CHALLENGE 1

# RENEWABLE ENERGY PRODUCTION

**Coordinator**
Hernán Míguez (ICMS, CSIC-US)

**Participating researchers**
Mariano Campoy Quiles (ICMAB, CSIC)
Luis Allan Pérez Maqueda (ICMS, CSIC-US)
Agustín Rodríguez González-Elipe (ICMS, CSIC-US)
Xavier Granados (ICMAB, CSIC)
Víctor Vilarrasa (IDAEA, CSIC) (IMEDEA, CSIC-UIB)
Xavier Obradors (ICMAB, CSIC)
Teresa Puig (ICMAB, CSIC)
José María Ripalda (IMN-CNM, CSIC)
Mariona Coll (ICMAB, CSIC)
Josep Fontcuberta (ICMAB, CSIC)
Alejandro Goñi (ICMAB, CSIC)
Mónica Lira Cantú (ICN2, CSIC-UAB-Generalitat)
María Bernechea (INMA, CSIC)
Pedro Atiénzar (ITQ, CSIC-UPV)
Mauricio Calvo (ICMS, CSIC-US)

## 1. INTRODUCTION AND GENERAL DESCRIPTION

The consequences of the production of energy employing conventional sources on environment and public health has encouraged the interest of the society in finding alternative methods to obtain power in a clean and efficient way. The development of renewable energy sources may be considered as one of the most suitable alternatives that can provide a solution to these problems (Directive (EU) 2018/2001). This chapter presents an analysis of the challenges and opportunities that the field of renewable energy production pose to our society. It is also about how the CSIC can contribute to tackle the former and take advantage of the latter, in order to position itself as a world leader in this field.

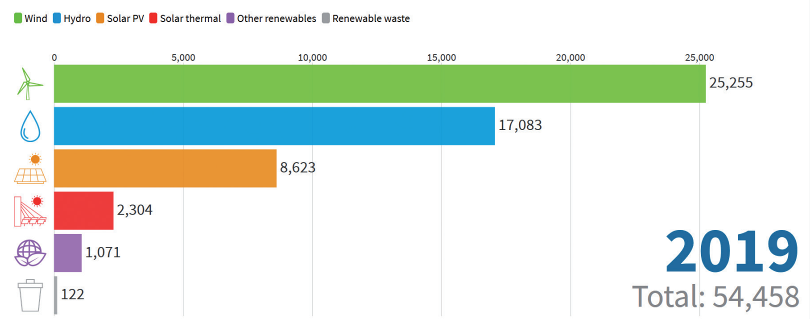
### 1.1. Structure of this chapter

The energy sources that will be considered under this chapter are mainly those based on the conversion of solar (section 8A.2 and 8A.3), wind (8A.4) and geothermal (8A.5) power into electricity. Other renewable sources like those taking advantage of the energy accumulated or carried by large artificial water reservoirs or rivers (hydroelectric), ocean ties or biomass are either not a subject of research within the institution, as it is the case of hydropower, or, on the contrary, the research activity carried out in our institution has been considered so significant as to devote entire chapters to them, as it is the case of biomass or hydrogen based technologies (please see Challenges 5, and 8, respectively). Also, some technologies go beyond production, as it is the case of those based on concentrated solar power, which offer the appealing possibility of storing the generated power in the form of thermal energy. These aspects will be considered in Challenge 2, focused on energy storage. In those cases in which solar energy is the primary source employed to generate some other kind of sustainable fuel, such as hydrogen, all the discussions and implications are left for the chapter specifically devoted to this fuel. Although not usually included in the list of renewable energy sources, we have included a section on nuclear fusion (section 1.6), as it is a highly promising source of clean energy. The activity in this specific field carried out in some of our laboratories is relevant enough as to deserve to be addressed specifically. The very relevant environmental and socio-economic implications of renewable energy production will be dealt with in Challenge 9. Both aspects have also political derivatives of great significance that could also be eventually addressed if this report is analyzed in an even wider framework.

## 1.2. Renewable Energy Sources: Current and Prospective Relevance

Approximately 15% of the total daily average consumption of energy in the world is extracted from renewable, non-polluting sources (WORLD STATISTICS). The main one of them is hydro, followed by wind, solar and the rest of renewables. In Spain, in 2019, out of the 261,020 GWh of electricity produced, 36.8% came from renewable technologies (RED ELÉCTRICA ESPAÑOLA). Spain is indeed internationally recognized as a world leader in renewable energy generation and consumption (INTERNATIONAL ENERGY AGENCY), which is the result of a robust electricity system with high shares of wind and solar PV. Unlike most other countries, in Spain, wind energy is the main source of renewable energy in terms of installed power, as shown in Figure 1, followed by hydro, and solar photovoltaics. The latter surpassed 8,000 MW of installed power capacity at the end of 2019, becoming the technology whose presence has increased the most in the complete set of electricity generation facilities, with an increase of 93,2% compared to 2018. This growing trend is shared by many other countries in the world, boosted by the need to realize a transition to a more sustainable economy.

**FIGURE 1**—Evolution of the renewable power installed by technologies (in MW) in the peninsular electricity system in the period 2006-2019. Source: Red Eléctrica Española.



The forecast for renewable energy technologies and markets worldwide is to be continuously reinforced. In this context, the European Union, which constitutes the political and regulatory framework that defines the directives to be followed by our country as well by all the rest of member states, is one of the most active players in the mid to long-term commitment to reach a decarbonized economy. It has established well-defined goals for 2030, such as:

1. 40 % reduction in greenhouse gas emissions compared to 1990;
2. 32 % total gross final energy consumption from renewables for the entire EU;
3. 32.5 % improvement in energy efficiency;
4. 15 % electricity interconnection between the Member States.

Out of this four goals, in two of them renewable energy plays a central role. While the third and fourth of these goals are clearly the subjects of Challenges 3 and 4, and the third one will be evidently fully included here in Challenge 1, the first one is also strongly linked to the subject of this chapter, given that a significant percentage of greenhouse gases originate in the energy system. This generic analysis reveals already the expected relevance of renewable energy production, both locally in Spain and in our nearest environment. The consecution of these goals has required from each Member State the implementation of an Integrated National Energy and Climate Plan 2021-2030, which can be consulted here in the webpage of the European Commission (European Commision).The Spanish plan is particularly ambitious and sets even higher standards than those requested by the European Commission. In fact, it aims at reaching an electricity generation based 100% on renewable energy for 2050.

### 1.3. Global Challenges

There are distinct generic aspects to the problem of actual implementation of renewable energy as the primary source of energy in the world. The main one is to reach the capability to *provide energy in enough quantity, on demand and at a competitive price*, just like conventional power sources currently do. The barriers towards this ultimate goal can only be overcome by improving the efficiency, stability, costs and manageability of the different clean technologies. These specific challenges have different mid and long-term implications for each one of the technologies herein considered, and will be separately addressed in each section of this Challenge.

Although all renewable energy technologies analyzed in this Challenge are, as a whole, at a very high technology readiness level, there is still a lot of room for improvement based on scientific and technical research. Further spreading of wind energy, so far the largest contributor to the electric power generation pool among all renewable power sources, requires new materials and electricity distribution networks capable of operating at extreme conditions. Photovoltaics, whose market is growing at a vertiginous pace, has still a lot of promising open routes in terms of novel materials and devices that could enormously reduce the costs of energy production and reach new niche markets such as transportation and wearable devices. Concentrated solar power offers the attractive possibility to store the energy as it is produced and, although it could also be made more efficient by improving the materials and processes involved in the cycle of energy production, its main challenge lies in the integration with other clean sources. Geothermal energy holds the enormous potential of being the only source of clean energy that is not fluctuating, but it is the less developed of them all and faces significant challenges in the efficiency of the processes required to use it, like the geographic localization of the available sources, which affects both the location of plants and distribution. All these challenges are confronted by the renewable energy community at a global scale.

