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SCIENCE & SOCIETY

THE ENERGY TRANSITION

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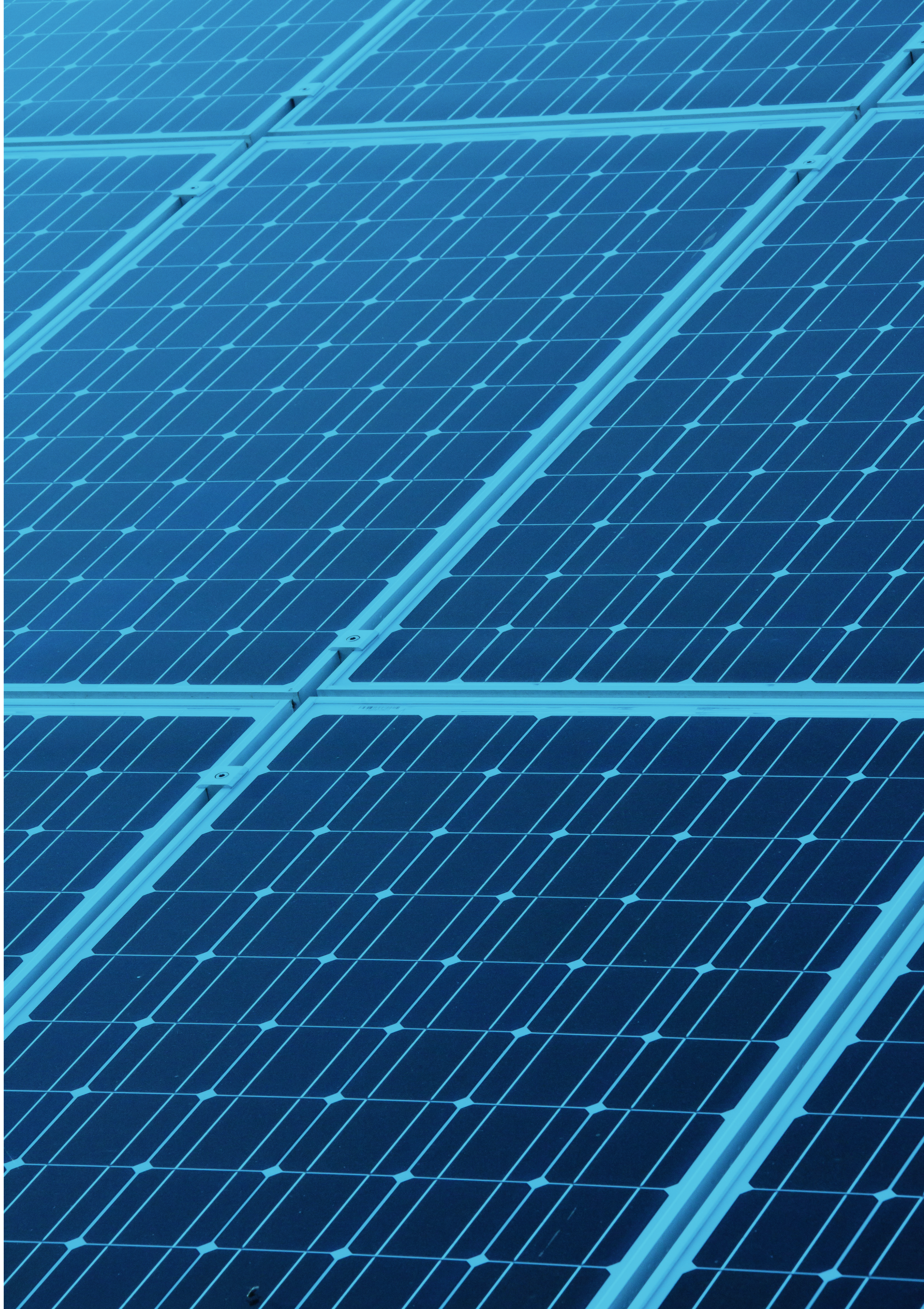

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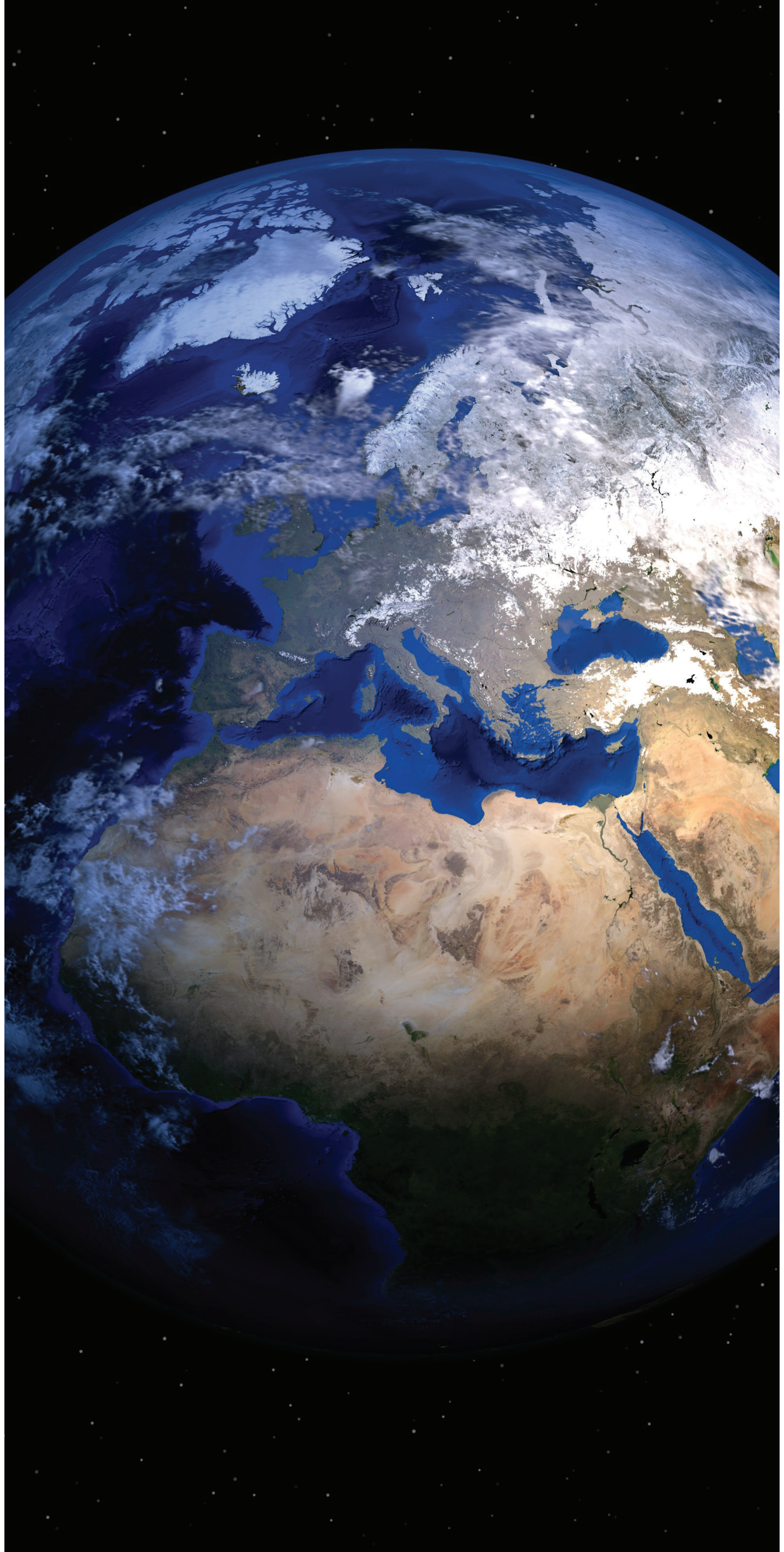

SCIENCE & SOCIETY

This is a new issue of the "INESC TEC Science & Society" magazine, created by INESC TEC to disseminate science to society in general and thus contribute to the global digital transformation, in the hope that it may be of interest to managers, politicians and technicians concerned with the topic addressed in each number.

This fifth issue is dedicated to energy transition, a topic that is currently of the greatest importance; we hope it will have the same acceptance obtained by the previous editions.

Once again, the authors are INESC TEC researchers and external personalities that we invited to ensure a more comprehensive view of the topic.

The magazine is distributed online, in PDF format, as well as on a platform that we have been improving, which allows more user-friendly access from mobile terminals. The full PDF version, obviously in a format closer to analogue, ensures a quality that is not achieved on digital platforms - whose characteristics are quite different; that is why an evaluation of alternatives is under way, to further improve the current experience.

I would like to thank all those who contributed to this issue, highlighting the work carried out by the Editorial Board and INESC TEC's Communication Service of INESC TEC - and, in particular, the invited theme editors and all the authors.

We sincerely hope that the result will be to your liking.

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EDITORIAL

THE ENERGY TRANSITION

The decarbonisation of the economy (and of society) is an essential component to tackle climate change and its terrible consequences. Although the term "transition" suggests continuity, strong measures were taken or projected, throughout the world (namely in the European Union); first, by cleaning the electricity generation mix (more renewables, no coal, less natural gas) and second, by transferring the consumption in transportation, industry, and domestic uses, from fossil fuels to electricity. Efficiency is, of course, among the concerns in all the cases.

This is a simplistic description of the energy transition, since accomplishing these objectives requires new developments in many technical domains and will change the way our societies are organised. Addressing some of the relevant issues is the main idea behind this special theme, so we are not trying to describe systematically all the details, but rather present original thoughts on selected topics, as a contribution to the readers' perspective of the subject - either because the topic is less obvious or because relevant questions, not always explicitly formulated, are answered.

We start with the 100% renewables goal for the electric system, something that is desirable and feared at the same time. Carlos Moreira and Rui Castro address this topic and share their view on the necessary changes to meet said goal and the overall consequences.

In the foreseeable future, the importance of distributed generation (namely Low Voltage solar photovoltaic production) will increase, as compared with the traditional centralised electric power system situation. The concept of security of supply and associated methodologies may need a reformulation because of the changes in the global flows of the electric system. Leonel Carvalho discusses the relevant aspects of present and future evaluation of the security of supply.

The Portuguese and the UE electricity markets operate according to a structure designed to accommodate conventional players (centralised generation companies, retail energy sellers) in a marginalist scheme, although feed-in tariffs (to remunerate the special regime production, i.e., CHP and renewables) were possible from the beginning. Should this organisation continue? João Saraiva analyses this question, while Jose Villar, Ana Antunes e Cláudio Monteiro discuss the active role of energy communities in the energy transition. Still regarding how the overall electric system is organised, but this time in technical terms, we feature an outlook on the role of energy conversion systems based on advanced power electronics, and their relevance to the fast development of smart grids and microgrids, issued by João Afonso, Carlos Antunes, Clara Gouveia and Vítor Monteiro. As pointed out before, the energy transition is more than to simply replace everything by electricity in this sense, we dedicate part of the material to specific energy related topics: buildings, industry, and mobility.

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It is widely acknowledged that buildings are responsible for a great share of global energy use; that's the starting point of Vítor Leal, who highlights the role of buildings as a giant "battery" of the energy system.

As for industry, Zenaida Mourão and Luis Guardão review the challenges and opportunities associated with the energy transition, taking advantage of other shifts in progress to reach a more efficient industrial sector, with a strong and positive impact on sustainability.

Mobility is one of the main sources of discussion, theories, proposals, and controversy. We will contribute to the topic of sustainable mobility through a specific outlook that deserves more attention. Ezra Raskova and Álvaro Costa present an alternative to the underground mode for public mobility and discuss its advantages and limitations.

Of course, a key element of the energy transition is a dramatic increase of the production of electricity from renewable sources, even if we are collectively able to be much more efficient. The topic of offshore parks is addressed by Bernardo Silva from a multi-technology point of view, with a common harvesting and transmission structure.

Answering one of the FAQ about the future of renewable energy sources, António Vallêra and Miguel Brito estimate the limits of solar PV generation, and its sufficiency to meet the electricity consumption, according to different electric mobility scenarios.

Storage has been discussed intensively - from the classic hydro storage and other forms of non-electric energy storage to mobile and stationary batteries -, but we opted to address the emergent topic of renewable gases and green hydrogen. Peças Lopes, Joel Soares and Bruno Santos contribute to the discussion of the advantages and difficulties of this approach, developing the idea of a hydrogen seasonal storage strategy.

Less than one year ago, we would stop here; but nowadays, it is important to convey the message that the recent events affecting Europe's energy supply do not justify dismantling what we have already achieved regarding climate change. For instance, there is no sense in reverting the decommissioning of coal-fired power plants. A final word to remember, within the same framework, all the issues associated with nuclear power - from safety and security concerns to the unsolved problem of disposal of radioactive waste.

Manuel A. Matos was born in 1955 in Porto, Portugal. He was with the Faculty of Engineering of the University of Porto (FEUP), Portugal, from 1978 (Full Professor since 2000) until his retirement in 2022. He is a researcher at INESC TEC since 1985, and presently coordinator of its Centre for Power and Energy Systems (CPES) and President of the Scientific Council of INESC TEC. His research interests include classical and fuzzy modeling of power systems, reliability, optimization and decision-aid, with application to renewables' integration, security of supply evaluation and smart grids

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INESC TEC ACTIVITIES

The INESC TEC activities in the energy sector are mainly undertaken by CPES (Centre for Power and Energy Systems), but other centres explored their competencies in different areas (computer science, ICT, etc.) to participate in multidisciplinary projects related to energy.

This includes support to prototype development and testing through laboratorial infrastructures such as SGEVL (Smart Grids and Electric Vehicles Laboratory) and others.

The impact on industry is a constant concern of INESC TEC in this sector, and long-term partnerships have been established with EFACEC, EDP, REN, EDA and EEM.

New partners (including international partners), reflecting the changes in the energy sector, emerged meanwhile, namely Sonae (Elergone Energias and Capwatt), Mota-Engil Renewing, SAP, ENEIDA, Dourogás, ENTSO-E, APG, TNO, and RWTH, among others.

The infographic presents data for the period **2017-2021,** mainly from CPES, but also including contracts developed by other centres.

