yttrium, praseodymium, neodymium, gallium and tellurium.

It should be considered that wind turbines and electric vehicles use magnets made of rare earths, and solar panels rely on metals such as tellurium and indium, amongst others. A typical 3 MW wind turbine may contain about 120 kg of neodymium in the generator's magnet and an average full electric vehicle may contain 2.6 kg of this element. A likely scenario for Europe in 2030 indicates about 350 GW of wind energy and 60 million electric vehicles, and the International Energy Agency foresees that in 2050 battery electric vehicles will reach 50 million per year [2].

Fig. 3. Wind power components (by Svdmolen, via Wikimedia Commons).

About 90% of the known global reserves of the needed rare earths are found in China. Therefore, substitution, reuse, recycling and higher materials efficiency are approaches necessary to deal with potential supply constraints [2].
Another good example of a practical electronic component related to energy is the light-emitting diodes (LEDs) that use semiconductors and electroluminescence to create light. LEDs contain a range of different metals, typically including rare earths. LED lighting is expanding its applications and forecasts show LED penetration reaching 72% for 2020. Hence, LEDs are a clear example of the rapid development of substitutes [2].
Onshore wind power relies mostly on slow and heavily geared turbines, which convert mechanical energy to electricity through electromagnets using copper induction coils. This is not ideal for offshore installations. There, direct-drive turbines use permanent magnets containing an alloy of rare earth metals. This is why one ambitious goal is to develop a totally rare-earth free magnet. Another aim is to use superconductivity in order to reduce mass and be able to scale-up the installations, overcoming current limitations [2].
Nevertheless, this is not only a problem for renewable energy technologies, because even the nuclear industry and the fossil fuel power sector use near critical materials, and fuel cells use Pt as a catalyst [2].

6. Conclusions

The development of new materials is intimately related to the development and evolution of low carbon energy technologies. Several research lines are being followed, and new ones must be started.
If one wants to do research on materials for energy, it should be stressed that the European Commission launched Horizon 2020 in which more than 5 billion € is available to invest in R&I to promote the Societal Challenge on Secure, Clean and Efficient energy.
The Materials Roadmap Enabling Low Carbon Energy Technologies [16] is a document that puts forward key materials research and innovation activities to advance energy technologies.

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