On the other hand, there are other challenges that belong to the realms of sociology, politics and philosophy and that might be equally important to actually transform the world energy production into a cleaner and more sustainable one. These are, for instance: the global political response to the claim of economically emerging countries for their right to use their oil, gas and coal to fulfil their need for large amounts of energy on demand; or, the growing disbelief, many times fueled by political interests or simply based on pure ignorance, in the impartial scientific analysis and warnings of the world main threats, and, particularly affecting the subject of this chapter, in the urgency to change to a more sustainable way of generating the energy our world needs. This sort of challenges is not being addressed in this Challenge, as it will be treated separately in Challenge 9, dealing with the economic, sociological and philosophical aspects and implications of energy production and processing as a whole.

## 2. PHOTOVOLTAICS

### 2.1. Impact in basic science panorama and potential applications

The conversion of sun light into electricity through photovoltaic (PV) technology will play a major role in the energetic paradigm shift towards a decarbonized society. Indeed, recent forecasts are predicting that several tens of terawatts of PV capacity will be deployed before 2050 (Haegel, 2019). This would represent an investment of several tens of trillions of euros. A number of factors will enable the realization of this forecast, including: 1) the fact that the sun delivers on Earth hundreds of times the World's energy consumption, being PV one of the most efficient technologies to convert light into electricity; 2) the existence of an already mature technology, based on silicon, whose cost is reducing very rapidly; and 3) the springing of myriad emerging PV families that are meant to enhance the performance of the existing technologies or broaden the PV deployability.

Current research trends are ultimately related to the sun being a source of abundant but dilute energy compared to chemical energy stored in fossil fuels. As a consequence, vast areas need to be covered with PV panels in order to harvest enough energy to match present and future demands. This already implies the use of abundant and non-toxic raw materials with as low as possible embodied energy. For the conventional technologies, this means that reducing embodied energy and/or increasing efficiency are very attractive development avenues. In the case of the emerging technologies, they would find a market beyond niche applications if they exhibit a significantly enhanced efficiency, or, alternatively if they can complement or extend the range of applicability of silicon.

Currently, most PV is deployed as solar farms. In the midterm, PV will be both centralized in more efficient farms and distributed throughout constructed land. They are expected to power portable devices, to be part of urban furniture, or to be integrated in buildings (BIPV), awnings, roads, vehicles, clothes, bags... This vision will become true as more versatile technologies reach the market. Traits of some future PV technologies include low cost, short energy payback times, semitransparency, flexibility, color tuning, camouflage appearance, lightweight, or hardness. In the long run, sustainability will increasingly become the dominant factor for the development or choice of PV technology.

### *Consolidated Technologies*

There are a number of photovoltaic technologies whose development started in the 1970s and that are currently commercially available. These include PV based on crystalline silicon heterostructures (luminous to electric power conversion efficiency: 26.7%), single-junction GaAs (29.1%), CIGS (23.4%), CdTe (22.1%) and stabilized amorphous Si:H (14.0%), with the number between brackets being the corresponding certified lab-scale record power conversion efficiencies [source: NREL chart, accessed on the 10th of March 2020], see Figure 2. Crystalline silicon (c-Si) is an indirect bandgap semiconductor, which results in a weak absorption that has to be compensated by very thick active layers. This motivated the search for alternative direct semiconductors that could be designed as thin films, and thus technologies based on CIGS, CdTe and Si:H were born. These technologies require less semiconducting material and lower processing temperatures, which leads to lower energy payback times compared to crystalline silicon. However, CIGS and CdTe are based on materials that are toxic and/or scarce. The most efficient single junction solar cells made to date is based on GaAs (generally speaking, III-V semiconductors), which is also the base for multi-junction solar cells that have reached efficiencies above 47% under concentration. As the cost is significantly higher than that of silicon, GaAs based PV has so far found mainly niche applications.

Despite the variety of technologies, crystalline silicon dominates the current PV market. The competitive advantages, given by a large production volume and decades of technological refinement, place silicon PV in a position that leaves little room for competitors attempting to offer lower prices. Silicon wafer cost currently represents 8.6% of utility system costs and an even smaller fraction of the levelized cost of energy. While the current efficiency record for silicon solar cells is 26.7 %, state of the art commercial silicon modules have efficiencies just above 20%. Silicon modules can also be made bifacial with a negligible increase in fabrication cost but with an energy production up to 30% higher by harvesting the backside light reflected from the ground.

### *Emerging photovoltaic technologies*

Given the current cost and performance of crystalline silicon, do we need other technologies? Despite the very impressive cost reduction and further efficiency optimization, crystalline silicon has a number of fundamental limitations that restricts its potential uses. First, the non-optimum electronic bandgap of Si appreciably limits its maximum efficiency unless tandem structures are designed. The efficiency is also severely affected by temperature, or by light impinging at non-normal incident angles. On the other hand, so far Si PV can only be made semitransparent by leaving gaps between cells (or drilling holes through it), and color can be tuned by using filters, both of which have strongly detrimental effects on the resulting efficiency. Moreover, silicon is heavy and brittle, which prevent its use where flexibility, lightweight or mechanically robust materials/structures are needed. Finally, the high temperatures needed to produce crystalline Si result in an unavoidably large embodied energy. So a number of technologies are being developed trying to tackle (some of) these issues.

Inorganic cells that build on the knowledge from CIGS use abundant and low toxicity materials, such as $Cu_2ZnSnS_4(Se)$, and currently reach efficiencies up to 12.6%. Quantum dot based cells are often processed from solution at low/moderate temperatures, which is an attractive trait. While the latter has led to lab scale cells exciding 16.5% power conversion efficiencies, the attempts to remove the undesirable lead have thus far resulted in much poorer performance. Technologies based on organic materials, also known as excitonic photovoltaics, include a plethora or subclasses, such as dye sensitized solar cells, evaporated small molecule, and solution processed binary/ternary bulk heterojunction photovoltaics. The latter has experienced a recent boom with the continuous synthesis of novel compounds that have taken their efficiency up to 17.4% (uncertified over 18%), while using non-toxic materials. Interestingly, organic photovoltaics promise very short energy payback times as well as the possibility to tune color, transparency and flexibility. They suffer, however, of poor stability thus far, and present an efficiency that should also be improved further. More recently, hybrid organic/inorganic lead halide perovskites have attracted a well-deserved attention as their performance has gone from less than 10% to the current 25.2% in less than ten years, which is an impressive value for a solution processed technology. Efforts in this case are placed on the replacement of Pb, improving stability and hybridizing with c-Si cells in multi-junction devices. Finally, other technologies are also appearing, such as solution processed all-oxide cells, which promise enhanced intrinsic stability and compatibility between different layers of the cell stack. Moreover, some oxides are ferroelectric, which could theoretically be through the so called bulk photovoltaic effect (<8% efficiency so far).

### 2.2. Key challenging points

The European Commission, after consultation with many stakeholders, established a SET Plan for the development of photovoltaics (SET, 2016). The SET Plan established a series of ambitious goals for the PV technology in terms of efficiency, cost, sustainability and integration.