784
PUBLICATIONS

10
PATENT APPLICATIONS

119
PROJECTS WITH INDUSTRY

22
INVENTIONS DISCLOSURES

65
PRIVATE PARTNERS

7
PUBLIC FUNDING ENTITIES

25,3 M€
TOTAL INCOME

FIELDS OF KNOWLEDGE

- Power Systems Dynamics Analysis and Operation
- Power Systems Planning
- Probabilistic and Fuzzy Modelling
- Optimisation and Decision-Aid
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- Power Systems Reliability
- Telecommunications for Energy Systems
- Robotics
- Applied Photonics
- Virtual Reality
- Electricity Markets and Regulation
- High assurance software

APPLICATION DOMAINS

- Power Systems Management
- Energy Analytics
- Forecasting Techniques for Energy Systems
- Large Scale Integration of Renewable Energy Sources
- Distributed Energy Resources Operation
- Electric Mobility
- Energy and Flexibility Management
- Smart Grids
- Multi-Energy Systems
- Robotics for Intelligent and Autonomous Energy Asset Inspection
- Electrical Assets Health Condition Management
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- Energy Operators Health and Security Sensoring
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- Smart Metering Deployment
- Cybersecurity and IoT for Electrical Infrastructures

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Power and Energy Systems

CAP
Applied Photonics

CEGI
Industrial Engineering and Management

CESE
Enterprise Systems Engineering

CRAS
Robotics and Autonomous Systems

CTM
Telecommunications and Multimedia

HASLAB
High-Assurance Software

HUMANISE
Human-Centered Computing and Information Science

LIAAD
Artificial Intelligence and Decision Support

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CPES - Laboratory of Smart Grids and Electric Vehicles

CESE - Laboratory of Industrial Robotics and Automation

CRAS - Robotics and Autonomous Systems Laboratory

CTM - Optical and Electronic Technologies Research Laboratory

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POWER SYSTEM OPERATION
THE CHALLENGE OF THE 100% RENEWABLES TARGET

Operating a power system with close to 100% renewables integration demands innovative forms of flexibility from the sub-second time scale up to hours and years. Flexibility sources can be found in multiple domains and its proper coordination is the key for successful system operation.

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Figure 1 Home Energy Management System (HEMS)

1. INTRODUCTION

Increasing requirements to reduce GreenHouse Gas (GHG) emissions, together with declining Renewable Energy Sources (RES) costs, triggered the consensual commitment to decarbonising the economy. In order to achieve this objective, it's crucial to overcome technical and economic challenges in the framework of the smart-grid concept.

To achieve a reduction of 80-95% in GHG emissions by 2050, the European Union expects that RES should hold a 97% share of the European power generation mix considering the high-RES scenario envisioned for the decarbonisation process [1] . A deep transformation of the power system is currently being implemented, through the massive integration of non-dispatchable RES, widely deploying high-energy efficient technologies, a stronger commitment towards electrifying the economy, and the elimination of coal as a source of energy. Decarbonising the energy sector requires electricity to be the key vector in this paradigm change. Since the potential sites for hydropower are already being exploited in Europe, renewable generation is expected to develop through biomass, geothermal and increased shares of Variable Renewable Energy (VRE) that are not dispatchable due to their fluctuating nature, such as wind and solar power. Most likely, the total cost of a 100% renewable power system would be higher than an equivalent power system with low carbon technologies – nuclear and carbon capture and storage, due to seasonal mismatches, among other aspects.

The traditional generators are typically synchronous rotating machines that are manageable and dispatchable in terms of power output, enabling a suite of services to the power grid, e.g., inertia and capacity to provide regulating power, therefore allowing a successful, secure, and stable operation of the power system. Increased variability resulting from the paradigmatic changes in the generation and demand side calls for more capacity to permanently assure the balance between generation and consumption. Hence, flexibility[2] is the key word: it allows the power system to manage changes in multiple technical dimensions, time scales, and geographies (local services versus systemic ones).

2.HOW TO REACH THE TARGET OF NEAR 100% RENEWABLES?

The path towards near 100% renewable power system will require the gradual implementation of certain elements, namely:

- More RES generation and more transmission capacity.
- A diversity of RES and energy carriers (hydrogen,

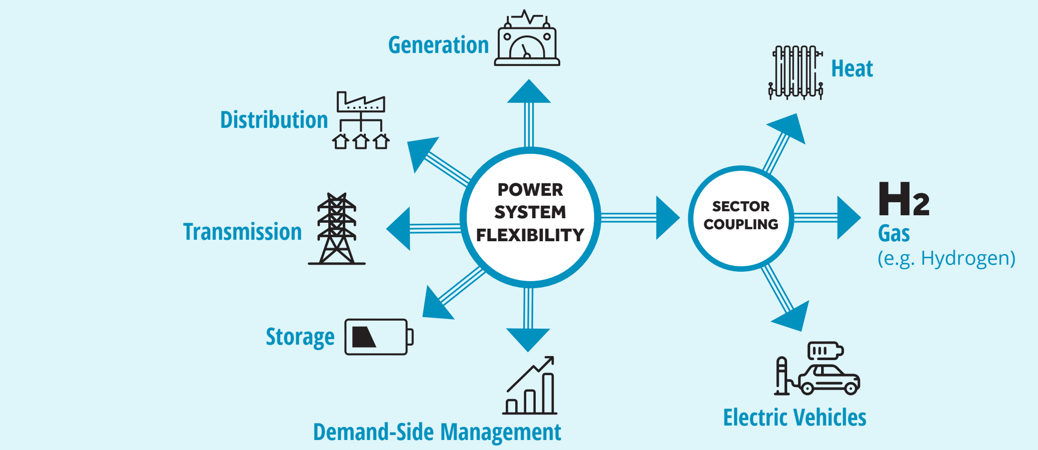

Figure 2 Drivers of the power system operation change. Source: IRENA – International Renewable Energy Agency [3] (adapted)

for instance), while fostering sector coupling (transportation, industrial heat).

- Well-thought integration of heat pumps and electric vehicles (EV) to reduce demand peaks and biogas needs.
- Energy efficiency and conservation measures (use less energy with a negligible loss of comfort) to smooth the load curve.
- Extensive use of "Power-to-X", "Power-to-H2" and "Power-to-H2O" technologies (desalination and water purification) to enable RES to convert surplus energy into other energy carriers. These energy carriers can be stored for later use.
- Enhanced cross-system coordination between transmission system operators (TSO) and distribution system operators (DSO) under a smart grid paradigm.
- Develop the interconnection capacity between countries, therefore achieving power system flexibility from the Pan-European market, based on effective collaboration among system operators.
- Provide innovative ancillary services (a variety of operations beyond generation and transmission that are required to maintain grid stability and security) from both conventional VRE sources and eventually innovative solutions using energy storage and variable speed hydro power.
- Evolution of market arrangements to reflect real system needs: markets operation closer to real-time, involving the full separation of energy and capacity-related services.
- Evolution of grid codes, identifying new requirements in advance, hence facilitating the transition to green power.
- Integration of distributed energy resources into the market, for instance, EV with Vehicle-to-Grid (V2G) capability.
- New operational procedures to enhance flexibility, for instance, advanced weather forecasting for accurate VRE generation forecasts.
- Dynamic line rating, i.e., operating the power lines closer to their thermal limits.
- Virtual power lines, i.e., utility-scale storage systems connected to the grid at the supply side, storing surplus that could not be transmitted due to grid congestion, and on the demand side, charged whenever grid capacity allows and discharged when needed.

Figure 2 shows the main drivers of the power system operation change.

3. THE CHALLENGES OF THE NEW PARADIGM OF OPERATING THE POWER SYSTEM

The progressive implementation of a near 100% renewable power system will require visible changes regarding its operation. Perhaps the most significant ones are related to the wide deployment of storage devices, implementation of demand-side programs, the transition to an inverter-based power system, and the emergence of microgrids, as discussed in the next paragraphs.

The time-variable nature (but increasingly predictable in its variability) of many RES makes it more challenging to match demand and generation, therefore the need for storage technologies that will change the mindset of the operation of the power system. A massive integration of storage devices (batteries, thermal, mechanical, hydrogen, and pumped hydropower) will need to be incorporated into the power grid.

In the past, demand for energy has been met by 'firm', easy-to-control power, where supply followed energy demand, and there was no effort taken to manage that demand. With increasing VRE in the grid, the situation changes, and demand-side management (DSM) is required to achieve the balance between not-so-easy to control variable generation and variable demand. Demand-side flexibility is expected to play an important role in a 100% renewable power system, with tomorrow's smart homes and digital technologies managing the assets. Smart charging EV, and time-of-use tariffs are also part of the solution. To fully exploit the potential flexibility from the distribution side (batteries and DSM), TSO should ensure that they do not cause technical problems to areas managed by DSO and vice-versa.

The 100% renewable grid will feature many distributed inverter-based generators (DC/AC converters), therefore composing an inverter-dominated grid. To overcome the shortcoming of a low inertia power system, grid-forming inverters (with the capacity to emulate virtual inertia) will play a crucial role. Advanced control functions, which are currently being heavily researched, must be designed to assure the proper operation of the power system steady state, but mainly in transient state, to prevent load shedding and ultimately blackouts.

The decentralisation of the power system will promote the advent of renewable-based microgrids that can be operated isolated from the main grid. The transient behaviour of these microgrids needs to be addressed to ensure their secure operation, making sure that they do not disturb the existing grid. Smart Transformers are expected to play a decisive role in this matter, by providing voltage and frequency control, black start, fault-ride-through provision, and reconfiguration of the distribution grid.

4.CONCLUSION

The 100% renewable power system is not just feasible and needed: it is already taking place. Countries like Iceland, Paraguay, Costa Rica, Norway, Austria, Brazil, and Denmark run 100% renewable power systems or with high incorporation of RES. In Portugal, data from 2021 show that renewables accounted for 59% of the electricity demand. The path towards a near 100% renewable power system is underway, and the operation of the power system must adapt to the new paradigm. This paper outlined the main changes that need to be implemented to achieve said goal. Flexibility is the keyword. Furthermore, we have identified the deployment of storage devices, the demand side programs, the relevance of inverter-based generators, and the arrival of microgrids as the main challenges the green power system must face. In short, the 100% renewable power system requires flexibility to maintain high stability and reliability standards.

[1] European Commission Energy Roadmap 2050, DG Energy, doi:10.2833/10759

[2] International Renewable Energy Agency, "Power systems flexibility for the energy transition", https://www.irena.org/publica-tions/2018/Nov/Power-system-flexibility-for-the-energy-transition

[3] International Renewable Energy Agency, "Power systems flexibility for the energy transition", https://www.irena.org/publica-tions/2018/Nov/Power-system-flexibility-for-the-energy-transition

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EVOLUTION OF THE SECURITY OF SUPPLY CONCEPT

The major evolution in the concept of security of supply is the result of demand-side developments, due to the profusion of dispersed photovoltaic generation on medium and low voltage grids and also the active participation of consumers in the electricity and services markets - especially those who have the capacity to defer consumption and/or store energy through electrochemical and/or thermal systems.

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The security of supply, in this case of electricity, is undeniably one of the major challenges that both Portugal and Europe must face in the upcoming years. In fact, vulnerabilities have been reported in this sector, particularly due to the lack of primary energy resources for electricity generation, leading to inevitable price spikes in wholesale markets. The need to mitigate the clear effects of climate change requires the fast decarbonisation of the economy and, consequently, of the electricity sector - which implies, on the one hand, the progressive declassification of fossil-fuelled power plants and, on the other hand, the increase in the demand via the electrification of consumption (e.g. electric mobility, air conditioning, water heating, etc.). Against this background, a new challenge arises: designing an electric power system (EPS) based mainly on renewable endogenous resources which can keep or even improve the security of supply standards to which modern societies have become accustomed to.

The solution to this challenge is not simple, and perhaps a recollection of the historical evolution of the national electricity system (SEN) - particularly in terms of generation and transmission subsystems -, could help. The SEN, as we know it today, results from the integration of various independent grids that supplied cities and/or regions and that were based on small hydro or thermal power plants (e.g., the Tejo Plant, in Lisbon). With the construction of large hydroelectric plants in the 1950s, 60s and 70, and the creation of the high and extra high voltage transmission grid, the system achieved a national span allowing not only to diversify the energy mix, but also to ensure the necessary redundancies towards the security of supply. In this accelerated expansion phase, which was characterised by the strong electrification of consumption and the relative abundance of oil, natural gas and coal, the security of supply was assumed as guaranteed if the installed capacity was greater than the maximum demand forecasted for the planning horizon, plus a gap or static reserve. Said reserve, which is nothing more than an extra generation capacity, is essential to cope not only with momentary power shortages caused by sudden outages and scheduled maintenance actions, but also to mitigate short-term deviations between production and consumption associated with forecasting errors. Basically, this gap quantifies the redundancy required for the generation system to guarantee the security of supply based on the logic that if the system can meet the maximum demand, then it should also be able to supply lower load levels. The minimum reserve required to

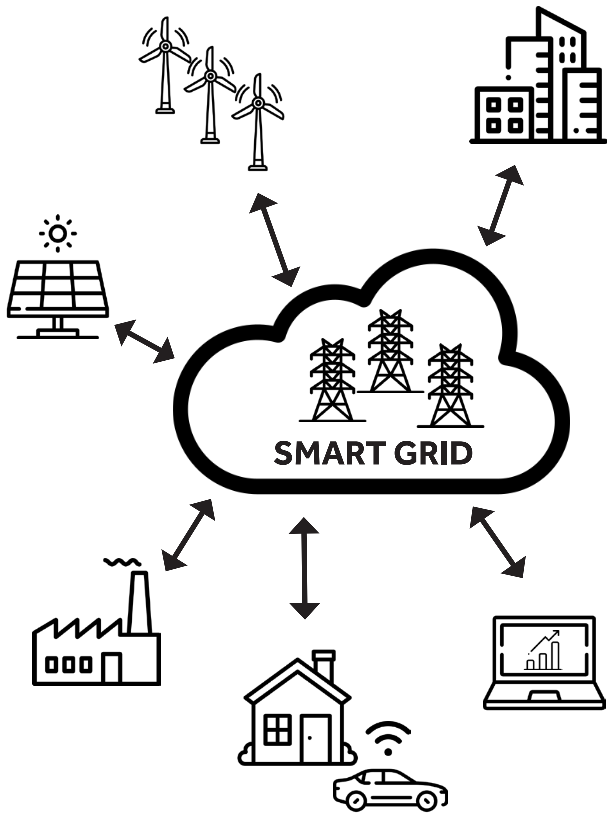

Figure 1 Energy security of supply elements

avoid excessive investment costs in idle capacity was defined through deterministic criteria based on the installed capacity of the largest unit and/or percentages of the maximum demand (e.g., 10% of the maximum demand). Currently, the SEN interconnects with the Spanish system and, through the latter, with the rest of Europe, allowing exchanges of energy and reserves between countries, promoting a more efficient use of generation resources of diverse nature available in distant areas. The collective effort in the progressive interconnection of European EPS has granted the access to greater redundancies and increasingly tighter requirements for continuity of supply. Currently, the security of supply monitoring report (RMSA – Relatório de Monitorização da Segurança de Abastecimento, in Portuguese) elaborated by the Directorate General for Energy and Geology (DGEG) defines as planning criterion an average of no more than five hours per year with load disconnection, which represents a remarkable availability of about 99.95%! Despite its simplicity, this new criterion represents an improved approach to define the static reserve levels, since it is based on a probabilistic modelling for the SEN operation. The tools for quantifying this indicator include extensive historical information about the variability of the primary renewable energy resources (hydro, wind, solar, biomass, etc.), of forced outage rates of generation units and interconnection circuits, of scheduled maintenance actions, of planned exchanges with Spain, and of the stochastic behaviour of the demand along the year.

These tools are extremely useful in a context where large quantities of power flow from the production centres to the bulk consumption. However, new sources of uncertainty are anticipated in the upcoming future, which will certainly influence the definition of the reserves required to ensure an adequate continuity of supply. On the supply side, the resilience of the generation system against the progressive scarcity of water must be properly addressed, since it not only affects the capacity of hydro units, but also of conventional thermal units if the water used as coolant becomes suddenly unavailable or increases in temperature. Dust clouds from the Sahara can also cause issues, as photovoltaic (PV) production is affected not only during such events, but also over subsequent days (because of dust deposition on the panels). The role of hydrogen in storing surplus wind and solar production is also an important issue to ensure firm capacity in the months when demand is at its peak.

In addition to these central issues, the security of supply concept will be most affected by the current developments on the demand side, fuelled by the profusion of dispersed PV production in medium and low voltage networks and the active participation of consumers in electricity and ancillary services markets, especially the consumers who can defer consumption and/or store energy through electrochemical and/or thermal systems. A first tentative approach to model such behaviour in security of supply studies is very much in line with the concept of the renewable energy community (REC), which aims to promote the use of local renewable energy sources to supply the local loads. Consequently, this approach bundles all these effects into net load diagrams according to the projects that are expected to be developed and connected to the distribution grids. Please keep in mind that this type of simplification does not account for the power and energy that consumers might have at their facilities over time, nor does it allow to understand when and if this capacity can be used for security of supply purposes. To understand these issues, let us look at the case of electric vehicles (EV), when a considerably high number is connected to the grid. If the EPS needs generating capacity, then momentary decrease of the total charging power can be an important lever, especially in cases where EV users do not need to use the EV over the following hours. Moreover, the anticipation of EV charging when there is an excess of renewable generation can also be beneficial, especially if it allows to avoid charging at peak hours. This reasoning can easily be extended to other equipment available in households, retail, or industry, whose utilisation can be adjusted over time and/or enables energy storage. Given this situation, it is expected that a significant part of the load can adapt itself according to the power available in the EPS, effectively contributing to the security of supply, which is clearly different from assessing its contribution based on immutable net load profiles. In an extreme scenario, the intelligent management of consumption, distributed generation and storage will allow the creation of real energy islands that will probably use the large power generation centres only in the event of a failure of local resources, which configures a situation resembling the initial development stages of the EPS. Hence, it is crucial to develop methodologies and tools to simulate the flexibility available in distribution networks in an adequate manner, both in temporal and spatial terms, to quantify the contribution of this important mechanism to the security of supply indicators and truly develop a reliable and sustainable EPS.

Figure 2 Hydroelectric dam

Leonel Carvalho received his B.Sc., M.Sc., and Ph.D. degrees in Electrical and Computers Engineering from the Faculty of Engineering of the University of Porto (FEUP), Portugal, in 2006, 2008, and 2013, respectively. In 2014, 2017 and 2018, he participated and won the competition organised by the Modern Heuristic Optimization Working Group from the IEEE PES Analytic Methods in Power Systems Committee, that aimed at exploring heuristic-based solutions for solving complex and emerging optimisation problems in electric power systems. His research interests include power system reliability assessment and the application of Artificial Intelligence to power system issues.

ARE MARGINAL BASED ELECTRICITY MARKETS COMING TO AN END?

Electricity Markets played a major role in power systems for about 30 years; but the increasing presence of infra marginal generation technologies are challenging their operation rules, and they'll probably be replaced by other more flexible and diversified trading mechanisms over the next 10 years.

Traditionally, power systems were organised in terms of vertically integrated companies, i.e., companies that provided all the services along the value chain of electricity: from generation to the relationship with end consumers. Since the 1980s and 1990s, power systems underwent a restructuring process in several countries and geographical areas , leading to their organisation according to generation, network transmission and distribution, and retailing activities. In Europe, electricity can be usually traded in day ahead markets typically operating in a marginal basis or by bilateral contracts. In addition, the governments of several European countries decided, early on, to adopt policies to boost the investment in renewable technologies, or to start using endogenous resources to increase the energy self-sufficiency. This was done, for instance, through the adoption of specific tariff regimes, as it was the case of the feed in tariffs still in use in Portugal to pay the Special Regime Generation (SRG).

Portugal and Spain integrate the Iberian Electricity Market (MIBEL) since 2007. The Iberian Market Operator receives, on day d-1 (the day before operation) buying and selling bids for each hour of day d. The generation bids are ordered by the ascending order of their price, leading to the aggregated selling curve. On the other hand, the buying bids communicated for each hour of day d are organised by the descending order of the bid price, leading to the aggregated buying curve. The intersection of these two curves determines the traded quantity, the accepted bids, and the market price. This price is interpreted as the marginal price of the Iberian system, admitting that the limit constraints of the interconnection lines are not active. It is still important to mention that these are uniform price auctions, that is, the price that each accepted buying bid will pay and that it will be paid to each accepted selling bid is not their bidding price, but in fact the system marginal price.

This uniform price rule has been discussed frequently because it means that any dispatched power unit is paid at the price of the last accepted bid, frequently coming from a thermal unit, even if its operation cost is reduced. Meanwhile, the SRG installed capacity increased along time and this evolution - together with the priority given to this generation - contributed to fuel this discussion. In

Figure 1 Electricity market

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fact, in mainland Portugal, SRG included, by 2021, 9 000 MW of (wind parks, solar PV units, small hydro and cogeneration, waste and biomass units) out of 19 200 MW installed capacity – with the Iberian Market Operator estimating the generation through said technologies on each hour of d day according to the aggregated selling curve, through zero price segments.. As a result, the presence of a large SRG generation at a certain hour of day d contributes to reduce the market price at said time the revenues of the Ordinary Regime Generation units.

For many years. this model was applied in the Iberian Market without major problems, namely because the market prices were much more reduced than they currently are. In fact, between 2007 and 2020, the average annual market price ranged from 69.68 €/MWh in 2008 to 33.99 €/MWh in 2020 (in this case, largely because of the demand reduction determined by the COVID 19 pandemic). However, since February 2021, the market prices are increasing; initially, because of the demand and natural gas price increases caused by the economic recovery at a global level, and then because of the increase of the CO2 licence prices in Europe. Since February 2022, the electricity market prices all through Europe escalated frequently to values above 200 €/MWh due to the increase of the natural gas prices.

Considering this evolution and the changes that are likely to occur in the Iberian generation systems until 2030, we will now explore some topics and try to address the question that we present in the title of this text:

i. in the first place, and until the end of 2000, the organisation of MIBEL in terms of a marginal based day ahead market was not questioned, namely because the average market prices were relatively low;

ii. in this period, the value of the feed in tariffs was larger than the average market price, which determined the payment of subsidies to the SRG that were internalised in the Tariff for the Global Use of the System, paid by end consumers. These subsidies were perceived as an incentive to new investments in these technologies, some of them not entirely mature;

iii. since 2021, the average market price increased, and it is now higher than the feed in values paid to most of the SRG technologies; so, feed in generation contributes to reduce the final energy price paid by consumers;

iv. in both cases, either before the end of 2020 or since the beginning of 2021, it is true that the price paid by end consumers for the active energy has a distant relation with the average market price;

v. for instance, in 2019 - and taking as an example a Portuguese average low voltage end consumer -, the Energy Tariff was responsible for about 40% of the electricity bill before taxes and the Tariff for the Global Use of the System accounted for 25%. A closer look at this tariff indicated that most of this value was related with the subsidies assigned to SRG, i.e., they were in fact related to generation costs. This means that the amount used to remunerate generation almost corresponded to 2/3 of the total, while the market prices only determined in a direct way 40% of the total;

vi. this increasingly distant relation tends to increase given the targets included in the National Energy and Climate Plan 2020 – 2030. According to this plan, the wind capacity is planned to increase from 5 400 to about 9 000 MW; the solar photovoltaic capacity from 1 400 to about 9 000 MW; and the hydro capacity from 7 200 to about 9 000 MW. This evolution will determine, for instance, that in periods with large wind and hydro generation or with large solar photovoltaic generation, the market prices will be reduced or even reach zero in many hours;

vii. this means that the energy prices paid by end consumers will be increasingly decoupled from market prices, while the revenues obtained by the surviving thermal units (namely natural gas units) will decrease. These units, together with hydro stations, will certainly play a crucial role in the system in terms of providing reserve services and inertia. Under these conditions, an important part of the revenues of these units will be increasingly associated with the provision of ancillary services;

viii. as a result, it will become increasingly difficult to explain to an end consumer the relevance of the day ahead market operating under a marginal basis, given that the final active energy price in €/kWh that is billed to him/her shows an increasingly indirect and decoupled relation with the market prices operating under a marginal basis.

Considering these comments, it seems clear that, by 2030, the electricity generated and effectively paid according to the day ahead market price will be increasingly reduced, since a larger amount of generation will be associated with other remuneration regimes. In addition, the annual number of hours with zero or close to zero market prices will tend to increase, so that the surviving Ordinary Regime Generation will have to get revenues by providing other services, namely reserves or signing contracts to provide inertia that will most likely be established in the coming years.

Therefore, having in mind this evolution and the difficulties and deficiencies associated to the current marginal based markets, we admit as very likely that the day ahead markets as we know them today will be eliminated and replaced by bilateral contracts - or even by marginal based intraday markets with a more reduced gate closure regarding the physical delivery, mainly used to trade small quantities of electricity or to adjust generation or demand pre-existent positions.

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WHAT IF CABLE CARS ARE THE MOST SUSTAINABLE SOLUTION FOR URBAN MOBILITY?

Dozens of cities have integrated urban cable cars into their public transportation networks. Advantages of cable cars include fast implementation, relatively low construction costs and environmental impact. However, due to the negative public perceptions, cable cars remain a sensitive subject.

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For decades, vehicles used in urban mobility were limited to trams, metros, buses, cars, bicycles, and ferryboats, while the sight of cable cars was reserved for mountain peaks. Recently, cable cars have been integrated into urban areas as 'urban cable cars'. This is a relatively new addition to public transportation modes, with the first urban cable car inaugurated in 2004, in Medellin. Since then, dozens of cities worldwide have introduced cable cars.

In the mid-80s, the travel demand between La Paz and El Alto was identified as the highest in the Metropolitan Area of La Paz. Given the difference of 420 meters, a cable car system was suggested. However, the network was designed only in 2012, and the construction was finished in 2014. Once completed, the cable car in La Paz has shortened travel time by 70 minutes connecting the richer city of La Paz with the poorer one in El Alto (Martinez et al., 2018). Currently, the city's cable car network includes 10 lines with 36 stations, and a total length of 30.60 km. In 2018, La Paz won the Guinness World Record of the largest cable car system in the world (Martinez et al., 2018).

Besides geographical reasons, the choice of adding cable cars into urban landscapes rather than a railway system has other benefits. The biggest drivers in opting for cable cars include relatively low construction costs, minimum changes to the urban structure, and significantly low environmental impact. The traditional metro project generally requires land acquisition, urban changes, and lengthy and costly construction works, and even then, the possibility of running into cost overruns that lengthen the project implementation and delivery is quite usual.

In environmental terms, cable cars are less harmful to the environment than the traditional railway-based transportation systems. While the operation of metro and light railway transit can be achieved without emissions, the construction phase causes high greenhouse gas (GHG) emissions. The average reported emission of a tunnelled railway line is 20 695 tCO2 per kilometre line, whereas at-grade constructions cause 1 400 tCO2 per kilometre line (Olugbenga, Kalyviotis, & Saxe, 2019). Due to the difficulties in securing the required at-grade space for railways in urban areas, and the desire for a minimal disruption to the urban structure, tunnelled options are more common than at-grade constructions. Respectively, the emitted amount of GHG emissions from the construction of one kilometre of a tunnelled railway is equivalent to 1 million journeys, wherein each journey extension is 150 km, made by private

cars, or half a million private car journeys between Lisbon and Porto. Once the built line replaces the corresponding number of journeys made by private cars, or other fuel-based public transportation means, that's when the metro or LRT line becomes worthwhile in environmental terms. In comparison to tunnelled railway systems, emissions from cable cars are insignificant.

Additionally, the implementation time of cable cars is relatively short. In Medellin, each of the three lines, K, J, and L, extending between 2 km and 4.5 km, was completed within 10-15 months (Dávila & Daste, 2013). In La Paz, the completion of three cable car lines with a total of 10 km in length was also finished in less than three years. Considering the limitation of 3-5 years in the office for a mayor or a Prime Minister, successfully completing a transportation project that would lead to significant improvements in quality of life is appealing to politicians.

In the midst of climate change concerns, the cable car solution offers not only an overall prompt reduction of GHG emissions after its construction, but also fast implementation.

After considering these advantages, it is not surprising that hilly cities are not the only ones contemplating the addition of cable cars into their landscapes. In 2016, Greater Mexico City introduced Mexicable on a busy road in Ecatepec. In comparison to the road transportation, Mexicable shortened the journey time by 17 minutes. In 2016, Brest became the first French city to adopt urban cable cars. Providing a connection between two sides of Penfeld River, the Brest Cable car was built with the intention of relieving the congestion on the city's two bridges. In the opening ceremony, the French environment minister praised cable cars as "...the solution of the future to reduce pollution on the planet" (DW, 2016).

Initially launched in developing countries, there are more and more politicians worldwide considering cable cars as a solution to urban mobility problems in their cities. Politicians are entitled to protect scarce resources including land, and non-renewable resources, as well as public money. Considering these concerns, cable cars seem to be a comparably better alternative to the traditional modes of travel. While some developing countries have paved the way on integrating cable cars into the city's public transportation network, the idea of cable cars in urban areas is still unacceptable to the general public, especially in the developed countries. Despite conceptual solutions, technological advancements, and design improvements, passenger experience including fear of heights, and cable car's interference with the urban aesthetics make this means of transportation a sensitive subject for the public perception.