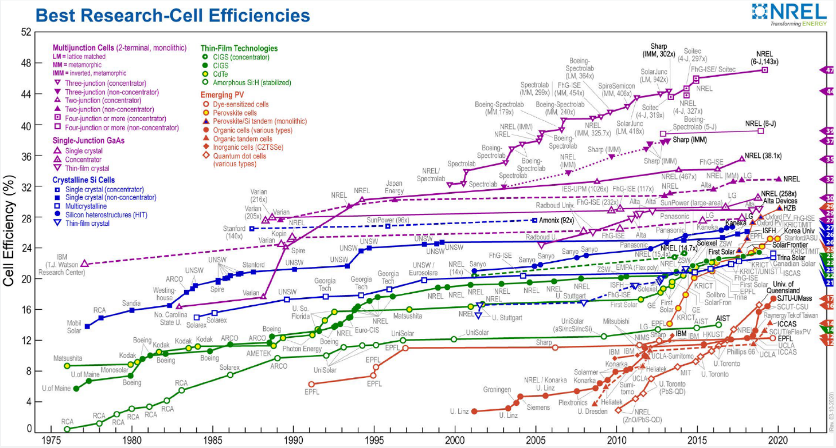
#### *Efficiency*

The goal of the SET Plan is to increase in 35% the PV module efficiency by 2030 compared to the values in 2015. This target is set for both commercial technologies (c-Si, CIGS, CdTe) and new concepts. The capacity of a PV installation is the product of many factors (cell efficiency, inverter efficiency, tracking, optical efficiency). The trends towards higher efficiency in each one of these factors reinforce the others in a synergistic nonlinear positive feedback loop. The nominal standard efficiency of modules in utility-scale new installations is increasing by 0.6% per year on average. At the current rate we will reach the practical limits of single junction photovoltaic technology within a decade, noting that 80% of the U.S. utility-scale systems installed in 2016 already used tracking. A similar trend towards higher inverter efficiencies has also been reported.

The only proven method to significantly increase the c-Si efficiency beyond the limits of conventional technology is the use of multi-junction devices. Making a realistic estimate including temperature and spectral variability effects, it has been shown that the energy production of a silicon solar cell can be increased by 23% by stacking on top of silicon a semitransparent solar cell with an absorption threshold (band gap) of 1.69 eV [Ripalda, 2018]. Strong efforts are placed on the fabrication of tandem cells hybridizing silicon and halide perovskites as well as quantum dot technologies.

Perhaps motivated by the current climate emergency, by scientific policies attracting researchers to the field and/or by the market pressure resulting from

**FIGURE 2**—NREL research cell efficiency chart for different technologies, accessed on the 10th of March 2020.



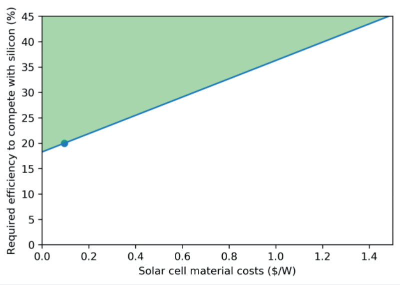
the advent of hybrid perovskites, most technologies have experienced a significant increase in certified efficiency values over the past five years. This is true for both conventional and emerging technologies, the only exceptions being amorphous silicon and dye sensitized solar cells (DSSC).

In the short term, demand for emerging PV technologies can be expected if these can exceed the efficiency of silicon single junctions or provide alternative benefits (see below). It is worth noting that the cell efficiency of multi-cation hybrid perovskite has rocketed up to values above 25% in one decade, a value that is already higher than those for multicrystalline and thin-film crystal silicon cells. Strong efficiency improvements at cell level have also been witnessed by both quantum dot cells and organic photovoltaics, currently exhibiting around 17%.

### *Cost*

The SET Plan aims at reducing “turn-key system costs by at least 50% by 2030 compared to 2015 with the introduction of novel, potentially very-high-efficiency PV technologies manufactured at large scale”. The current cost structure for a large scale PV system is 0.10 \$/W for silicon wafers, 0.25 \$/W for other components and costs in PV modules, 0.21 \$/W for support structures and trackers, 0.06 \$/W for power electronics (inverters), 0.04 \$/W for land

**FIGURE 3**—The green shaded area represents the parameter space of PV technologies competitive with silicon in terms of dollars of capital investment per peak watt of capacity. The blue dot is the current status of commercial silicon PV technology.



acquisition, and 0.45 $/W for balance of system costs (taxes, profit, margin, minor expenses) (Fu, 2017). Thus the cost of PV generated electricity is now mostly determined by costs other than that of the device itself. In this context, increasing the energy efficiency not only results in a higher return on investment, but also lessens the environmental impact of PV installations. The second consequence of such cost structure is illustrated in Figure 3, where the green area is the parameter space of PV technologies competitive with silicon in terms of dollars of capital investment per peak watt of capacity. Clearly, emerging technologies should combine sufficient efficiency with the use of abundant materials deposited through processing schemes exhibiting low thermal and vacuum budgets in order to become competitive technologies. While many of these factors have been proven for some of the emerging technologies at cell level (e.g. hybrid perovskites and organics), upscaling is still work in progress.

## 3. CONCENTRATED SOLAR POWER (CSP)

### 3.1. Impact in basic science panorama and potential applications

A concentrated solar power (CSP) plant generates electrical energy with a thermal power block that uses the heat produced by concentrating the sun irradiation by means of mirrors or heliostats. Three main designs are commercially used: (i) parabolic trough power plant, (ii) power tower systems and (iii) linear Fresnel technology. Currently, the installed capacity worldwide is around 5.5 GW (Concentrating Solar Power Projects, 2019) [Source: National Renewable energy laboratory (NREL), “Concentrating Solar Power Projects,” 2019.], whilst the roadmap proposed by the International Renewable Energy Agency (Remap Case 2050) estimates an ambitious total installed capacity of 633 GW by 2050 (Solarpace, 2020) [Source: Global Energy Transformation - A roadmap to 2050. IRENA, 2018]. Thus, a huge deployment of CSP technology is expected. Spain is leader in concentrated solar energy production with 50 operating plants with 2.3 GW cumulative capacity (Solarpace, 2020). Most of them (45) are parabolic trough, while three are power tower systems and two have linear Fresnel technology. Moreover, the first commercial power tower plants in the world were constructed in Sanlúcar la Mayor (Sevilla), PS10 in 2007 and PS20 in 2009, with 11 y 20 MW, respectively. Places such as the US, Southern Europe, the Gulf region, Chile and South Africa have a great potential for concentrating solar power (Lilliestam, 2018). According to the international energy agency a total of 40 projects are to be commissioned over the next five years (IEA, 2020). Most projects, 21, will be towers, followed by 15 parabolic troughs and 4 linear Fresnel technology. Moreover, projects will grow, typically greater than 100 MW to benefit from economy of scale.

A concentrated solar power plant consists of the basic following elements: (i) solar field, (ii) receiver, and (iii) thermal power block. The total efficiency of the plant is the product of the efficiencies of the different elements. Thus, it is determined by the optical, receiver, and power block efficiencies. Moreover, these efficiencies depend on concentration ratio and receiver temperature (Cahen, 2017). Therefore, increasing the plant efficiency implies increasing the concentration ratio and/or temperature. Nevertheless, it should be also considered that technologies for increasing efficiency might lead to an increase in construction costs that should be taken into consideration. CSP electricity price is currently higher than that obtained from PV, but CSP has the possibility of incorporating a thermal energy storage unit to produce electricity even without solar irradiation (dispatchable renewable energy technology). Thermal energy can be stored as sensible, latent, or thermochemical heat. Storage of heat is nowadays cheaper than storage of electricity. Moreover, new solutions are expected that couple CSP thermal cycle to other applications such as water desalination systems.