Given the advantages, is it possible to overcome the public backlash against cable cars over aesthetical issues for the sake of sustainability?

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Figure 1 Cable cars in La Paz, Bolivia. (Source: 2022 Mi Teleférico. Image taken from https://www.miteleferico.bo/nosotros/nuestras-lineas)

BUILDINGS
A SECTOR PARTICULARLY WELL SUITED TO THE ENERGY TRANSITION

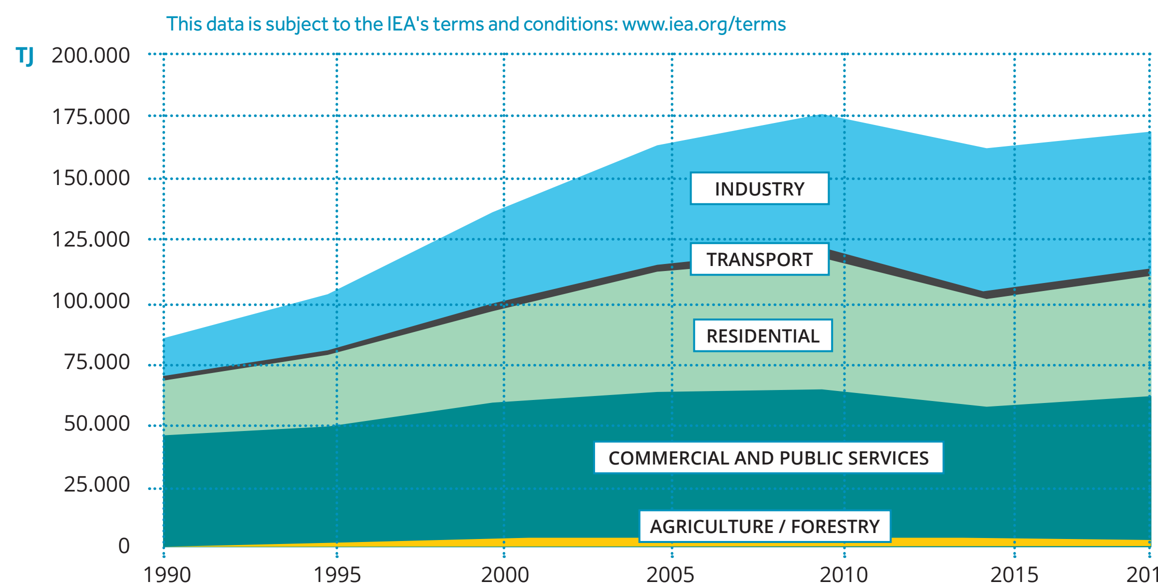
How buildings can contribute to all important dimensions of the energy transition.

Figure 1 Smart automation

AN IMPORTANT SECTOR

Buildings account for around 27% of the consumption of final energy in Portugal (IEA, 2022), and 42% in the European Union (EUROSTAT, 2022). In the European Union, they are the first consumer sector, while in Portugal they are the second, along with Industry and behind transportation. The milder climate in winter, less tradition in the use of generalised heating at home, and a particularly high car ownership are the likely explanations for these Portugal vs EU differences.

In terms of electricity, the current share of the buildings sector in Portugal is 62% of the total. Since 2000, the consumption grew by 32% in the residential buildings subsector, and 46% in the services buildings subsector (Figure 2).



Source:
IEA World Energy Balances

Documentation:

Figure 2 Consumption of electricity per sector in Portugal (source: IEA)

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Hence, it is a sector that is already very relevant, due to the weight it represents in consumption - whether of final energy or electricity. But it also seems a sector particularly suited to the energy transition, for the reasons explained below. Let's start with a summary of the main features of the energy system that are expected to be necessary for the transition to a more sustainable paradigm:

1. Efficiency in energy use;

2. Electrification of energy uses, whenever this is compatible with the intended services;

3. Production of electricity from renewable sources, preferably close to the place of use;

4. Storage capacity and time flexibility when using energy.

5. Use of green hydrogen and/or synthetic fuels (SF) when it is not possible to obtain the services required only through properties 1-4.

Feature 5 should be perceived as a last resource solution, and not as an alternative of equal merit compared to the 2-3-4 set, since it is an option that will always be much less efficient, in a well to wheel analysis. This aspect has often been overlooked, but it becomes clear when one considers that the efficiencies in the production and use of hydrogen / SF are much lower than those associated with the direct use of electricity.

Let us analyse the positioning of the buildings sector in relation to each of the above key features.

EFFICIENT USE OF ENERGY

The main uses of energy in buildings are for the control of indoor temperature (with a clear predominance of heating in OECD countries), heating water for sanitary uses, domestic appliances, lighting (in services buildings) and electronic equipment. With regard to heating and cooling, there is ample scope for reducing needs, through improved insulation and solar protection, and more adequate control of ventilation; and as far as lighting is concerned, there is still a very large margin for better controls, switching off where and when not needed (the first rule of energy efficiency!).

ELECTRIFICATION OF USES, AND PRODUCTION OF ELECTRICITY FROM RENEWABLE SOURCES.

Practically all the energy services required in buildings can be provided through electrical

energy, so there are no significant obstacles here. Traditionally, heating by Joule effect (air and water) was not recommended, as it is less efficient in terms of primary energy than the use of gas; however, the evolution in heat pump technologies and the greater availability of electricity from renewable sources make it possible to obviate this inconvenience. Also, the local production of electricity often finds advantageous conditions in buildings– at least, and since batteries are expensive, in the service buildings sector, where there is greater synchronisation between production and demand. A (re)evolution is taking place with the installation of photovoltaic panels on rooftops and facades. Solar thermal panels for water heating, if correctly installed and maintained, are also a mature and still sensible technology.

ENERGY STORAGE AND TIME OF USE FLEXIBILITY

While storage of electrical energy is "difficult" (or, at least for now, expensive), heat storage is relatively easy and inexpensive. Combining the existence of thermal mass and a well thermally insulated envelope, it is easy to store heat for several hours or days. Many of us already have this experience in heating water in electric cylinders with a bi-hourly rate, in which the resistance only works during the night.

There is a big potential for temporal displacement of loads also in heating and cooling (load shifting, in the language of demand-side management). However, this requires a considerable interior thermal mass at buildings, , in addition to proper insulation. Unfortunately, the trend of the last few decades towards fast and cheap construction has led to the adoption of low mass solutions with little thermal inertia. However, there are still many older buildings with significant thermal mass. And retrofitting solutions for low inertia could be developed, using phase change materials (PCM) to increase the thermal mass of newer buildings (Leal and Almeida, 2021). Moreover, in refrigerators and freezers, solutions with PCM could be developed to create load shedding capacity for a few hours.

USE OF GREEN HYDROGEN AND/OR SYNTHETIC FUELS

Unlike in Industry and transportation, in the case of buildings, nearly all energy services can be supplied through electricity. Nevertheless, the production and storage of hydrogen may be an appealing solution to use it for surplus electricity production during the day, and/or for mid-term storage. The economic viability of this solution is not yet clear; one may, however, observe that there are no significant technical obstacles to its adoption in some types of buildings (the larger ones).

NEED FOR RESEARCH AND DEVELOPMENT

In the buildings sector, there are already many solutions, technically mature and with increasing economic attractiveness, which can be applied and produce very significant advances towards decarbonisation. The main challenge in this field is the training of the professionals in the design and construction, as well as the creation, of regulatory instruments necessary for the transformation of the market.

There are, however, areas where progress could be greater and/or faster using innovative solutions derived from R&D. Some areas ate particularly in need: solutions to increase the thermal mass of the compartments; refrigeration equipment with load shifting capability; integrated lighting and solar protection solutions.

In addition to the technologies "per se", the creation of tools for analysing solutions and supporting the identification of the most

Figure 3 Smart cities

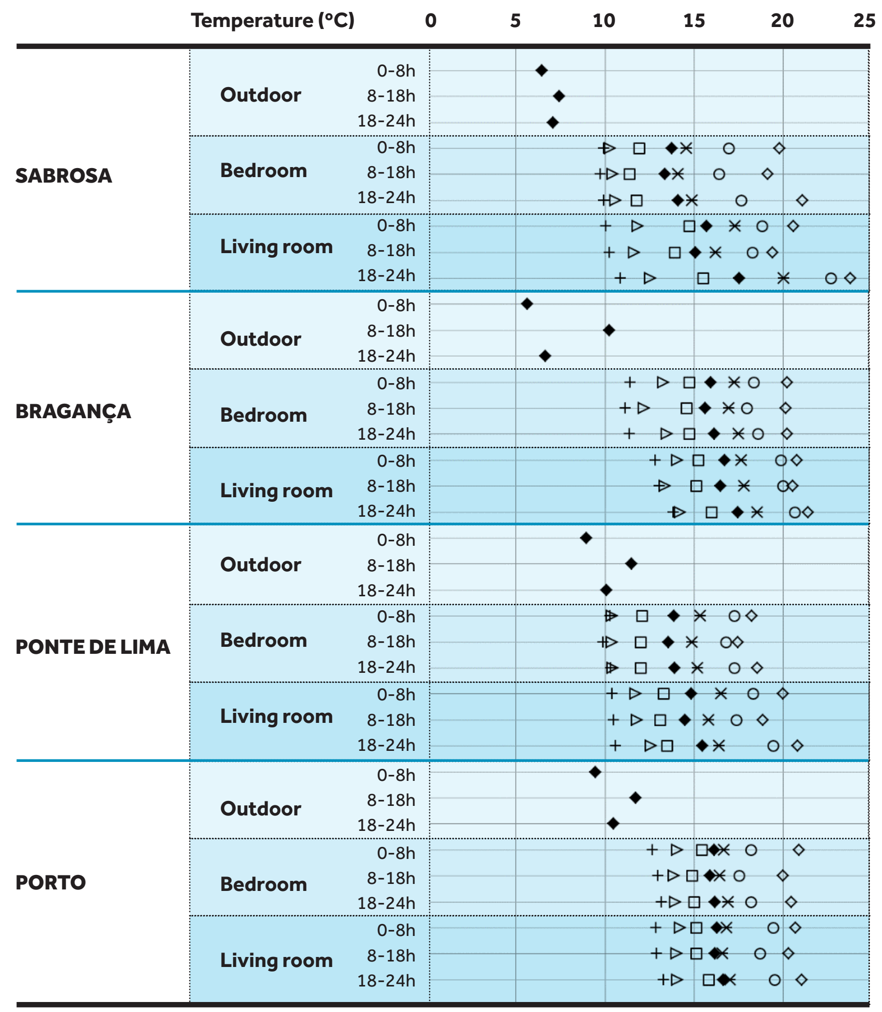

Figure 4 Temperatures in 160 households of students in the municipalities of Sabrosa, Bragança, Ponte de Lima and Porto, in the winter of 2013-14 (Magalhães et al, 2016)

technically and economically appropriate solutions is also of the utmost importance. Too often architects and designers quickly focus on a solution when it would be advantageous to consider multiple options before focusing on a specific solution. Tools to assist properties identification and improvement in buildings are equally important.

PORTUGUESE SPECIFICITIES

It is known that, in Portugal, indoor temperatures during winter are below the 18-20°C generally recognised as the recommendation for thermal comfort. A monitoring of about 160 households of high school students in four municipalities in the northern region of showed that less than 1/3 were in the comfort range, and that parts of the population even register temperatures around 12°C (figure 4). Energy rehabilitation in these cases tends to cause smaller energy savings than those calculated by theoretical models, because of the effect known as rebound effect. This does not mean that it is not necessary: it is a question of quality of life.

Moreover, the fact that we have a significant daily temperature amplitude, where in winter the daily maximum temperature is usually above 10°C, creates particularly favourable conditions for air-air heat pumps, in conditions of efficient and lower cost than air-to-water pumps that are being adopted in many countries in central and northern Europe.

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OPPORTUNITIES AND CHALLENGES OF A DIGITAL, CIRCULAR, AND SUSTAINABLE INDUSTRY

The path towards a carbon neutral and circular industry poses immense challenges, but there are also opportunities - more flexibility, increased self-consumption, and less dependency on volatile fossil fuel and electricity markets. To fully benefit from these opportunities, companies need to consider optimisation of production plans and energy efficiency improvements. New digital tools, such as the multi-objective advanced planning and scheduling, can be particularly useful in providing an optimised compromise between fulfilling delivery dates and minimise overall energy consumption.

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THE WORLD OF TOMORROW, TODAY

The energy transition carries with it the promise of a smarter, greener, fair, and (almost) waste-free world. However, this will require a major overhaul of our economies as more than 80% of world's energy use is supplied by coal, crude oil, and natural gas. And, with few exceptions, by imported fossil resources.

At the EU-27 level, the transition aims to reduce current levels of greenhouse gases (GHG) emissions by 50% in the next ten years and to reach carbon neutrality by 2050. On paper, the main strategy looks straightforward - full decarbonisation of electricity and heat production alongside massive electrification of the energy use in buildings, transportation, and industry. Additional sectorial strategies are also envisioned for hard to abate sectors, such as the production and use of green hydrogen for industry and long-haul transportation, and the integration of carbon capture and use for industrial processes emissions.

THE (SUSTAINABLE) FUTURE OF INDUSTRY

In industry, characterised by an heterogenous structure – i.e., some sectors are dominated by few big companies, while others are more fragmented, with many small and medium enterprises (SME) -, and a variety of products, production processes and systems, the full decarbonisation and electrification face considerable challenges.

Only one third of the energy use is associated with driven systems (e.g., compressed air, ventilation, refrigeration), which are already mainly powered by electricity. The main energy need, covering the other two thirds, is in the form of thermal energy for processes and other thermal needs.

Half of this corresponds to high temperature processes with (currently) limited potential for low carbon options. The other half has a wider spectrum of options, from direct integration of solar thermal energy and industrial heat pumps for lower temperatures, to replacing fossil fuels with hydrogen and bioenergy for medium range temperatures. Notably, as 20 to 50% of the heat production is lost as waste heat, there is a significant potential for immediate energy efficiency improvement through heat recovery and reuse.

While there are few commercial options for hydrogen-based technologies, or limited approaches to high temperature processes, recovering and reusing waste heat, integration of local renewable sources – solar photovoltaic (PV) or thermal -, and using heat pumps to either replace or boost lower temperature processes, have viable

Figure 1 Circular sustainable economy

commercial alternatives already, which could contribute significantly to the industrial energy transition.