In recent years, the high cost pressure and industry development produced significant cost decrease and learning rates increasing 20%. Such trend is expected to continue in the near future (Lilliestam, 2017). Significant efforts have been done to reduce the electricity cost of CSP with the goal of being competitive with conventionally generated electricity without subsidies. The EC H2020 program has recognized the importance of research focused on this cost reduction. Thus, in the Work Program it is specifically stated that it is needed to "improve the competitiveness of the CSP technology, by demonstrating cost reductions and increased performance and reliability of CSP plants, therefore strengthening the European industrial sector and improving the prospects for CSP deployment in Europe". There are 26 active H2020 projects within CSP topic. The same objective is shared by the SunShot program from the Department of Energy of the USA government. Within the targets of such program is the aim of reducing the cost of electricity by an additional 50%, to 5¢ per kilowatt hour for dispatchable CSP, between 2020 and 2030. Based on these further cost reduction in CSP, for countries with high solar irradiation such as Spain, a high development of complementary photovoltaic and CSP plants is expected, as they are economically more interesting than the integration of electricity storage or fossil back-up systems (Pitz-Paal, 2017).

### 3.2. Key challenging points

The European Solar Thermal Electricity Association set a strategic research agenda 2020-2025 for the development of the CSP energy (ESTELA, 2012, 2016). In this agenda detailed research topics and related targets for this industry are presented for the next future. Three main objectives have been proposed which serve to identify the main global challenges that the technology poses:

Challenge 1: Increase efficiency and reduce generation, operation and maintenance costs. In order to reach this goal, the development of novel materials that could outperform currently employed ones has been identified as one of the key achievements that will lead to a more efficient CSP technology. More specifically: new advanced mirrors, with improved reflectivity and durability (antisoiling coatings); new receivers, made of selective coatings with better optical properties and new engineered materials capable of standing higher temperatures; new heat transfer fluids, based on low melting temperature mixtures or pressurized gases, as well as absorber tubes that can stand higher pressures and direct the steam generation. Other challenges to improve the technology belong to the realm of engineering, such as new conversion cycles and systems, which require advanced power cycles and thermal storage system integration schemes or advanced hybridization schemes with other renewable energy sources. It is also relevant to improve control, prediction and operation tools.

Challenge 2: Improve dispatchability, which implies hybridization and integration systems, and in particular integration with large steam plants, with gas turbine and combined cycle plants, or with biomass or PV plants. Also, it involves hybridization, for the direct systems, using the same molten salt mixture as high temperature fluid and heat storage medium. This objective also covers advances in storage, which is one of the most attractive features of this technology, a concept that will be further detailed in Challenge 8B.

Challenge 3: Improve Environmental Profile. It is worth describing some of the solutions that are currently being explored and might indicate the path to go for the next decade. One of the most actives and promising fields of research affecting CSP technology is that of outstanding solar-thermal absorbers. Sophisticated solutions such as three-dimensional structured graphene metamaterial (SGM) have been recently proposed (Lin, 2020). Moreover, significant efforts are being done in raising the temperature of the process to increase efficiency. In commercial CSP plants, the state of the art is the use of molten nitrates with maximum working temperatures limited to about 565 ºC, as both heat transfer fluid and heat storage material. The thermal decomposition of nitrate salts can result in changes in their composition or potential risks of NOx emissions. So, there is also active research to propose new fluids for higher temperatures. In this field new proposals are expected by using more complex mixtures with larger operational ranges of temperatures and improved thermal properties such as higher thermal conductivity. Moreover, new corrosion studies are required as experimental conditions of use are quite harsh. Proposals of new materials or coatings will be also needed.

## 4. WIND ENERGY

Energy harvesting from wind is one of the most extended and implemented renewable energy sources. Accordingly, it is expected to be the largest contributor to the energy target planned in the SET-plan. In Europe, wind generation power achieved 169 GW at the beginning of 2018, almost 16 GW being offshore and 153 GW onshore. By 2020, it is expected to achieve 210 GW, supplying 14% of the global demand. By 2030, it expected to grow up to 350 GW from which 70 GW would be offshore, thus achieving up to 30% of the power demand (SET, 2018). Remarkably, in Spain, during 2019, out of the 36.8% penetration of the renewals achieved in the pool of energy of the electrical system, 20.6% corresponds to wind (REESA, 2020).

The high expectations for the implementation of wind energy as a reliable and cost competitive energy resource integrated in the grid has led to the opening of an attractive market and, simultaneously, has set significant and numerous challenges. This interest was based on the advantages of the wind technology in terms of reliability, long and efficient life, low investment and maintenance costs, and low environmental impact. In turn, the intrinsic irregularity of energy generation based on wind, requires the development of specific strategies and technologies to adapt the electrical grid.

## 4.1. Impact in basic science panorama and potential applications

### *Inland*

The evolution of wind generators in the last decades, specially for inland installations, has been based on the power production of each unit. In the last generation, a typical power of 2-3 MW per unit has been achieved, being the power limited by the impact of the large size of the blades of the turbine blades and the inconstant blowing regime of the wind, as well as by the requirement of an optimization of the LCOE (Levelized Cost Of Energy) concerning maintenance and investment costs. The production of wind generators attends industrial criteria to minimize costs of civil works, transport and installation. From the point of view of the selection of the site, additional requirements are: an adequate averaged wind speed and the proximity of electrical connections to grid with enough capacity to drain the power generated. The so-called wind farm includes all the items required for the connection to the grid, and this pattern is reproduced by all manufacturers and investors. There are more than 100 manufacturers worldwide that warrant a competitive market. Most of them operate and manufacture in Europe: Siemens-Gamesa, Vestas, General Electric, Enercon, Nordex, Goldwind, Suzlon, etc. Each one accumulates more than 10.000 operating generators, the first of this list surpassing already 50.000 units.

Although the market has a high level of competence, and the technologies do not differ in a high degree, there is room for innovation and development to diminish the maintenance costs, increase the operating time and life time, diminish their carbon footprint, and avoid the extensive use of the so called strategic raw materials. All this research and innovation is required if we want wind energy to be a major player within the future energy systems.

### *Off-shore*

Major advantages of wind power generation by off-shore farms are the available room for large turbine blades and the constant blowing rate of the wind.

These advantages have pushed the manufacturers and investors to consider building wind generators of higher power, but pose several challenges associated to the structure of the wind generator, which must be adapted to strong winds, the extreme conditions of the wet and salty environment, the low temperatures, and the few days that the generator can be accessed for maintenance and building up. The development of 10 MW wind turbines is now achievable.

An additional shortcoming concerns the link of the remote placement of the wind energy collectors in off-shore plants with the land grids. This requires the development of specific sea networks able to concentrate the energy in farm nodes that, acting as energy islands, enable energy transport to other nodes and lines in the land. New power electronics developments, functionalities based on the unique properties of high temperature superconducting (HTS) materials and the development of procedures for an effective environmental protection and anti-icing functions, are new strategies to be deployed to cope with the requirements of a safe and efficient off-shore operation. New devices based on the unique performances of the superconducting materials, such as fault current limiters, simplified electric generators able to work at low rotational speed in direct connection to the turbine or robust systems for energy storage to prevent short time failures, and cables with ultra-low impedance are presently being tested. HTS materials are now produced in 100's of kilometres per year, being the cost one of the most relevant challenges for the application.

### 4.2. Key challenging points

Despite the apparent maturity of wind generators, the two essential elements, generator and grid integration, are in continuous development. In what follows, we identify a series of technical challenges affecting the performance of the generator and other parts of the windmill, as well as others aspects specifically related to grid interconnection, although this matter will also be dealt with in Chapter 8D, focused on electrification strategies.