This new ecosystem of low-carbon options will also allow lower dependence on volatile fossil fuel and electricity prices, reduce operational energy costs, and increase the availability of flexible assets (e.g., thermal and electrical storage, heat pumps, electrolysers). Moreover, it will require a new generation of digital tools to allow better management of the increasing variability and flexibility of local industrial energy systems.

ENERGY COSTS @ INDUSTRY

Energy - traditionally considered an indirect cost in industry - now places important challenges to those who depend on it to produce goods, on account of its rising costs, and type (solar, electrical, gas, etc.) and offer (solar energy production forecasts, electrical energy daily cost profiles, etc.) variability. In order to remain competitive in regional and global markets, managers need, more than ever, to find ways to balance operating costs against profitability, which is an especially difficult task for SME.

OPERATIONAL EFFICIENCY VS EFFICIENT USE OF ENERGY

Industrial companies have carried out major actions to improve their operational efficiency, acting upon predictive maintenance, setup and changeover minimisation, human resources upskilling and adequate selection and use of manufacturing execution system (MES), enterprise resource planning (ERP) and planning and scheduling tools.

Energy efficiency is essentially achieved using more recent, more productive and efficient machines and ancillary equipment, although further improvements may be achieved through the use of planning and scheduling tools. The vast majority of SME do not have the capability to renew all their productive resources and, as such, one frequently witnesses a mix of distinct generations of machines capable of producing the same products and their variants at the shop floors.

Faster, more energy efficient machines do not always mean faster changeovers; towards fulfilling all customer orders, all machines, old and new, must be used to full extent.

So, what do we need and how do we come up with a production plan (allocate and sequence production orders in machines) that's both optimised for customer service and uses energy in an efficient way?

CHALLENGES TO ACHIEVE ENERGY EFFICIENCY IN INDUSTRY

Data acquisition models and policies that support decision-making and keep our information secure need to be properly designed and implemented, as they are crucial to achieve operational and energy efficiency. This usually implies deploying an industrial Internet of Things (IOT) platform. Industrial companies need to know their machines, products, and process characteristics and how they relate to energy consumption.

A production plan that's globally optimised for customer service and efficient use of energy is often not optimised at machine level. We need to increase the acknowledgement of this duality among human resources who often have difficulty in understanding why production orders on their machines are no longer properly ordered, in their opinion.

We need to implement, when and as much as possible, flexibility on when operations are performed depending on energy availability and tariffs. Without this flexibility, there will be not enough freedom to obtain better solutions.

OPPORTUNITIES THAT ARISE FROM KNOWING YOUR PRODUCTION SYSTEM AND PROPERLY USE ENERGY OFFER

Being able to correctly characterise the processes and production systems' energy consumption characteristics, together with information on current and forecasted product demand and energy offer and prices, will allow the use of tools such as Multi-objective Advanced Planning and Scheduling to obtain solutions that provide an optimised compromise between fulfilling delivery dates and minimising overall energy consumption.

The energy demand profile resulting from these optimised solutions will allow more sustained negotiation of energy purchases and emphasise the company role within renewable energy communities.

Industrial companies will be able to increase margins or be more competitive. They'll also be more resilient and face variability with knowledge and confidence, adapting production plans.

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POWER ELECTRONICS FOR SMART GRIDS AND MICROGRIDS

In recent decades, power electronics technologies have contributed to important developments in electrical power systems, in terms of electricity generation, transmission, distribution and end-use, culminating in the advent of smart grids and microgrids, which are essential to enable the integration of generation from renewables with energy storage technologies and their coordinated operation.

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POWER ELECTRONICS

Power electronics is the technological area associated with the use of electrical and electronic components for the conversion, control, and conditioning of electrical energy. By using systems that employ power electronics, it is possible to process the power flow from the production to the loads and vice-versa, allowing, in both cases, a highly efficient and reliable operation. In particular, power electronics is used when the aim is to change the way that electrical energy is made available, either in the conversion of alternating current (AC) to direct current (DC) (using rectifiers) or from DC to AC (using inverters), either to change the amplitude of voltages and currents, both in DC (using switched power supplies), and in AC (using voltage regulators or dimmers), or even to change the frequency value (using cycloconverters or by combining rectifiers and inverters). Power electronics technologies can be used for a wide range of applications, from solutions of low-power applications (e.g., in the order of mW in mobile communication systems) to solutions of high-power applications (e.g., in the order of GW in high-voltage DC power transmission systems). Due to the technological evolution, it is possible to design power electronics solutions with lower costs, greater efficiency, and increased functionalities, including fault-tolerant operation. Power electronics will remain crucial to support new technological solutions (Figure 1): systems for energy production from renewable sources; energy storage systems; load management systems; green hydrogen production systems; electric mobility systems (including rail, road, maritime and aerospace transportation); telecommunications systems; systems for improving power quality and power flow control (including active power conditioners and solid-state transformers), and energy-use systems in industries and homes (automation and robotics, motor control systems, lighting, air conditioning, household appliances, etc.) (AFONSO, 2020) (AFONSO, 2021).

SMART GRIDS AND MICROGRIDS

The decarbonisation of the economy, combined with the need to renew the electricity grids, triggered a paradigm shift in electrical power systems, increasing the capacity to integrate decentralised production based on renewable energy sources and new services and markets that promote the active participation of consumers (LOPES, 2019).

This led to the emergence of the smart grid concept, which is understood as an active grid capable of dealing with the greater complexity of the electrical power grid operation, through new

Figure 1 Examples of applications using power electronics technologies.

monitoring, automation, and control solutions. These new solutions aim to ensure a safer and more efficient power grid operation from a technical and economic point of view, enabling new services to consumers, producers, and prosumers. More specifically, smart grids involve the integration of diverse technologies into the power grid that establish a bidirectional flow of information on its operation and performance - from the generation to the transmission, distribution and end-user systems.

Power electronics technologies take on a special relevance in several applications (Figure 4) associated with electric vehicles, decentralised renewable energy generation and energy storage solutions. These interfaces must ensure the optimal connection to the power grid, while minimising the impact of these technologies on its operation.

Power electronics converters, commonly identified as smart inverters, currently enable the integration of local control algorithms to support voltage and frequency regulation, as well as communication and remote control (IEEE, 2018). With these monitoring and communication technologies for information collection and remote actuation, the inverter can locally adjust its power operation according to the power grid conditions, avoiding the unwanted disconnection of renewable-based production units, while allowing for their integration into energy management and grid optimisation systems.

The flexibility of the inverters and their interoperability allows to explore strategies concerning active consumption management with benefits for the consumer, the energy communities and the power grid operation. For example, in the case of an electric vehicle, when connected to the grid, it can charge in a controlled manner when operating in G2V (grid-to-vehicle) mode, also supporting the power grid or even the home where it is connected, by operating in V2G (vehicle-to-grid) or V2H (vehicle-to-home) modes (MONTEIRO, 2016)(GOUVEIA, 2013).

Figura 2 Smart charging

The flexibility of smart inverters is also essential to microgrids, aiming at fault detection and protection strategies, as well as reliable operation with high standards of power quality. Defined as a distribution power grid that integrates distributed generation, electrical energy storage and flexible loads that operate in a controlled and coordinated way, the microgrid can operate interconnected to the distribution power grid or islanded from the main grid (ANDRE, 2017).

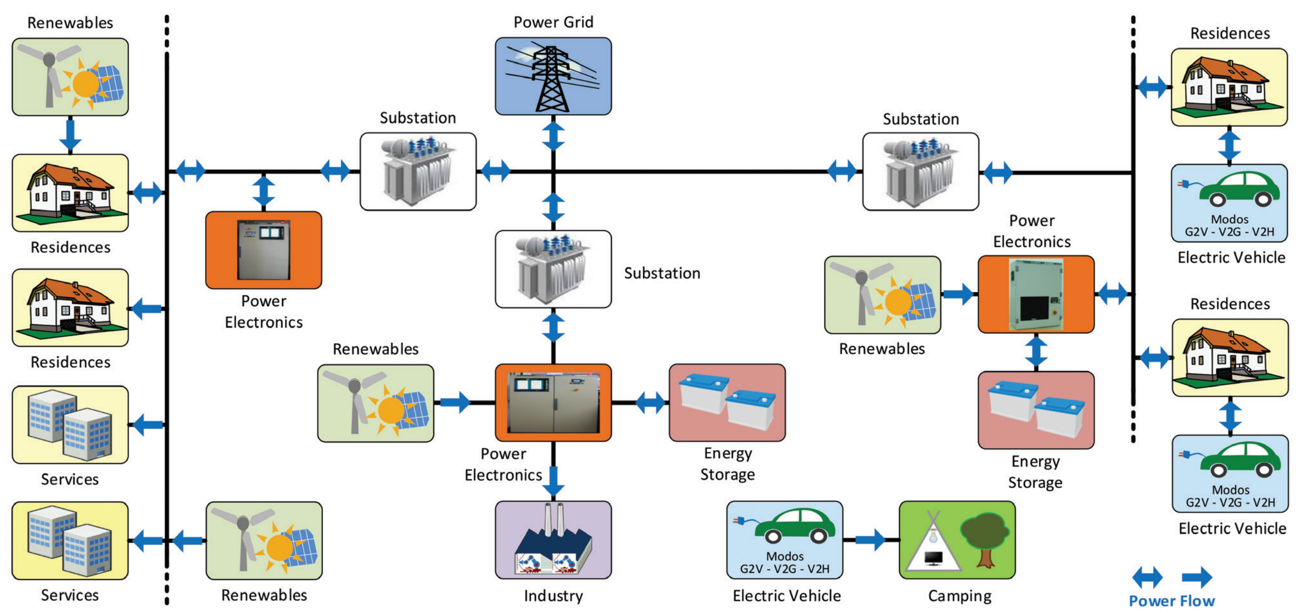
The new regulatory frameworks for collective self-consumption, together with concerns about the electrical power system security of supply and resilience, have led to a growing interest in microgrids. At the same time, the flexibility of smart inverters has also contributed to the definition of different microgrid topologies (DC, for example) and the integration of different technologies (from conventional generators to electrolysers), enabling different business models, ranging from rural and remote electrification, energy communities and data centres.

From a perspective of the power system resilience, the microgrids allow for local blackstart and can also be aggregated into clusters of microgrids, supplying the loads of a region through local strategies of service replacement (MONTEIRO, 2016). However, these operating modes require specific control strategies of the inverters and synchronisation mechanisms (GOUVEIA, 2013)(MONTEIRO, 2021).

Regarding power electronics applications in grid infrastructures, the main objective is to increase the transmission capacity and improve the power grid stability and power quality. However, due to high costs, its integration is mainly verified in power transmission networks, with the installation, for example, of FACTS (Flexible Alternating Current Transmission Systems) and STATCOM (STATic synchronous COMpensator). However, it is expected that, in the upcoming years, new solutions for the distribution power grid will emerge - where, in addition to congestion management, the use of such equipment will also foster improved voltage regulation capabilities and increase the flexibility of the power grid infrastructure (MONTEIRO, 2021)(ZHU, 2021).

Figure 3 Smart energy inverters

In conclusion, given the goals of decarbonisation and the perspectives of technological evolution, the future electrical power grids will become systems largely dominated by power electronics technologies, from power generation to final consumption, including the power grid management. This new paradigm requires to the definition of control strategies that integrate all system components (individually or aggregated) in microgrids, as active elements in the optimisation, operation and reliability of the global power system. The contribution of power electronics technologies will also be essential to mitigate the estimated number of about 770 million people without access to electricity in the world (INTERNATIONAL ENERGY AGENCY, 2021), and about 3.5 billion suffering from connection to electrical grids with low power quality (AYABURI, 2020).



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ENERGY COMMUNITIES AS A DECARBONISATION DRIVER OF THE ENERGY SYSTEM

Energy communities can contribute to the decarbonisation of the energy system, but their regulation and support mechanisms, and the administrative processes for licensing and commissioning, need to be improved to boost their fast development, also contributing to a more active role of end consumers in energy processes.

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THE ROLE OF THE ENERGY COMMUNITIES

Renewable energy communities (REC) and collective self-consumption (CSC) can play an important role when individual self-consumption (ISC) is difficult to implement due to lack of space, inadequate consumption profile, financing difficulties, or surplus valorisation. The motivations can be economic, but also self-sufficiency, environmental, and social.

The concept of REC was introduced by the European Directive No. 2018/2001 (European Government, 2018) which sets goals regarding the promotion of the use of energy from renewable sources. In Portugal, the first legislation on REC was Decree-Law 162/2019 (Portuguese Government, 2019), replaced by Decree-Law 15/2022 (Portuguese Government, 2022) on the organisation and operation of the national electric system, which includes improvements to several aspects of the previous regulation of self-consumption.

A CSS/REC can be a condominium, with a common photovoltaic plant on the roof. It can be a village or a neighbourhood, with one or several PV plants on neighbouring land. It can be a heterogeneous organisation of neighbouring consumers where the surplus from large rooftop industries or public buildings is shared among smaller bordering consumers. It can simply be an agglomeration of ISC, who wish to manage and share their surplus production with their neighbours.

REC are a process of local aggregation that grants strength and decision-making power to consumers, who turn to own and make the energy resource available - which, combined with increased energy literacy, will be an important transformation and democratisation driver of the electricity system, with the creation of new business models. However, the infrastructure to share energy locally will still be needed, so the public service network will continue to play a key role, with the need for smart metering equipment and more complex and innovative local electricity distribution protocols.