From the research point of view, the field requires efforts to develop materials with specific electrical and magnetic properties in order to lightening the mill structures and enabling the construction of larger and more efficient generators. It also demands the development of new devices to improve the grid resilience. In addition, the development of materials to ensure continuous operation in extreme conditions during long time and efficient forecasting models for optimization of resources and minimizing environmental impact should be promoted following the trends developed by the European Green

Deal. Key points regarding these issues encompass the following aspects: i) regarding the generator, simplification, reliability, improve efficiency, decrease inertia, reduce maintenance cost and expand the time between maintenance actions; ii) concerning the turbine, decrease corrosion and improve anti-icing or de-icing functions in extreme conditions, that call for the development of improved materials and functional coatings; and iii) regarding grid integration, improvement of wind forecasting and energy storage and management procedures, in order to apply reliable predictive models.

Although incremental improvement in these aspects is expected by the application of current technologies, breakthroughs are still expected through the incorporation of radically new technologies based on HTS materials. This will be the case for the design of novel current limiters, transformers, and hybrid energy storage systems as SMES to enhance power and safety of the grid and to protect the generator against electrical events. For this, it is mandatory to reduce the HTS materials cost and increase their production capacity and strong efforts are being devoted to prepare HTS tapes with a low cost/performance ratio (Puig, 2020). Other issues, where the incorporation of HTS solutions can be an option with respect to standard alternatives based on permanent magnets, concern the system design and aim at diminishingthe weight of the generator and its kinetic moment, at increasing the power density and to apply the concept of “direct drive” or medium speed to avoid or diminish the complexity of the gear box. HTS also allows facing the impact of the critical raw materials required by the permanent magnet alternatives. All these call for an improvement in HTS manufacturing procedures and costs, magnetic field behaviour of the critical current, homogeneity of the wires, quench resilience and in mechanical properties, topics that are matter of research challenges nowadays.

In wind farms located off-shore and in other placements with aggressive environmental conditions, emerging problems deal with the effect of salty water, the usually stronger wind and the low, very frequently minus zero, temperatures that lead to increasingly higher maintenance costs. Formation of ice aggregates on the blades and other components may be a critical problem in cold climates (Golovin, 2013). The foreseen progression in the installation of wind facilities in locations where corrosion is very severe makes the finding of protection solutions and in-place analytical monitoring techniques critical to reduce the environmental impact (Kirchgeorg, 2018). Innovative surface engineering solutions, in-situ and automatic monitoring and alarm systems will be some of the future developments that will be implemented to reduce aging of the facilities and derived environmental deleterious effects.

## 5. GEOTHERMAL ENERGY

Geothermal energy utilizes the heat from the Earth interior to produce electricity and/or deliver heating and cooling. The highest heat gradients are found around tectonic plate boundaries and in active volcanic areas. A remarkable characteristic of this renewable energy is its capacity to provide a constant output of energy if required. Thus, geothermal energy can cover the base of smart thermal and electricity grids. However, only a small portion of the geothermal potential is currently being exploited, leaving a huge potential for further deployment ahead (Bertani, 2016). Geothermal energy can be classified into power generation and/or direct use of heat. Power requires of high enough temperature to boil a fluid to move turbines. Once the fluid condensates, its heat can still be used, maximizing efficiency. Heat can also be used in a cascade way, using it in various applications that require a progressively lower temperature, to enhance efficiency (Shortall, 2019).

### 5.1. Impact in basic science panorama and potential applications

The global installed capacity of geothermal power plants is 11 GWe, 3 GWe of which are installed in Europe in 127 geothermal power plants (Uihlein, 2018) (Dumas, 2018). Geothermal energy represented the 6.8 % of the energy supplied by renewables in 2017 (IEA, 2018). 93 % of the installed capacity worldwide is concentrated in ten countries: United States, the Philippines, Indonesia, Turkey, Mexico, New Zealand, Italy, Iceland, Kenya and Japan. Currently, Spain does not produce electricity from geothermal energy. The generalization of the use of geothermal energy for heating and cooling purposes can significantly contribute to reach carbon neutrality (HEAT ROADMAP EUROPE, 2019). If the geothermal power development targets of all countries are met, the installed capacity would reach 32 GWe in 2030 (Matek, 2016). Furthermore, it is estimated to scale up by one order of magnitude by 2050 provided that research and development comes up with innovative solutions for reducing the current pre-development costs and high risks (Limberger, 2018) (De Simone, 2017).

### 5.2. Key challenging points

To generalize the use of low-enthalpy geothermal systems to climatize buildings. Representing half of the total energy demand, building climatization through heating and cooling requires to undergone a profound transformation to decarbonize the sector and achieve near Zero-Energy Buildings (nZEB). Geothermal energy is a ubiquitous renewable source and, as such, it can be used anywhere in the planet for heating and cooling purposes through Ground Source Heat Pumps (GSHP) and Underground Thermal Energy Storage (UTES).

To lower the temperature required for generating electricity from medium-enthalpy geothermal systems. Such achievement would imply generating electricity at shallower depths, facilitating operations because permeability of geological media usually decreases with depth. Furthermore, it will enable the combination of geologic carbon storage with geothermal energy production.

To attain enhancing permeability in tight rock for high- and very high-enthalpy geothermal systems. Deep geothermal systems rarely present enough permeability to be operated without having to stimulate the wells. Effective stimulation techniques with a low induced seismicity risk should be developed to permit enhancing reservoir permeability without inducing large earthquakes. Improving zonal isolation is key to stimulate individual fractures in a controlled way, rather than stimulating the whole open well simultaneously. Combination of hydro-fracturing and hydro-shearing should permit creating a reservoir permeable enough to circulate fluids between the doublet of wells without imposing an excessive pressure gradient.

To mitigate corrosion and scaling issues caused by the high reactivity of chemical species in high temperature environments. Geochemical modelling can assist the operators of geothermal plants to set the optimum operating conditions in order to minimize corrosion problems and clogging due to scaling. Such issues imply elevated maintenance costs and replacing equipment, like pumps. Methodologies to reduce these problems as well as potential ways of utilizing precipitated minerals will be necessary as geothermal energy scales up.

*To forecast induced seismicity in order to minimize the risk of inducing perceivable and damaging earthquakes as a result of geothermal energy production.* Forecasting injection-induced seismicity is a big challenge that will require of ground-breaking solutions. Current protocols have proven unsuccessful and thus, a new paradigm is required.

## 6. FUSION: AN ALTERNATIVE CLEAN ENERGY SOURCE

Fusion energy has been, since many years, a promise of unlimited, safe and carbon-free electricity energy source. Fusion is a source of heat-related generation route, which could become a base load of electricity source or even an energy source for renewable fuels (Hydrogen for instance). The most suitable nuclear reaction for fusion reactors is D + T = He + n + 17.6 MeV, where D is deuterium and T tritium. Since the concentration of deuterium in the oceans is rather high and tritium can be generated through the nuclear reaction of neutrons with Li, there exists enough fuel to generate the energy required for mankind for millions of years. This reaction, however, requires a temperature (T) in the range of 100 millions degrees and to achieve a plasma density (n) high enough to overcome the Coulomb repulsion during a long enough time.

### 6.1. Impact in basic science panorama and potential applications

Historically, the progress towards the fusion goal made a quantum leap with the design of tokamaks as magnetic confinement systems for plasma. Initiated in the Kurchatov Institute in Moscow in the late 60’s, since then several tokamak models have been built and plasma properties for fusion were tested all around the world. All this R&D led to the largest international scientific installation ever organized (35 countries, a cost of at least 10 bn€ in 30 years of life), the International Thermonuclear Experimental Reactor (ITER). ITER is nowadays under construction in Cadarache (France), ignition should start in 2023 and its design is based on the best materials available in the early 2000s. ITER is an experimental reactor, still not intended to generate usable energy. Electricity is instead scheduled to be generated in the next prototypes, the so-called DEMO reactors, being at present in the initial stage of design in several continents (Europe, Japan, China, ...) and which should incorporate novel materials and technologies. Overall, these “classical” fusion technologies based on low temperature superconductor (LTS) materials are expected to generate clean energy beyond mid-21st century.

A game changer appeared just after ITER was designed in 1986: high temperature superconductors (HTS) and the development of high magnetic field conductors based on $REBa_2Cu_3O_7$ coated conductors (REBCO CCs, where RE stands for Rare Earth or Y), which allowed the development of ARC (Affordable, Robust, Compact) tokamak reactors (Sorbom, 2015). HTS magnets are expected to generate magnetic fields of 12 T at the center of plasma, compared to the 5 T of ITER, which has a huge effect on the energy gain that can be achieved with a fusion reactor, which is proportional to ~ $B^3$ while the power density is ~$B^4$. As a consequence, ARC compact reactors (~500 MW) have a core radius of 1.5 m instead of 6.2 m of ITER and the overall plasma volume is 10 times smaller (Whyte, 2016).

A key issue of ARC reactors, besides the smaller size and the lower cost, is the long term life expectance. While in ITER replacing any material in the core becomes a tantalizing technological problem involving very complex robotics, ARC reactors are much more compact and demountable, thus making accessible the inner vacuum vessel for any replacement. This novel design has an enormous impact in the long term requirements on materials and engineering devices of the fusion reactors, particularly it reduces the concerns on irradiation effects by enabling spare replacements.

ARC fusion reactors are, therefore, a very recent breakthrough requiring still intensive R&D of materials and plasma physics, but they have the potential to bring fusion energy to reality much sooner and much cheaper. First estimates and technological development plans of the novel spin-off companies (for instance, Commonwealth Fusion System in US and Tokamak Energy in UK) is that 2030 is a reasonable horizon to have net fusion energy generation. Fusion energy appears again, therefore, as a unique opportunity to become a clean energy source in a reasonable time scale.

### 6.2. Key challenging points

There are many scientific and technical challenges associated to the compact fusion reactors, many of them related to the relevance of neutron (14.1 MeV) irradiation effects on the vessel, magnets and other advanced materials around the core of the reactor. But even if these issues are significant, the most relevant challenge is to further improve the performance of REBCO CCs and the corresponding magnets.

The requirements related to CCs are multiple because tokamak reactors are composed of different magnets working under different physics conditions. Some of them are:

- Achieving high critical current densities under these extreme conditions; this is a very challenging objective which is even stronger when we consider that low cost manufacturing techniques are needed to obtain competitive km-long conductors.

- Achieving a high figure of merit cost/performance (€/kA m, i.e. cost of 1 m of CC having 1 kA of critical current), needed to advance in low cost chemical methodologies, such as Chemical Solution Deposition (CSD), and high throughput production (fast growth techniques) of REBCO CCs (Obradors, 2014).
- Development of efficient stabilization architectures against quenching, since lifetime of magnets depend critically on the fast propagation of quench.

In conclusion, among the demands of R&D related to compact ARC fusion reactors we should consider many issues related to the plasma handling and materials working under extreme conditions, but the technological development of HTS materials and magnets stands as the most relevant challenge.

## 7. CONCLUSION

From all the facts and figures presented in this chapter, it can be stated that our country is called to play a key role in the future development and commercialization of renewable energy. We have natural resources, a high level of technological advancement already achieved and the international recognition of our position in this field at all levels. There is, therefore, a clear opportunity to overcome the endemic and historical dependence of our economy on highly fluctuating activities such as tourism and construction and try to establish ourselves as world leader in a technological field. Coordinated efforts devoted to renewable energy by all potentially contributing national actors should be highly encouraged. In this context, CSIC have all the potential to become a central piece in this picture if proper planning and allocation of resources are in place.

## CHALLENGE 1 REFERENCES

References **(by Section)**

*Section 1. Introduction*

**Directive (EU) 2018/2001** of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources.

https://ec.europa.eu/energy/topics/energy-strategy/national-energy-climate-plans_en

**International Energy Agency**, https://www.iea.org/countries/spain

**Red Eléctrica Española**, https://www.ree.es/en/press-office/news/press-release/2019/12/spain-closes-2019-10-more-installed-renewable-power-capacity

**Red Eléctrica Española**, https://www.ree.es/en/press-office/news/press-release/2020/03/renewable-energy-already-exceeds-installed-power-capacity-of-other-sources-of-energy-on-the-Spanish-peninsula

**Regulation (UE) 2018/1999** of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council.

**World Statistics**, https://www.worldometers.info/energy/

*Section 2. Photovoltaics*

**Anaya, M., Lozano, G., Calvo, M. E., Míguez, H. (2017).** ABX3Perovskites for Tandem Solar Cells. *Joule,* 1: 769-793.

**Bernechea, M., et al. (2016).** Solution-processed solar cells based on environmentally friendly AgBiS2 nanocrystals. *Nature Photonics,* 10: 521–525.

**Essig, S. et al. (2017).** Raising the one-sun conversion efficiency of III–V/Si solar cells to 32.8% for two junctions and 35.9% for three junctions. *Nature Energy,* 2: 17144.

**Francisco-López, A., et al. (2019).** Equal Footing of Thermal Expansion and Electron–Phonon Interaction in the Temperature Dependence of Lead Halide Perovskite Band Gaps. *J. Phys. Chem. Lett.* 10, 7: 2971-297.

**Fu, R., Feldman, D., Margolis, R. (2017).** U.S. solar photo-voltaic system cost benchmark: Q1 2017. Tech. Rep. NREL/TP-6A20-68925.

**Gomez, A., et al. (2019).** Ferroelectricity-free lead halide perovskites. *Energy & Envirom. Scien.,* 12: 2537-2547.

**Haegel, N. M. et al. (2019).** Terawatt-scale photovoltaics: Transform global energy, *Science,* 364: 836–838.

**Harillo-Baños, A., Rodríguez-Martínez, X., Campoy-Quiles, M. (2020).** Efficient Exploration of the Composition Space in Ternary Organic Solar Cells by Combining High-Throughput Material Libraries and Hyperspectral Imaging. *Adv. Ener. Mater.,* 10, nº 1: 1902417.

**Jurado, J. P., et al. (2019).** Solar Harvesting: a Unique Opportunity for Organic Thermoelectrics? *Adv. Ener. Mater., 9,* nº 45: 1902385.

**Khenkin, M. V. et al. (2020).** Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures. *Nature Energy,* 5: 35-49.

**Lopez-Varo, P., et al. (2016).** Physical aspects of ferroelectric semiconductors for photovoltaic solar energy conversion. *Physics Reports,* 653: 1-40.

**Machado, P. ET al. (2019).** Band Gap Tuning of Solution-Processed Ferroelectric Perovskite BiFe1–xCoxO3 Thin Films. *Chem. Mater.* 31: 947-954.

**Pérez-Tomás, A., Lira-Cantú, M., Catalan, G. (2016).** Above-Bandgap Photovoltages in Antiferroelectrics. *Advanced Materials,* 28: 9644-9647.

**Ripalda, J. M. et al. (2018).** Solar cell designs by maximizing energy production based on machine learning clustering of spectral variations. *Nature Communications,* 9: 5126.

**SET (2016).** Plan - Declaration on Strategic Targets in the context of an Initiative for Global Leadership in Photovoltaics (PV).