SUMMARY OF PORTUGUESE REGULATION

In a CSS/REC, consumers and producers close geographically join to produce energy and share the surplus with other members. The agreed sharing rules determine the allocation coefficients

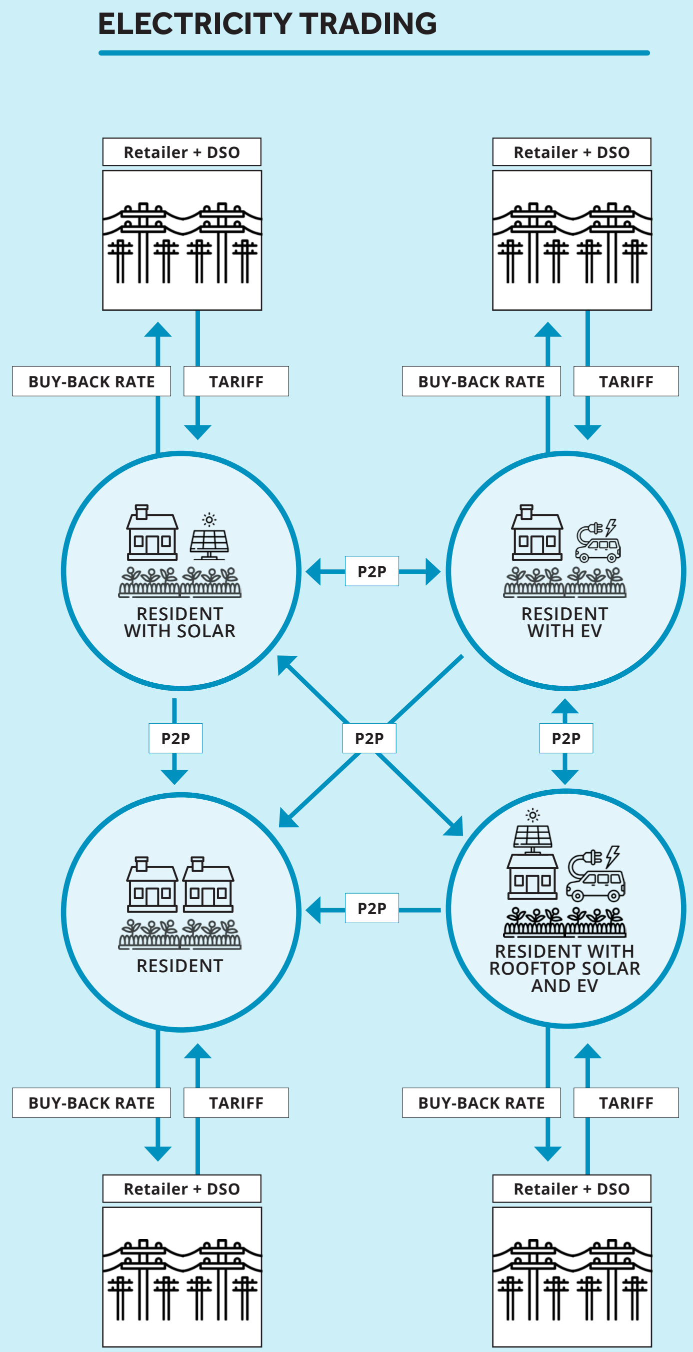

Figure 1 Adapted from "Innovation landscape brief: Peer-to-peer electricity trading, " IRENA, 2020

(AC) with which the distribution system operator (DSO) calculates, from the meter readings, a) how much energy is supplied by suppliers and how much is self-consumed from local production, and b) for each community resource that is injecting energy, the amount to allocate among consumers, thus defining the path followed by the energy. This path determines the access tariffs to be paid for the self-consumed energy (Rogério Rocha et al., 2021). Usually, no access tariffs are paid for the voltage levels of the supposedly unused grid. Additional subsidies may also apply, such as partial or total exemption of the CIEG in the case of Portugal.

AC can be fixed, proportional to consumption, or dynamic and calculated by the REC itself, the latter (already in Decree Law 15/2022) being the ones that actually allow implementing business models adapted to the requirements of each REC (Rogério Rocha et al., 2021).

While ACC are oriented towards simple energy sharing schemes (for buildings or condominiums), REC seem to be oriented towards more complex business models and need to be set up with a legal personality. Both must be not-for-profit initiatives. Finally, citizen energy communities can include non-renewable generation sources and own and manage their own distribution network, being subject to the same restrictions on proximity between the resources that comprise them. They primary goal cannot also be financial profit.

BUSINESS MODELS

The way investments in generation resources (e.g., photovoltaic panels), flexible resources (e.g., batteries), and energy management systems are made, and the profiles and activity sectors of the members and actors involved in a REC, lead to different business and governance models (Moreno et al., 2022). Indeed, members with a consumer profile sought to reduce energy costs without engaging in production activities, while members with a promoter profile invest in generation assets to monetise them, and companies providing energy services may develop and operate the REC management systems. Moreover, surplus can be shared with simple rules or in local markets (Mello et al., 2020), for which financial compensation to the owners of

Figure 2 Photo credit: CIFOR on Visualhunt

the surplus must be specified, leading to the settlement rules as an integral part of the business model (Mello, Villar and Saraiva, 2022).

Important challenges to encourage the participation in CSS/REC are, for example, adding additional services for the members (USEF, 2019), and promoting their active role in the system operation through business models that encourage aggregation and participation in the provision of flexibility services to the system.

EXAMPLES OF CSS/REC

Collective renewable energy production in Portugal is starting more with the CSS model and less with REC, but there is still no public information about how these projects work. In several cases, the initiatives are stuck in a bureaucratic limbo, waiting for approval from national entities. The following examples are projects that are in the design and registration phase at the DGEG.

The parish of Vila Boa do Bispo is setting up a local REC. The legal form is Cooperative of Public Interest, because this REC is an initiative of the Parish Council. The first project of this REC will produce photovoltaic energy to share between the local Fire Brigade, Casa do Povo and the Parish Council itself.

In Alta de Lisboa, a condominium with more than 150 apartments in eight buildings is expanding its solar photovoltaic production systems: from simple self-consumption systems for the common parts of the buildings to an CSS, in order to share local production among all the condominium owners, in addition to the common parts of the buildings.

In Oeiras, a condominium of six apartments took the initiative to install a small solar photovoltaic plant to start a collective self-consumption model and share electricity among its condominium owners.

REGULATORY LIMITATIONS AND IMPROVEMENTS

Limitations to CSS/REC projects still exist and solutions are needed.

The payback of CSS/REC is still not very favourable when compared to the payback of ISC, but access tariffs for shared energy could also consider the direct and indirect benefits to the country of individuals and companies investing in decentralized renewable production.

Bureaucratic and administrative support tools must be made available, such as support in drafting the regulations governing the operation of the CSS and support in contacting the official entities (DGEG, Energy Services Regulatory Authority and E-Redes).

The implementation of dynamic sharing systems should be accelerated to accommodate the business models appropriate to each situation. The role of the DSO in the energy sharing processes could also be reduced. The current model relies on virtual meter readings, which do not need to be managed by the DSO and could be the responsibility of a third-party entity. This would open new opportunities for new technological innovation services, reducing the difficulties that the DSO is facing in adapting to this new form of energy sharing.

Therefore, and since other technologies s (feed-in tariffs for renewables, tax exemptions on the purchase of electric vehicles, etc.) benefited from aids, it would be beneficial to acknowledge the positive externalities in the energy transition technologies and support them to accelerate the implementation of CSS/REC for their contribution to this transition and the resilience of the electricity system.

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HYBRID OFFSHORE FARMS

HARVESTING OFFSHORE ENERGY THROUGH THE COMBINATION OF DIFFERENT GENERATION TECHNOLOGIES

The current EU energy situation requires innovative technologies to attain affordable, resilient, and renewable energy... and there is an ocean of opportunities to explore

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When thinking about offshore energy, wind power comes directly to our minds. In fact, this technology is the major responsible for offshore energy generation, being already on a commercial state. From the 2000s decade onwards, wind power industry had a massive and sustained growth, with great emphasis on Europe. Portugal is one of the good practice examples regarding wind power integration - which, allied with favourable hydro power, allowed achieving considerable share of renewable integration in its electricity mix. Many other countries are pursuing wind power generation and, more recently, photovoltaic (PV) generation to attain the so-called sustainable electricity by reducing the fossil-based fuels need and consequently CO2 emissions.

Notwithstanding, the major spots for wind power generation are already in use across Europe. In addition, the plans for decommissioning nuclear power plants, carbon markets and more recently, the natural gas price increase, are putting an additional burden on electricity generation, where wind power plays an important role. Aware of the challenges, the European Commission (EU) has anticipated the need of going offshore with an expected amount of 60 GW of offshore wind and 1 GW of ocean energy, to be installed by 2030 (European Commission, 2020). According to WindEurope association (WindEurope, 2020), by the end of 2020, 25 GW of offshore wind power were installed in Europe. These farms are typically installed close to shore in monopiles or through foundation jackets. However, the floating technology, already deployed in Viana do Castelo offshore farm, unlocks the possibility for going further offshore, exploring deeper water depths.

Offshore energy is not strictly associated with wind power. As a matter of fact, several developments have been made on wave energy harvesting. Some interesting concepts have been explored, but failed on real-word tests due to the inability of the wave energy converters' (WEC) on withstanding the wave forces. Recently, some companies are presenting successful designs to generate electric energy through the wave motion at offshore level. Moreover, PV technology has also been utilised over water through floating devices. Even though most of the projects are implemented on rivers or dams, there are some pilot projects at offshore level, presenting very satisfactory results, namely in terms of withstanding harsh sea conditions (e.g., sea storms). Despite being reduced in size and on maturity, wave and floating PV are seen as an interesting alternative for offshore energy harvesting.

All the offshore renewable technologies share the common challenge of the interconnection to mainland. The connections must be performed through the adoption of underwater cable circuits, which brings high costs. The connection costs together with the offshore farm costs leads offshore projects to having a high levelised cost of electricity (LCOE), meaning that the €/MWh generated tend to be higher than onshore similar projects. In this sense, the need of having more renewable-based electricity at lower costs, motivates exploring the possibility of combining different generation resources on hybrid offshore energy farms.

Hybrid offshore energy farms will make it possible to harvest more renewable-based electricity from the sea and, by sharing the same interconnection infrastructure, will allow reducing the connection costs, contributing for lower LCOE. Although more installed capacity commonly means the need of more cable capacity, more energy generation may not have that impact, if the offshore hybrid systems are designed to exploit the correlation between the renewable sources, increasing the usage of the given connector cable. This means that for a given offshore wind farm, a certain amount of hybridisation can be installed (i.e.,: wind + wave energy, wind + floating PV, wind + wave + floating PV) making a better use of the interconnection infrastructure, harvesting more renewable-based energy, not impacting on using a cable with more capacity - thus not increasing interconnection costs and consequently, helping on reducing the LCOE.

WHAT IS THE IDEAL OFFSHORE TECHNOLOGY MIX?

Offshore hybrid farms, as previously stated, are composed by a combination of different offshore generation technologies that share a common interconnection infrastructure. There are two ways of pursuing a hybrid offshore farm. The first consists of hybridising existing offshore wind farms with other technologies to increase the generated electricity without exceeding the interconnection cable capacity, by exploiting the correlation of involved energy sources. The second solution consists of building a hybrid farm from the scratch. On both cases, it is of upmost importance determining how much of each technology will constitute the hybrid farm. To achieve such fulfilment, it is necessary to have renewable resource data and computational models responsible for simulating different combination of technologies to determine what is the best set to be implemented. There is also additional data related with specificities of the geographic location, such as water depth, sea soil composition and environmental restrictions, that must be incorporated to the problem, to shape the solution for the case that is being analysed. Thus, there is not a common solution that can be extrapolated for everywhere, but there will be important guidelines that could be considered for different geographic areas.

WHAT IS THE AMOUNT OF HYBRID OFFSHORE RENEWABLES THAT CAN BE CONNECTED TO MAINLAND POWER SYSTEM?

The renewable integration, especially from offshore, will depend on the mainland onshore grid connection capability, on the interconnection technology (high voltage direct current – HVDC or high voltage alternate current- HVAC) and on the dynamic stability aspects of mainland grid. So, it is important to perform an thorough assessment to determine the maximum interconnection volume and locations.

From a regional scale point of view, it is necessary to determine the connection capability of each onshore substation, defining a hypothetical amount of connection capacity. Moreover, at the system level, it is important to understand the impact of transposing the regional interconnection capacity to the power system operation. To do so, a set of analysis on N-1 operation and dynamic security assessment must be performed to determine the effective capacity for secure offshore farm interconnection. In this sense, the adoption of offshore grids (HVAC or HVDC) may also pave the way for increasing the interconnection between countries and globally the share of renewable energy integration.

HOW TO MAINTAIN OFFSHORE HYBRID FARMS?

Maintenance is one critical aspect related to offshore operations, since it is hard to be performed, especially on harsh sea conditions, and it is quite expensive (at least in comparison to mainland maintenance operations). It is consensual that the hybrid offshore farms will need maintenance, with different requisites that vary according to the selected technology mix; it is crucial to assess how to deliver it at the most affordable way. Determining the maintenance needs and the best timeframe to perform such actions, requires the incorporation of computational tools combined with accurate monitoring of the hybrid farms and involved renewable resources and sea conditions forecast. Digitalisation will play a key role on monitoring, together with proper models, and they will help decision makers on determining the most cost-effective maintenance schedules.

INESC TEC is part of the EU-SCORES project, where many of the aforementioned challenges will be addressed to establish a roadmap for hybrid offshore farms for EU and major key findings that may also be used on other locations. In addition, the project will also tackle the logistics and environmental aspects related to the massive construction of those type of renewable-based powerplants soon.

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IS THERE A LIMIT TO SOLAR PHOTOVOLTAIC ENERGY IN THE GENERATION MIX?

The fraction of solar PV has no upper bound in the future electricity mix if we adopt an intelligent model for the simultaneous decarbonisation of the power and transportation sectors.

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In many sunny countries, such as Portugal, solar photovoltaic (PV) energy, with reference costs of 0.03 to 0.04€/kWh, is the cheapest alternative: ~1/3 of that from new nuclear or biomass generation plants. This is one reason why solar energy will be one of the main instruments for the decarbonisation of the electric system – and of the economy.~

The obvious question is: what are the limits to the penetration of solar PV energy in an electric system? What fraction of the generation mix may be solar?

Let us first consider the impact on territory: if it were to satisfy, for instance, 50% of future generation needs, wouldn't it occupy an unacceptably large area of the territory?

If we assume a future total need of 90TWh/year in Portugal 2050, and a PV generation of 1.5GWh/ha.year (resulting from present technology), in order to satisfy 50% of the total demand, an area of 283km2 would be necessary. This is about the same area as that of the Alqueva lake, and only 0.3% of the territory. If the area is carefully chosen, with involvement of local population, its implantation is not a problem (contrary to biomass, which, for the same generation of electric energy, would require an area of dedicated forest >40% that of the country).

Let us now consider the impact of massive penetration of solar PV in the balance of the electric system. Here we do have a problem, resulting from the time variability of PV generation, and its incapacity to adjust to demand, just like wind. Presently, solar+wind generation is less than 40%, hydropower is ~20%; with ~3GW of cross-border connections with Spain, and 4.6GW of natural-gas powered generation capacity, it has been possible to balance the system. However, in the future decarbonised system, solar+wind will be >80%, hydro only ~10%, and natural-gas is undesirable: the central issue of the future electric system will be imbalance. The central issue will cease to be the economic and environmental costs of generation, it will be the cost of balancing the system.