**Vezie, M. S., et al. (2016).** Exploring the Origin of High Optical Absorption in Conjugated Polymers. *Nature Materials,* 15: 746-753.

*Section 3. Concentrated solar power*

**Almendros-Ibáñez, J.A., et al. (2019).** A review of solar thermal energy storage in beds of particles: Packed and fluidized beds. Solar Energy, 192: 193-237.

**Cabeza, L.F. (2019).** Thermal energy storage in solar energy systems: editorial. Solar Energy, 192: 1-2.

**Caccia, M., et al. (2018).** Ceramic–metal composites for heat exchangers in concentrated solar power plants. Nature, 562(7727): 406-409.

Cahen, D., et al., Concentrated Solar Power: Components and materials. EPJ Web of Conferences, 2017. 148.

**Carrillo, A.J., et al. (2019).** Solar Energy on Demand: A Review on High Temperature Thermochemical Heat Storage Systems and Materials. Chemical Reviews, 119(7): 4777-4816.

**Concentrating solar power on the road to 2030 (2016).** ESTELA: Brussels.

**Concentrating Solar Power Projects. (2019).** National Renewable energy laboratory (NREL),: Golden, CO, USA.

**Gauché, P., et al. (2017).** System value and progress of CSP. Solar Energy, 152: 106-139.

https://www.iea.org/articles/is-concentrating-solar-power-forecast-to-contribute-to-global-energy-storage-over-the-next-five-years. 14/03/2020].

https://www.solarpaces.org/csp-technologies/csp-potential-solar-thermal-energy-by-member-nation/spain/. 14/03/2020.

**Lilliestam, J. And Pitz-Paal, R. (2018).** Concentrating solar power for less than USD 0.07 per kWh: finally the breakthrough? Renewable Energy Focus, 26: 17-21.

**Lilliestam, J., et al., Empirically observed learning rates for concentrating solar power and their responses to regime change. Nature Energy, 2017. 2(7).**

**Lin, K.T., et al. (2020).** Structured graphene metamaterial selective absorbers for high efficiency and omnidirectional solar thermal energy conversion. Nat Commun, 11(1): p 1389.

**Ortiz, C., et al. (2019).** The Calcium-Looping (CaCO3/CaO) process for thermochemical energy storage in Concentrating Solar Power plants. Renewable & Sustainable Energy Reviews, 113: 18.

**Pitz-Paal, R. (2017).** Concentrating solar power: Still small but learning fast. Nature Energy, 2(7).

**Solar Thermal Electricity Strategic Research Agenda 2020-2025 (2012).** ESTELA: Brussels.

**STE Storage Value (2016).** ESTELA.

*Section 4. Wind power*

**(a) Golovin et al.: Designing durable icephobic surfaces**, doi:10.1126/sciadv.1501496; **(b) Susoff et al. (2013)** Evaluation of icephobic coatings—Screening of different coatings and influence of roughness, dx.doi.org/10.1016/j.apsusc.2013.06.073

**Granados, J. et al. (2018).** *Synchronous generator for wind turbines*, Patent Publication Application US 2018/0062484 A1. Concesión en España ES 2656821 B1(2018)

**Kirchgeorg T. et al. (2018).** Emissions from corrosion protection systems of offshore wind farms: evaluation of the potential impact on the marine environement. doi.org/10.1016/j.marpolbul.2018.08.058

**Puig T. et al (2020).** Nature Communications 11, 344

**Reesa (2020).** El sistema eléctrico español: avance 2019

**Set-Plan Offshore Wind Implementation Plan**. Final adopted by SET-plan Steering Committee 13 June, 2018

*Section 5. Geothermal Energy*

**Bertani, R. (2016).** Geothermal power generation in the world 2010–2014 update report. Geothermics, 60: 31-43.

**De Simone, S., Carrera, J., Vilarrasa, V. (2017).** Superposition approach to understand triggering mechanisms of post-injection induced SEISMICITY. GEOTHERMICS, 70, 85-97.

**Dumas, P., Garabetian, T., Pinzuti, V., & Marchitelli, C. (2018).** EGEC geothermal market report. Key Findings.

**HEAT ROADMAP EUROPE (2019).** The legacy of Heat Roadmap Europe 4. Scenarios, recommendations and resources for decarbonizing the heating & cooling sector in Europe and completing the strategic long-term vision of the EU. 2050 Heat Roadmap Europe

**IEA (2018).** Renewables Information 2018, OECD Publishing, Paris, https://doi.org/10.1787/renew-2018-en.

**Limberger, J., Boxem, T., Pluymaekers, M., Bruhn, D., Manzella, A., Calcagno, P., Van Wees, J. D. et al. (2018).** Geothermal energy in deep aquifers: A global assessment of the resource base for direct heat utilization. Renewable and Sustainable Energy Reviews, 82: 961-975.

**Matek, B. (2016).** Annual US & Global Geothermal Power Production Report, Geothermal Energy Association, Washington, USA: 36.

**Parisio, F., Vilarrasa, V., Wang, W., Kolditz, O., & Nagel, T. (2019).** The risks of long-term re-injection in supercritical geothermal systems. Nature Communications, 10(1): 4391.

**Shortall, R., Uihlein, A. (2019).** Geothermal Energy Technology Development Report 2018, EUR 29917 EN, European Commission, Luxembourg, ISBN 978-92-76-12543-3, doi:10.2760/303626, JRC118299

**Uihlein A. (2018).** JRC Geothermal Power Plant Dataset - Documentation, EUR 29446 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-97264-5, doi:10.2760/203858, JRC113847

*Section 6. Fusion: an Alternative Clean Energy Source*

**Gutierrez, J. et al. (2007).** Strong isotropic flux pinning in solution-derived $YBa_2Cu_3O_{7-x}$ nanocomposite superconductor films. Nature Materials 6: 367-377

**Llordes, A. et al. (2012).** Nanoscale strain-induced pair suppression as a vortex-pinning mechanism in high temperature superconductors. Nature Materials 11: 329-336

**Obradors, X., Puig, T. (2014).** Coated conductors for power applications: materials challenges Superconductor. Science and Technology 27, nº 044003: 1-17

**Soler, L., et al. (2020).** Ultrafast transient liquid assisted growth of high current density superconducting films. Nature Communication 11, nº 344: 1-8

**Sorbom, B.N., et al. (2015).** ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets», Fusion Engineering and Design 100: 378-405

**Whyte, D.G. et al. (2016).** Smaller & sooner: Exploiting high magnetic fields from new superconductors for a more attractive fusion energy development», Path, Journal of Fusion Energy 35: 41-53

**TABLE 1—**List of challenges to be addressed for the Challenge 1

| | SHORT TERM (< 5 YEARS) | MID TERM (5-10 YEARS) | LONG TERM (> 10 YEARS) |
|---|---|---|---|
| **PHOTOVOLTAICS** | • Create a CSIC PV technology platform as a vehicle to communicate and find synergies between PV technologies. Position CSIC as expert on PV related topics at national/ international levels.<br>• CSIC to consolidate links with the most relevant energy institutes working on PV<br>• Proof of concept hybrid photovoltaic technologies based on two PV technologies.<br>• IP protection and dissemination of novel device concepts, materials and processing protocols.<br>• Determination of main factors limiting device stability in the different technologies.<br>• Demonstration of emerging solar cell technologies with high efficiency and durability for small scale applications (e.g. powering IoT)<br>• Rise public awareness of the energy problem. | • CSIC to gain critical mass on priority PV topics. Possible creation of a CSIC Institute of Energy Research to unify efforts in a multidisciplinary approach to the energy challenge. Coordination of a European Energy Flagship (international leadership). Cooperation to reduce non-PV related cost of the systems.<br>• High efficiency solar cell technologies with no scarce or toxic elements.<br>• Demonstrated long term stability for selected PV technologies. IP protection on encapsulation strategies.<br>• Demonstration of ultrahigh PV efficiency >50%.<br>• Proof of concept hybrid PV/ non-PV technologies.<br>• Achievement of high TRL for novel concepts that facilitates a wide deployment of building integrated photovoltaics.<br>• CSIC/Industry co-development of upscaling and manufacturing process for selected PV technologies. | • CSIC to exploit the generated intellectual property on PV.<br>• Demonstration of solar cell technologies with energy return on investment greater than 50 for unrivaled energy generation sustainability.<br>• Achieving high TRLs for hybrid concepts with very high efficiencies.<br>• Availability of a large palette of efficient and durable solar cell technologies to enable nationwide deployment at all levels (solar farms, buildings, public infrastructure, designs, textiles, advertisement infrastructure, portable devices, vehicles, etc.). Wrapping cities on PV. |

| | **SHORT TERM (< 5 YEARS)** | **MID TERM (5-10 YEARS)** | **LONG TERM (> 10 YEARS)** |
|---|---|---|---|
| **CONCENTRATED SOLAR POWER** | • Development of new high temperature range (low melting point and high stability temperature) fluids<br>• Development of nanofluids with improved thermal properties (heat capacity or heat conductivity | • Developments in Latent and sensible heat storage systems (achievement of higher TRL)<br>• Development of new receiver materials and coatings with high absorptivity and high thermal stability<br>• Studies in Materials compatibility with new thermofluids<br>• Advanced solar mirrors<br>• Integration with high temperature power cycles<br>• Global CSP systems cost reduction (LCOE 5-7 c€/kWh) | • Integration of CSP with other technologies (such as water desalination)<br>• Achievement of high TRL of new thermochemical storage systems<br>• Hybrid systems integration (such as CSP/PV) |
| **WIND ENERGY** | • Improve passive and active de-icing systems and their integration in blades and other components<br>• Development of new low-weight structural materials for the building of lighter structures<br>• New corrosion protective coatings and materials<br>• Improve sensitivity of distributed analytical monitoring systems<br>• Design and test under device working conditions of novel (cost/performance) competitive HTS nanostructured materials<br>• Design of simplified generators using HTS and easy grid integration for high power wind mills.<br>• Develop new coating to avoid corrosion and icing in the blades | • Incorporate automatic operation systems for de-icing.<br>• Connect monitoring systems with integrated alarm procedures both for operational and environmental control.<br>• Development of new low ac losses HTS conductors with improved quench resilience and cryogenic systems<br>• Implementation of HTS devices for ultrafast electrical protection as HTS fault current limiters and SMES | • Development of new wind mill concepts and designs that outperform the current technology (e.g., sea movable structures, structures based in more than one tower, etc.) incorporating all the energy efficiency, aging and monitoring systems developed previously.<br>• Incorporation of singular test facilities and pilot plants in collaboration with engineers and wind energy industry |

| | SHORT TERM (< 5 YEARS) | MID TERM (5-10 YEARS) | LONG TERM (> 10 YEARS) |
|---|---|---|---|
| **GEOTHERMAL ENERGY** | • Adaptation of the legislation to regulate the efficient use of geothermal resources<br>• Development of techniques to efficiently enhance permeability of hot tight rock with a low risk of inducing seismicity<br>• Successful demonstration of 5 MWe geothermal power plants in Enhanced Geothermal Systems (EGS) | • Achievement of high TRL for Organic Rankine Cycles (ORC) or kalina cycles to generate electricity at temperatures well below 100 °C<br>• Development of reliable forecasting methodologies of induced seismicity<br>• Scale-up of 5 MWe geothermal power plants in deep hot rock<br>• Technological development of geothermal energy production in deep volcanic areas in pilot tests | • Generalization of the use of shallow geothermal resources to climatize buildings and district heating<br>• Achievement of high TRL for the combination of geologic carbon storage with geothermal energy production at industrial scale<br>• Widespread deployment of 5-30 MWe geothermal power plants in deep hot rock |
| **FUSION** | • Design and test under device working conditions of novel (cost/performance) competitive HTS nanostructured materials.<br>• Development of computational tools to analyze HTS behavior on the device system.<br>• Dedicated programs to strengthen joined collaborations between CSIC, institutions and industry. | • Investigation of the wire-to-device properties like thermal runaway, electromagnetic and mechanical properties, ac losses, electrical insulation, joints, geometries for compact fusion reactors | • Prof-of-concept for HTS tapes and magnets for the compact fusion concept |

## ONE SLIDE SUMMARY FOR EXPERTS

### Challenge

Develop the knowledge and technology needed to substitute the use of contaminant power sources by clean and renewable ones.

### Approach

The actual implementation of renewable energy as the primary source of energy in the world requires reaching the capability to provide energy in enough quantity, on demand and at a competitive price, just like conventional power sources currently do. The barriers towards this ultimate goal can only be overcome by improving the efficiency, stability, costs and manageability of the different clean technologies. These specific challenges have different mid and long-term implications for each one of the technologies considered, i.e. Photovoltaics, Concentrated Solar Power, Wind, Geothermal and Fusion.

### Social and economic impact

There is an urgent environmental and economic need to substitute the traditional fossil based power sources, highly contaminant and main contributors to the greenhouse effect, for cleaner and renewable ones. This field will play a key role in the transition to a more sustainable economy worldwide. From a national perspective, it can be stated that our country is called to play a central role in the future development and commercialization of renewable energy. The existence of natural resources, a high level of technological advancement already achieved and the international recognition of our position in this field at all levels indicate that there is a clear opportunity to overcome the endemic and historical dependence of our economy on highly fluctuating activities such as tourism and construction and try to establish ourselves for the first time as world leader in a technology based market.

### Involved teams

CSIC's research is aligned with European initiatives such as the EERA (European Energy Research Alliance). Its main strength lies in the high quality and wide diversity of expertise hold inside the institution, mainly, but not only, in the area of Energy Materials Science and Technology, with very relevant active public and industrial projects. Current activities target both the improvement of existing technologies and the development of new concepts and focus mostly in technology readiness levels (TRL) ranging from proof-of-concept to technology demonstration.

## ONE SLIDE SUMMARY FOR THE GENERAL PUBLIC

### Challenge

Develop the knowledge and technology needed to substitute the use of contaminant power sources by clean and renewable ones.

### Approach

The actual implementation of renewable energy as the primary source of energy in the world requires reaching the capability to provide energy in enough quantity, on demand and at a competitive price, just like conventional power sources currently do. The barriers towards this ultimate goal can only be overcome by improving the efficiency, stability, costs and manageability of the different clean technologies. These specific challenges have different mid and long-term implications for each one of the technologies considered, namely, Photovoltaics, Concentrated Solar Power, Wind, Geothermal and Fusion.

### Social and economic impact

Our world faces serious environmental and economic challenges. Climate change is directly linked to economic activity and specifically to the way in which we produce the energy we need. Thus, reducing the impact of human activity on the environment requires finding new cleaner ways of producing the energy we consume. For this reason, the development of stable, reliable, efficient and profitable renewable power sources is of outmost importance, now more than ever. Also, from a national perspective, this challenge poses an opportunity for our country to become a world leader in a technology based field in which we have already a strong position. This will help us overcome the endemic and historical dependence of our economy on low added value activities.

### Involved teams

CSIC's research is aligned with all relevant national and international initiatives in renewable energy, and has a long tradition of productive cooperation with industrial partners working in this field. Current activities target both the improvement of existing technologies and the development of new concepts.