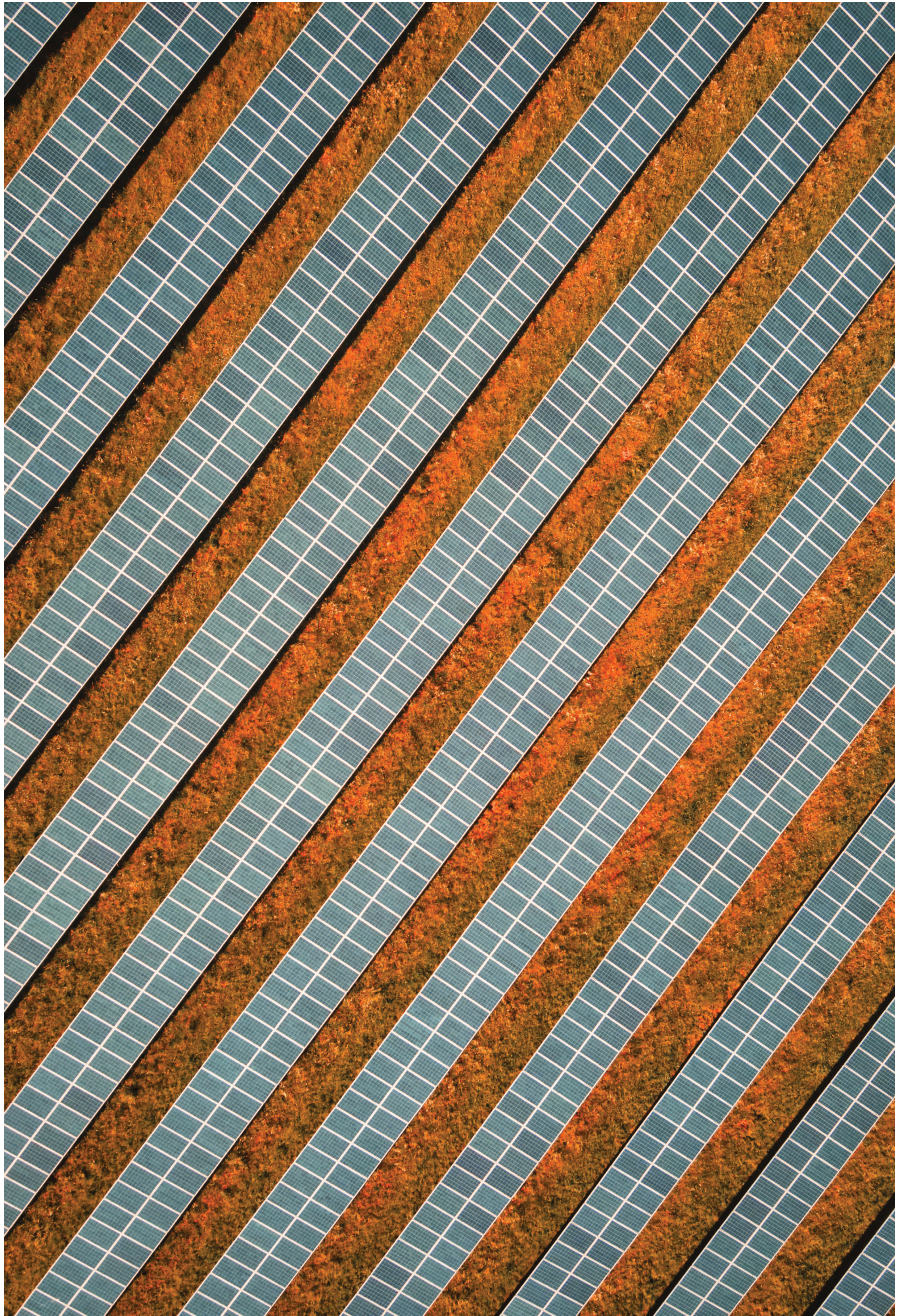
The problem is illustrated in Figure 1A, where we represent, for a winter week in Portugal 2050, the time-series of demand and of the various generation sources (their relative proportions inspired by the data in the Roadmap for Decarbonisation Portugal 2050[1]), directly reflecting the resources (sun, wind, water, and biomass), with no attempt yet to balance the system. In Figure 1B, we represent demand and the system generation deficit function (at times of generation excess, the function is negative), after all classical means to balance the system have been put to work at their maximum possibilities: water management in the dammed reservoirs, including pumped storage in periods of excess generation, and power management of the thermal biomass plants (with maximum power in times of system deficit, and minimum in times of excess), leaving out only import/export. The imbalance is still brutal, with deficits reaching 9GW (when the sun sets and evening demand is high), and excess generation reaching >20GW (when the sun shines and the wind blows strong).

Does this mean that, in this decarbonised model system, the limit of penetration for solar PV and wind has been largely exceeded, because the system is irremediably imbalanced?

No, it is always possible to balance it, through a combination of (1) additional storage systems (beyond the foreseen reservoirs and pumped hydro plants), (2) generation overcapacity (with curtailment in times of excess) and (3) import/export. The problem is the costs associated with said solutions, which may easily surpass generation itself if badly designed, resulting in excessively expensive electric energy.

There is, however, another possibility, which may be the key for low-cost solutions: to turn a substantial fraction of demand into a flexible load. In other words, instead of trying to adjust generation to demand, find substantial sectors of demand that may adapt to generation availability.

First, we observe that domestic, commercial, and industrial general demand has some capacity to adjust to availability (e.g., management of heating/cooling systems), but very limited, quite insufficient for a relevant system balancing effect. Which relevant sectors may then adjust consumption to availability?



One of them is green hydrogen production via electrolysis. Electrolysers may work at maximum power in times of availability in the system, and reduce or even cancel consumption, in times of lesser abundance or deficit. In addition, stored hydrogen might be used in fuel cells to inject power back into the system in times of need, acting as a firm power reserve. However, the degree of penetration of hydrogen technologies (influenced by high costs and low efficiency) in the economy is still not clear. If green hydrogen production remains limited to present values, the weight of the sector will be insignificant; on the contrary, if hydrogen becomes an energy vector with an impact like that of natural gas, its relevance for system balance becomes substantial.

Another sector, the impact of which is much safer to estimate, is road transportation, which presently resorts to an energy equal to 135% of electrical consumption in the form of fossil fuels and must be urgently decarbonised. The electrification of vehicles with batteries brings about an efficiency gain, relative to internal combustion technology, of a factor of ~2.5, so the additional electric energy demand by road transportation would be ~54%, a substantial fraction indeed. Moreover, the mechanical power on wheels of the present ~7 million vehicles is ~600GW, 100 times the average power in the grid. The impact of electrification of road transportation on the electric system will be huge. Hence, the relevant question: is it possible to turn this massive demand into a flexible load, which adjusts to availability?

If we carry on with present technology, with battery charging being carried out by plugging the vehicle to a power socket, the answer is yes, but in a very limited way. The vehicles which consume most are the heavy, long-range trucks, and they need immediate fast charging, they cannot afford to wait for times of excess generation in the grid. On the contrary, private light vehicles may be parked 99% of the time, have all the time available, but no consumption, except during long-range trips, when their owners again want fast, immediate charging.

Let us imagine, instead, that vehicles exchange their discharged batteries for charged ones, an operation that takes a couple of minutes, in service stations, where batteries remain coupled to the grid for an average time of 24h, during which period they act as a totally flexible load while charging. The nominal power of these resident batteries, which amount to ~10% of total on-board batteries, will be 60GW, much more than necessary

- to absorb all power generation excess
- to support the system, as a firm power reserve, in case of deficit.

In Figure 1C we demonstrate the impact of these models of decarbonisation of road transportation, by displaying

- the generation deficit function resulting from a rigid total demand, already shown in 1B, as a reference
- the deficit function resulting from partial flexibilisation of road transportation demand, in a model of battery charging by plugging the vehicle to a power socket (including a vehicle-to-grid component of grid support with use of vehicle batteries)
- The deficit function resulting from the total flexibilisation of road transport demand, in a model of battery swapping, BS (also including a battery-to-grid component, which interestingly is much less relevant than the dominant effect of demand flexibility).

This last function demonstrates that system balance is easily achievable, even with a penetration of 44% of solar PV generation (and 85% of solar+wind), if we adopt an intelligent model of powering road transportation, turning its consumption into a flexible load.

Finally, the answer to the original question: there is no foreseen limit to the penetration of solar PV generation. The optimum fraction for Portugal will be around 40-50%, as already pointed out by the National Roadmap, and we demonstrated that there will be no problem with its implantation nor with the electric system stability – provided we embrace the correct options.

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Figure 1A **A WEEK OF JANUARY 2050: DEMAND AND GENERATION (BY RESOURCE: SOLAR, WIND, ...)**

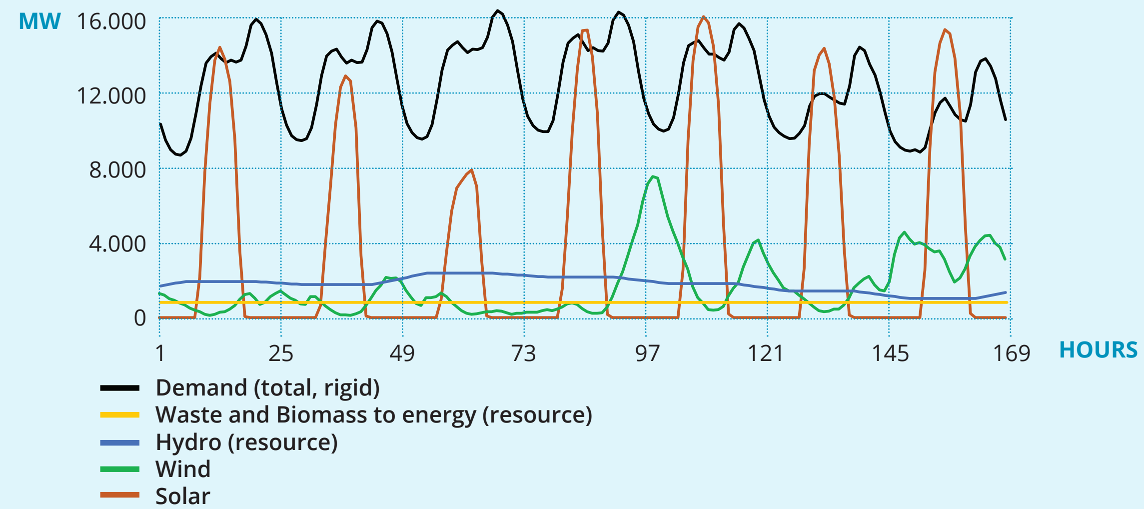


Figure 1B **A WEEK OF JANUARY 2050: DEMAND AND GENERATION DEFICIT:**
1. Raw (reflects the raw resources, with no attempt to balance) and
2. Attenuated by management of thermal and hydro generation (with pumped storage)

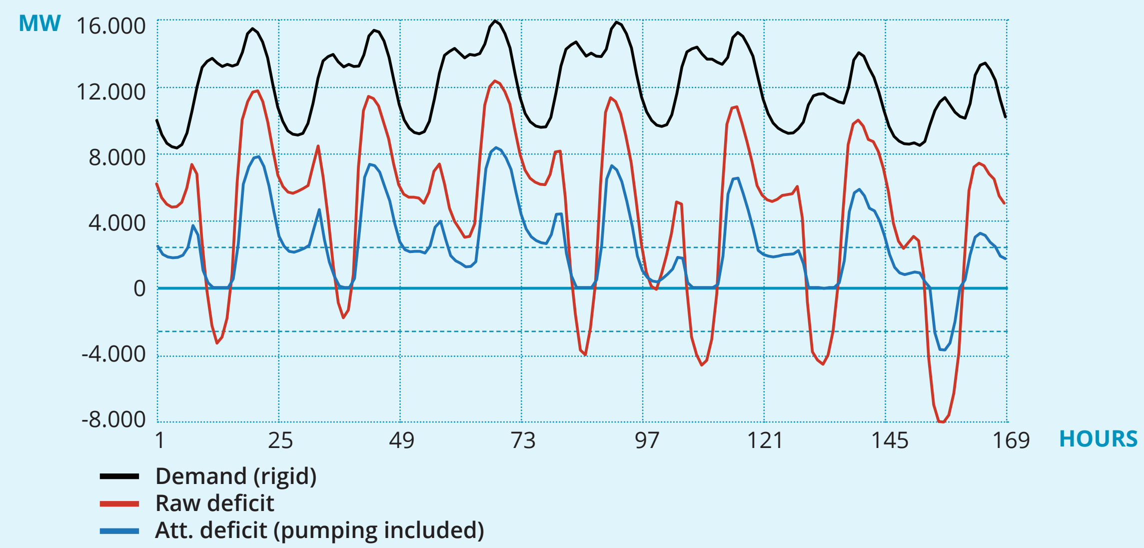
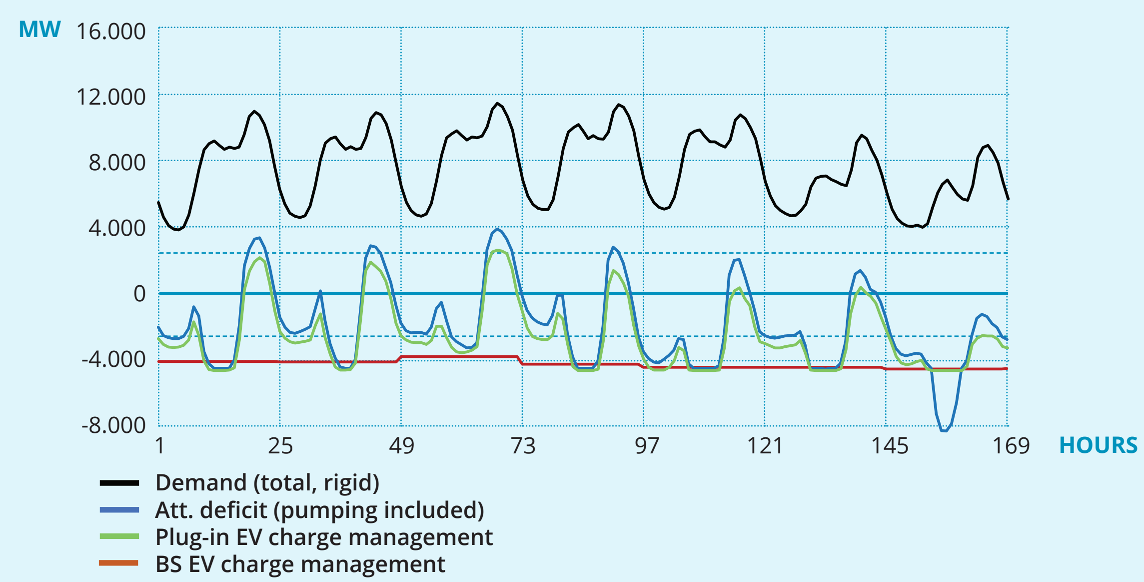


Figure 1C **A WEEK OF JANUARY 2050: DEMAND AND GENERATION DEFICIT ATTENUATED BY:**
1. Managem. of thermal and hydro generation (with pumped storage);
2. Added man. of Plug-in EV charge (V2G included);
3. Added man. of BS (battery swapping) EV charge.



MULTI-ENERGY SYSTEMS AND RENEWABLES GASES FOR A LOW CARBON ECONOMY

This article discusses the role of renewable gases in the energy transition needed to achieve a low carbon and sustainable economy. It also presents the current challenges, opportunities, and benefits from a joint management approach of different types of energy networks and sectors that interact at different levels in a building, city, or region – the multi-energy systems concept.

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Figure 1 Green hydrogen

1.THE NEED FOR AN ENERGY TRANSITION

Climatic change does no longer represent future threats, since the changes are already happening all over the world. Heat waves and prolonged droughts in Europe, hurricanes and floods in Asia are hitting the planet. These effects determine the need of decarbonisation of the world economy and, consequently, of a growing electrification of the economic activity - together with the utilisation of renewable power sources to produce electricity. However, the complete decarbonisation of the society and of the economy will not be possible without exploiting another energy vector – Hydrogen (H2) – a renewable gas, if produced from electrolysis of water and using electricity obtained from renewable sources, mainly wind power and solar photovoltaic (PV). The use of biogases is also expected to increase. In fact, the need for industrial high temperature heat, the need for new green fuels for long-range road transportation, maritime and air transportation justify the exploitation of H2 as a complementary vector to support a faster decarbonisation path. Apart from this, H2 can also be used to provide seasonal energy storage by using the excess of renewable generation under a power-to-power (P2P) solution and providing adequate security of supply levels to the power system.
The progressive electrification of the economy, together with an increased use of renewable gases, where sector coupling plays an important role, and the need to optimise the use of heat leads to the development of multi energy systems, requires an overall optimisation on the planning and operation of these infrastructures, with a common goal: Sustainability.

2.CHALLENGES AND OPPORTUNITIES – THE ROLE OF RENEWABLE GASES

Increased integration of renewable power sources brings the challenge of dealing with variable generation. The production of green H2 using renewable electricity can play a significant role in the context of the decarbonisation of the energy sector. In fact, the production of H2 can bring significant flexibility for the power system, if electrolysers are exploited as flexible loads able to address frequency changes, as well as seasonal storage of renewable electricity by developing a P2P solution, blending H2 into natural gas grids or by injecting directly to dedicated H2 infrastructures.

The variability of renewable generation will lead to surpluses of renewable energy in some periods of the year, and to scarcity of energy in others. As the excess of renewable electricity is seasonal, usually during spring (for wind) and in summer (for PV), there is a high interest in storing the surplus of electricity and electrolysers arise as a new load that may absorb this energy. H2 can then provide a seasonal storage solution if one can store this H2 in large reservoirs like caverns, which happens to be the case in Portugal - where large salt caverns are already used to store natural gas for use it in late autumn or winter. This solution can lead to the deployment of a sector coupling approach, where H2 is used to blend natural gas that is going to fuel combined cycle gas turbine plants or is directly used by stationary fuel cells (used also to produce heat that can be of interest for industrial cogeneration) or used by H2 turbines, leading to a P2P solution. The adoption of a P2P solution, where a H2 plant is used, provides a firm capacity to the power system, which allows keeping the security of supply levels within the desired limits.

The main technical challenges on the electricity sector relate to the efficiency increase in the P2P solution (electrolysers and H2 power plants) and the adaptation of the cavern reservoirs to store H2. Additionally, there are also regulatory challenges regarding the definition of an adequate framework for the P2P solution economic viability when dealing with the surplus of renewable generation, while assuring security of supply.

H2 is also used by the industry in several domains: oil-refining, ammonia for production of fertilisers, methanol production and steel production. In these industrial facilities, self-production of renewable electricity should be promoted via PV plants and cogeneration facilities, where natural gas should be blended with green H2.

The mobility sector is one of the main consumers of fossil fuel. Therefore, it is urgent to replace fossil fuels by green electricity and use biofuels and H2. H2, as a renewable gas, may play a central role in the decarbonisation of the mobility sector, namely for urban and regional buses, trains, long travel heavy transportation, and maritime and air transportation in the long-term. Green H2 can also be used nowadays as a sustainable aviation fuel (SAF) after duly conversion, contributing to decarbonise the aviation sector. The main technical challenge is how to store the amount of H2 required for an extended driving range within the vehicular constraints of weight, volume, efficiency, safety, and costs. Therefore, high-range and heavy-duty transportation should be the preferable mean of H2 deployment, as batteries should be more effective for light-duty.

At the buildings level, energy systems pose a unique challenge, which is the idiosyncrasy of the consumers, especially the particular renovation needs of old buildings. Energy poverty is also rising great concerns in the current geopolitical energy context and supply scarcity. Therefore, demand side response and energy efficiency, together with comprehensive techno-economical methodologies, are key to draft new decarbonisation pathways and increase its pace. Furthermore, in renovations where architectural challenges are massive, there are no silver bullets, so every technological approach should be considered in a multi-energy design.

3. MULTI-ENERGY SYSTEMS

An approach based on multi-energy systems is the step forward that must be taken to ensure an efficient and flawless energy transition, while ensuring that all the benefits of renewable electricity and gases and flexible loads (e.g., electric vehicles) are properly utilised.

In technical terms, a multi-energy system considers different types of energy networks and sectors that interact at different levels in a building, city, or region, as shown in Figure 2. The optimised operation and planning of multi-energy systems is expected to bring several benefits to the global system, like delivering cost-effective energy services, increasing reliability and quality-of-service, enhancing overall security of supply, while reducing the impact over the environment.

Green H2 may play an important role to foster multi-energy systems implementation. In fact, the H2 economy has grown exponentially in the past few years and presents an opportunity to research and develop new technological solutions to accelerate the energy transition.
Despite the potential benefits, there are still several challenges that one must overcome to achieve the implementation of the concept:

- Isolated institutional and market structures for the different energy sectors;
- Complicated technical, economic and market-related interdependencies between energy systems that are not holistically addressed by network operators;
- High operational and management complexity due the integration of multiple energy carriers;
- Lack of tools ready to guide the design and planning of integrated and interdependent energy systems.

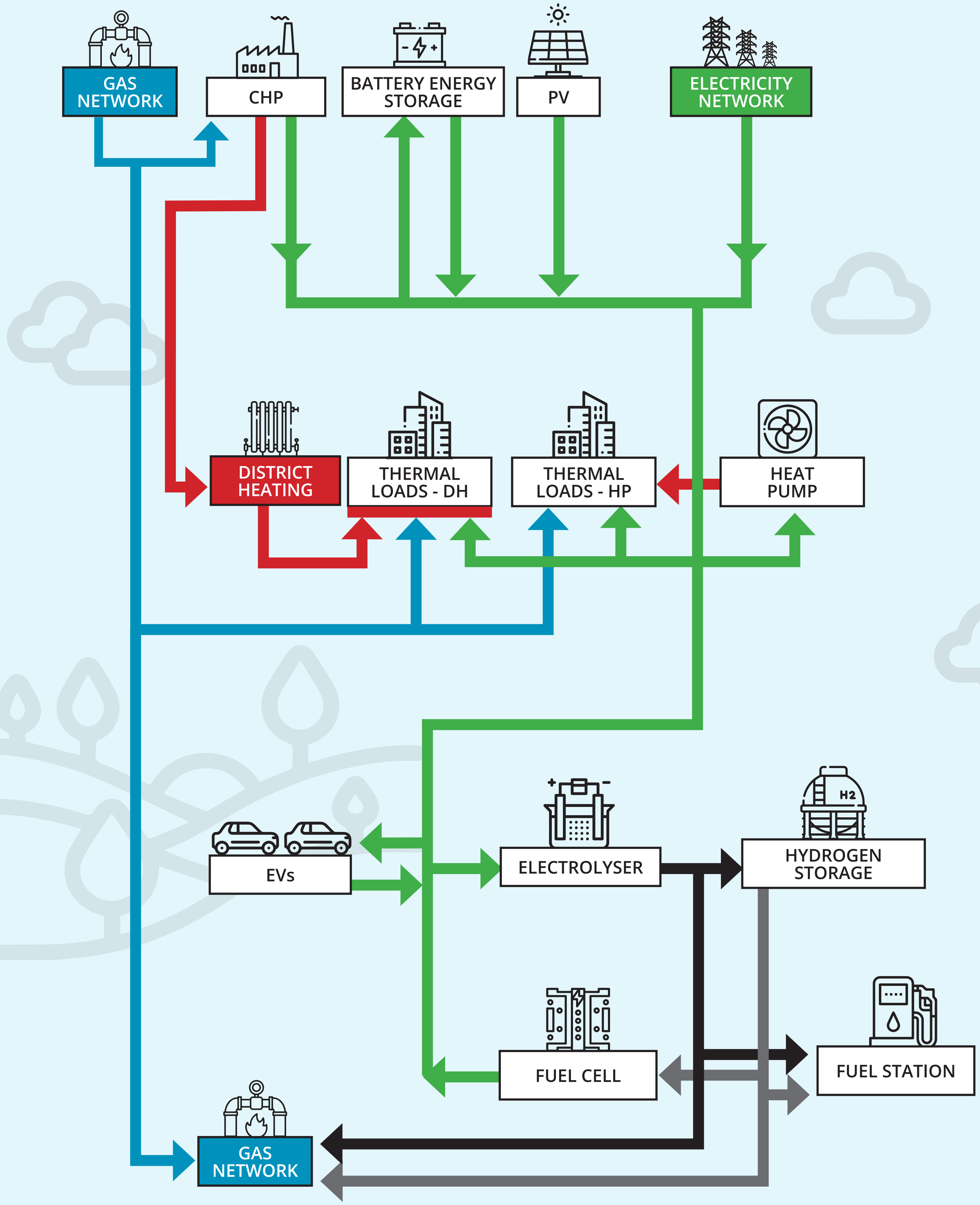

Figure 2 Hypothetical structure on a multi-energy system

Several efforts have been made in the last years to overcome these challenges, together with significant technical advancements in terms of operational and planning tools, and at the level of markets coupling.

4. NEXT STEPS

To effectively achieve the desired energy transition, several gradual measures should be put into practice, in different phases:

A. Phase 1 – Electrification of the economy will increase and advance renewable energy technologies deployment to decarbonise the electric power system.

B. Phase 2 – With a decarbonised electricity system, the development of new management approaches and tools to supervise and keep power system reliability levels should be a priority. Efforts should be made to decarbonise heating and transportation sectors, together with an investment in the real-world implementation of multi-energy systems. Renewable gases, namely H2, will increasingly decarbonise the energy sectors where electricity cannot effectively solve the decarbonisation problem.

C. Phase 3 – Reform regulatory and market frameworks to facilitate and leverage general electrification and general implementation of the multi-energy systems concept. Renewable gases will achieve the main support for the decarbonisation of the economy, using H2 in the industry and mobility sectors, fostering endogenous resources, while optimising renewable energy harvesting.

D. Phase 4 – Enforce a general implementation of the multi-energy systems concept, coupling electricity, gas, and heating networks together with the flexibility of multi-vector resources. Joint operational planning and long-term investment planning should be mandatory.

Figure 3 shows the global roadmap for a low carbon economy.

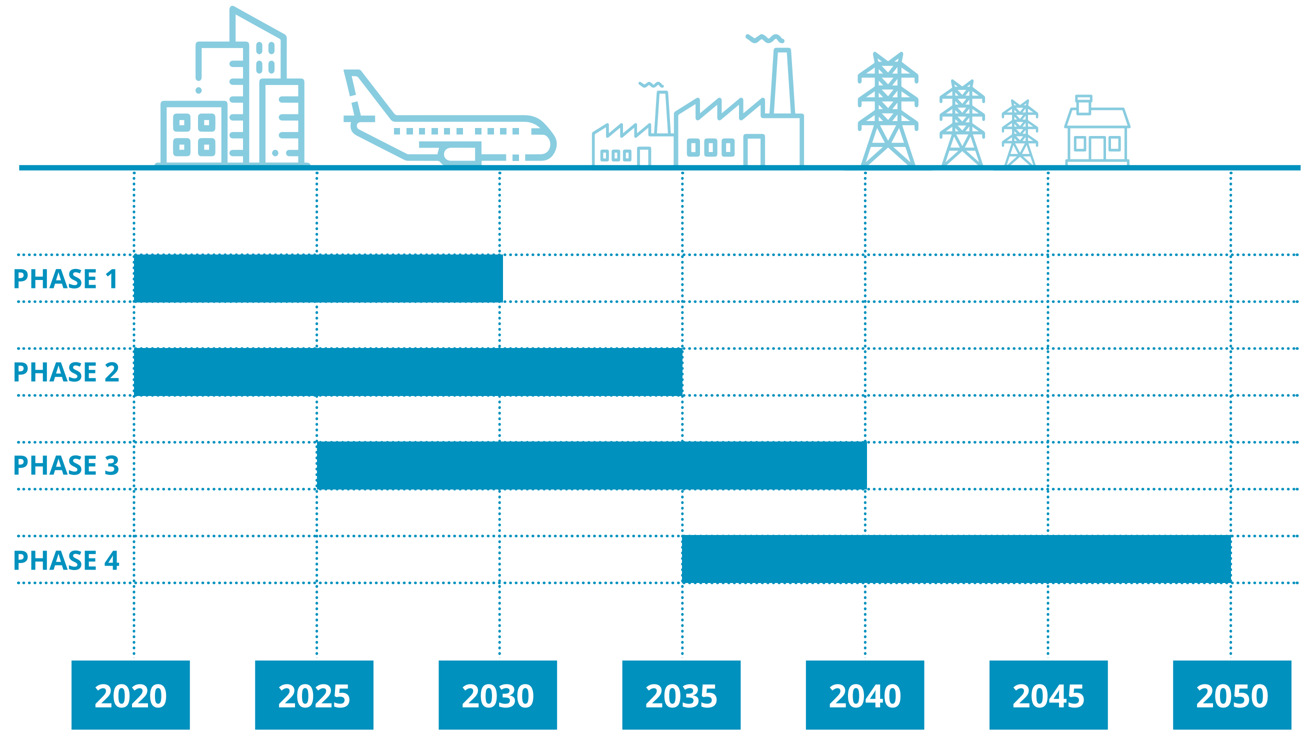

Figure3 Roadmap for a low carbon economy

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